ENERGY EFFICIENT ENGINE

PRELIMINARY DESIGN AND INTEGRATION STUDIES

David E. Gray
Pratt & Whitney Aircraft Group

SUMMARY

This paper summarizes the results of the NASA sponsored Energy Efficient Engine Preliminary Design and Integration Studies conducted by Pratt & Whitney Aircraft, with the assistance of Boeing, Douglas and Lockheed. A mixed exhaust, direct drive fan turbofan configuration was selected from the four candidates considered. This choice was based on its ability to exceed study goals of 12% lower TSFC and 5% lower direct operating cost by the 1990's with commercially acceptable technical risk and relative mechanical simplicity. The evaluation leading to configuration selection is discussed. Necessary technology advancements are identified and related to the goals.

INTRODUCTION

A NASA sponsored fuel conservative turbofan analytical effort conducted in 1974 and 1975 - The Study of Turbofan Engines Designed for Low Energy Consumption - indicated that over a 15% fuel savings was possible by utilizing projected 1985 technology. The estimation of this potential assumed major improvements in component efficiencies, availability of advanced materials, and structural innovation.

Four turbofan design configurations - direct drive and geared fan engines with separate or mixed exhausts - were each found to provide, within 2%, the same fuel savings potential. This closeness made it impossible to clearly segregate a preferred configuration and to ascertain the necessary unique technology advancements.

More detailed study of the four candidate configurations, including detailed airframe-engine system evaluation, was needed before a choice could be made. The Energy Efficient Engine Preliminary Design and Integration Studies were initiated by NASA in 1977 to provide the additional information necessary for engine configuration selection and to firmly establish vital technology development requirements prior to starting technology demonstration and proof testing.

DEFINITIONS

TSFC — thrust specific fuel consumption

DOC — direct operating cost

EPA — Environmental Protection Agency

EEE — Energy Efficient Engine

FAR 36 – Federal Aviation Regulations - Part 36

EPNdB – Effective Perceived Noise ~ dB

CANDIDATE CONFIGURATION DESCRIPTIONS

Conceptual designs of the four candidate engine configurations which combined a common high spool with various low pressure spool components and exhaust systems for parametric study were defined. General engine arrangements are illustrated in figure 1. Engine components were defined through regression analysis of many different configurations followed by more refined analysis of several attractive approaches. The following paragraphs describe the selected components at the 10,700 m (35,000 ft), Mach 0.8 cruise design point.

High Pressure Spool Components

A 10 stage high pressure compressor was selected to produce an 18:1 pressure ratio at a 445 m/sec (1460 ft/sec) inlet corrected tip speed. The combustor was conceptually designed with two combustion zones for low emissions. A two stage, high pressure turbine, with a loading coefficient (1) of only 1.2, was selected for high efficiency.

Low Pressure Spool Components

Low pressure spool configurations differed considerably depending on the fan drive mechanism - direct or gear.

Parametrically defined direct drive fans ranged from 6 to 9 bypass ratio with corresponding pressure ratios from 1.8 to 1.6. The pressure rise per stage of a three stage low pressure compressor was adjusted as necessary to hold overall compressor pressure ratio constant at 39:1. High loading coefficient, low pressure turbines had 4 or 5 stages dependent on the fan bypass ratio. A typical 7 bypass ratio engine with separate exhausts had a 1.74 pressure ratio fan, rotating at 470 m/sec (1550 ft/sec) tip speed. The fan and low pressure compressor were driven by a 2.5 loading coefficient, low speed, 5 stage low pressure turbine. With the 7 bypass ratio mixed exhaust configuration, the fan pressure was reduced to 1.66 to equalize turbine exhaust and fan exhaust total pressures for efficient mixing.

The range of bypass ratios studied for the geared drive fan configurations were 7 to 11 with fan pressure ratios from 1.75 to 1.45. The low pressure compressor rotated at 2½ times fan speed resulting in one less stage than required in the direct drive configurations to produce the same overall pressure ratio. A typical 9 bypass ratio engine with separate exhausts had a gear driven fan with a 1.58 pressure ratio and a 380 m/sec (1250 ft/sec) corrected tip speed. A high speed, 3 stage low pressure turbine with a loading coefficient of only 1.5 was utilized. A star reduction gear was positioned behind the fan. Gear generated heat was rejected in a fuel/oil cooler and a supplemental air/oil cooler located in the fan duct. The fan for the mixed exhaust configuration had a tip speed of 360 m/sec (1175 ft/sec) with a pressure ratio of 1.52.

---

(1) Loading coefficient relates turbine work output to available kinetic energy. Low values imply light aerodynamic loading for increased efficiency.

Exhaust Systems

The separate exhaust configurations included three-quarter length fan cowls with full acoustic lining for low noise. The mixed exhaust configurations included a forced mixer with a predicted mixing efficiency of 85% on a gross thrust basis. The efficiency prediction is based on JT8D and high bypass ratio mixer model test programs.

CONFIGURATION EVALUATION

Configurational capabilities were measured against the study goals of figure 2. The JT9D-7A, the most widely used current operational high bypass ratio engine, was used as the baseline. The TSFC goal includes the effects of isolated nacelle drag at a 10,700 m (35,000 ft), Mach 0.8 cruise condition. The direct operating cost reduction goal encompasses, in addition to fuel costs, the effects of propulsion system weight, price, and maintenance costs. The DOC goal penalizes weight and cost increases which could otherwise negate the operating economy attendant with TSFC. Stringent environmental goals were established which required incorporation of technological concepts aimed at substantial exhaust emissions and noise reductions. Goals for performance deterioration with operating time and for thrust growth allowance were set to assure continued fuel savings over the lifetime of the engine family. In combination, the study goals directed attention to expected requirements of future commercial transport engines of the 1990's.

Boeing, Douglas and Lockheed assisted in an engine-aircraft system evaluation of the four configurations. They first projected the spectrum of new commercial transport aircraft possible in the 1990's. Forecasts are obviously imprecise; however, many new aircraft are expected to be introduced in that time period. Each selected two representative aircraft - a domestic and an international service design. Advanced technology wide body aircraft, illustrated in figure 3, ranged from a Boeing 86,300 kg (250,000 pound) domestic twin-jet to a Douglas 210,000 kg (600,000 pound) international tri-jet.

For each of the study aircraft, the airplane companies conducted integration studies to size engines, determine installation effects, and define aircraft performance characteristics. A most important integration consideration was the potential for high interference drag with long, acoustically treated nacelles. This problem was addressed in under-the-wing installations by applying minimum drag nacelle-to-wing positioning criteria based on the aerodynamic development and testing of current high bypass ratio engine installations. Tail engine installations were positioned to maintain present high bypass ratio engine installation interference drag levels and to provide necessary nacelle-to-ground clearance during takeoff rotation. The airplane companies also estimated airframe noise, fuel burned, and aircraft weight as inputs into Pratt & Whitney Aircraft's direct operating cost, noise, performance deterioration, and thrust growth comparisons.

Results of the evaluation against goals are summarized in figures 4 through 6 for 7 bypass ratio, direct-drive configurations and 9 bypass ratio, geared configurations. TSFC and typical mission fuel burned reductions relative to scaled JT9D-7A powered equivalent aircraft are shown in figure 4. All four configurations exceeded the study TSFC goal as shown on the figure. Although a fuel burned study goal was left unspecified, fuel savings is a more important parameter than TSFC reduction. Fuel burned reductions varied substantially in response to differences in the ranges and payloads of the six aircraft types. The Boeing shorter range, domestic twin-jet exhibited the least fuel burned reduction amounting to approximately 60 percent of that for the very long range Lockheed international quadjet. A comparison of the capabilities of the four engine configurations was obtained by averaging the results obtained with each engine configuration in the domestic and international aircraft as illustrated on figure 4. On this basis, mixing of the engine exhausts and reduction gearing each increased the fuel savings potential by an additional 2-½%.

DOC and fuel burned trends were similar as can be seen by comparing figures 4 and 5. Using the average values of the results, mixing of the engine exhausts reduced DOC by 1.1%. Gearing, including the effects of gear set maintenance costs, reduced DOC by an average of 0.7 percent. It was additionally noted that, for many of the domestic aricraft, the DOC reduction potential was small. Bypass ratio of the direct-drive engine configurations was reduced from 7 to 6.5 for a small DOC improvement of about 0.2 percent based on parametric analysis.

The overall evaluation against goals results are summarized in figure 6. As previously noted, all configurations exceeded the TSFC goal and approached, or exceeded, the DOC goal. By incorporating an advanced two stage, low emissions combustor, all of the configurations were calculated to meet 1981 EPA carbon monoxide and unburned hydrocarbons emissions goals. However, all configurations were assessed to be incapable of meeting the oxides of nitrogen goal with known emissions technology. Noise goals could be met by the four configurations with projected advancements in fan source noise and acoustic absorption technologies. The effects of opened-up blading tip clearances, erosion, turbine airfoil creep and distortion, leakage, and foreign object damage were examined to assess performance deterioration. The engines were estimated to have a 4000 operating hour TSFC deterioration rate approximately one-half that of the JT9D-7A. Equal thrust growth potential of over 20% from the initial rating was predicted for all four configurations by compressor supercharging and higher turbine temperature.

Based on this evaluation, only mixed exhaust configurations were considered further. The mixed exhaust configurations embodied all of the propulsion technology advances requiring further development in engines with separate exhausts. The additional fuel savings and DOC benefits associated with mixing were judged to outweigh the added development risk of the exhaust mixer.

Preliminary designs were executed for direct-drive and geared, mixed-exhaust engine configurations. High spools with one and two-stage turbines were considered for each engine configuration. The probability of success for achieving each individual propulsion system technology advancement included in the preliminary designs was estimated. The individual technology probabilities were statistically summed to arrive at an overall engine configuration probability curve for improving TSFC. Similar analyses were made for weight, price and maintenance costs. Sensitivity factors were applied to these results to arrive at fuel savings and DOC reduction for each configuration on an equal probability of success basis.

Figure 7 lists the relative advantages identified in this evaluation for one and two-stage high pressure turbine engines. The overall comparison resulted in 0.7% less fuel savings, but over a 1% DOC advantage for the one-stage turbine approach. By the use of advanced, high strength blade and disk alloys expected to be available by 1985, the one-stage turbine could be designed with only 60% of the two-stage turbine airfoils without exceeding allowable stresses in the blade-disk attachment region. A corresponding 6% engine acquisition cost reduction and a 10% lower engine maintenance cost were estimated. The one-stage turbine blades would operate transonically for a 3% loss in efficiency, however. After considerable deliberation, the one-stage turbine approach was chosen for cost reduction.

Relative advantages of the geared fan and direct drive fan configurations are compared in figure 8. Additional fuel savings of 1-½% for the geared fan configuration derive from the higher propulsive efficiency of the larger diameter fan. The 10% lighter direct drive fan engine installation was estimated to have an equally lower cost and a 4% lower maintenance cost. A net DOC advantage of 0.5 to 1.0% resulted for the direct drive fan configuration. Degradation of the geared fan advantages relative to the conceptual study reflected the low probabilities of achieving both the originally assumed gear efficiency of 98.8% and the very low gear system bearing and gear replacement rate.

Preliminary design analyses identified several unique requirements of the geared engine high speed low rotor system which increased engine complexity. Last stage low pressure turbine blade pull stresses were estimated at 4.48×10^8 N/m^2 (65 ksi) requiring use of blade and disk materials usually reserved for the high pressure turbine. An additional mid-engine bearing compartment with intershaft and high rotor bearings was found necessary to avoid low rotor critical speeds within the engine running range. An additional fan rotor roller bearing was also required to uncouple fan and low pressure turbine induced rotor vibration. Failure analysis indicated that sophisticated containment and fast acting low pressure turbine gas blow-off devices would very likely be required to avoid nacelle penetration by high kinetic energy engine parts in the event of the 1.49×10^4 to 3.73×10^4 kW (20,000 to 50,000 hp) gear system internal failure. Based on the preliminary design analyses and the results shown in figures 4 through 7, the mixed exhaust, direct drive turbofan with a one-stage high pressure turbine was selected as the Pratt & Whitney Aircraft proposed configuration for the Energy Efficient Engine.

DESCRIPTION OF P&WA'S ENERGY EFFICIENT ENGINE PRELIMINARY DESIGN

The Energy Efficient Engine cycle parameters are listed in figure 9. The engine has a 38.6:1 overall pressure ratio at the cruise design point for a 3 to 4 percent fuel consumption improvement relative to present engines. A bypass ratio of 6.5:1 and fan pressure ratio of 1.74:1 were selected from the parametric study to minimize direct operating cost. The design turbine rotor inlet temperature at cruise was set at 1205°C (2200°F) to minimize fuel consumption. There is margin for over 20% thrust growth by supercharging to 45:1 overall pressure ratio while increasing turbine rotor inlet temperature by 110°C (200°F).

The propulsion system cross-section is shown in figure 10. The main design features of the propulsion system are an integrated engine/nacelle structure to improve engine performance retention, advanced clearance control concepts to achieve high component efficiencies, and a low maintenance, one-stage high pressure turbine.

The fan is a shroudless, single-stage, hollow titanium design with a pressure ratio of 1.74:1 and a corrected tip speed of 470 m/sec (1550 ft/sec). The four-stage low pressure compressor incorporates controlled endwall loss concepts, low loss airfoils, and increased aerodynamic loading. The high pressure compressor is a high inlet corrected tip speed (405 m/sec, 1325 ft/sec), 10-stage design with 1.7:1 average aspect ratio airfoils. Compressor pressure ratio is 14:1 driven by the one-stage high pressure turbine. High strength titanium and an advanced high strength nickel base alloy (MERL 76) disk materials are used in the rear section to permit the higher rotor speeds and increased temperatures associated with high overall pressure ratio. The compressor has active clearance control, controlled loss endwalls and reduced loss airfoil concepts to raise efficiency levels.

A staged vortex burning and mixing (vorbix) combustor is used for low emissions. This combustor is conceptually derived from the NASA Experimental Clean Combustor. Design changes were conceived relative to the experimental burner to make it commercially practical without sacrificing low emissions characteristics. An oxide-dispersion strengthened, film-cooled, louvered combustion zone liner is incorporated to provide commercial durability at the elevated compressor exit temperatures encountered in the engine.

The one-stage high pressure turbine is designed with a low 1.6 loading coefficient, which requires a high disk rim red-line speed of 530 m/sec (1730 ft/sec). The disk is of high strength MERL 76. Single crystal alloy blades with up to a 56°C (100°F) higher metal temperature capability than present are used to minimize compressor coolant bleed air. The four-stage low pressure turbine counterrotates relative to the high pressure turbine to minimize interturbine gas turning and pressure loss, and is designed for a 2.4 loading coefficient. The turbine uses titanium-aluminide airfoils in the cooler rear stages to save weight. Active clearance control is incorporated in the turbine section to increase efficiency.

The exhaust mixer is a scalloped design with low pressure loss and high mixing efficiency. High temperature titanium is the preferred mixer material. Its lightweight, one-piece superplastic forming capability allows engine weight savings and reduced fabrication costs relative to conventional welded-up steel units. A full authority digital electronic control is used to reduce operating cost and to provide efficient engine operation. The nacelle features an integrated engine/nacelle structure to restrain engine deflections caused by thrust and cowl loads.

Pratt & Whitney Aircraft has established flight engine design goals from this study of 15.3 percent TSFC improvement and a 6% DOC reduction relative to the JT9D-7A. Fuel savings of over 15% are also made possible with the selected engine configuration. Boeing, Douglas, and Lockheed evaluations of this engine resulted in fuel savings ranging from 11 to 26% and DOC reductions of from 3 to 15% compared with JT9D powered equivalent aircraft.

The realization of the Energy Efficient Engine potential is keyed to successful development of the many state-of-the-art advancements in fuel saving concepts included in the preliminary design. Technology must be balanced with practicality to ensure airlines acceptance of future energy efficient turbofan engines. Based on preliminary design analysis, critical propulsion technology areas have been identified which need to be translated into commercially acceptable hardware before the fuel savings promise can be realized (fig. 11). The remainder of the paper describes these technologies and the related benefits.

Active Clearance Control & Nacelle Load Sharing

Rotor blades and the engine cases have different rates of thermal expansion which can create large rotor tip-to-case clearances during cruise operation where up to 90% of the fuel is consumed. Cruise efficiency can be improved if these clearances, and the resultant leakage, are reduced. The thermal active clearance control system bathes the compressor and turbine cases with hot or cool air to precisely match the case diameter to the rotor tip diameter during cruise while providing sufficient tip clearance to avoid rubs during take-off roll, rotation and climb-out. The result is up to 55% reduced blade tip clearance during cruise with the benefit of over a 1.5% improvement in compressor and turbine efficiencies (fig. 12).

Active clearance control is already being introduced into the turbine sections of operational high bypass ratio turbofan engines as knowledge of case thermal response increases with operational experience. Computerized, finite element thermal and structural modeling techniques are being developed for the engine rotor system, engine static structure, and nacelle. These models permit the full use of active clearance control in the compressor and turbine sections for a 3% fuel savings.

The energy efficient engine is being designed with short, stiff rotors to minimize rotor deflections under thrust, gravitational or gryoscopic loads. A load sharing nacelle is included to minimize engine backbone bending which has been identified as a major cause of engine performance deterioration from rub induced blade tip wear.

Load sharing is achieved by structurally attaching the fan duct walls to the engine cases. These ducts act as structural "beams" in parallel with the engine case beam. The larger diameter fan ducts are inherently stiffer than the engine cases and will carry the majority of the load. This reduced load on the engine cases will keep deflections low. In conjunction with active clearance control, the rigid rotor systems and load sharing are projected to reduce the long term 4000 hour TSFC deterioration to approximately half that of current high bypass (fig. 13) ratio engines.

Advanced Internal Aerodynamics

Many new aerodynamic concepts have recently been analytically or empirically identified which, in total, can produce major component efficiency improvements. The improvements involve both better airfoil performance and lower losses in the endwall regions of the gaspath.

Titanium fan blades on operational high bypass ratio turbofan engines require inter-blade shrouds to limit blade vibration stress to an acceptable level. Shrouds reduce fan efficiency by upsetting the airflow through the fan. Fan efficiency can be increased over 2% by eliminating shroud induced aerodynamic losses shown in figure 14.

Vibration can be controlled in shroudless blades by elongating blade chord 50% but this increases the fan assembly weight. One way to reduce weight is to hollow-out the titanium blades. The problem becomes how to make hollow titanium fan blades inexpensively.

Superplastic forming manufacturing techniques have recently been developed to mold titanium into complex shapes, at low cost. Superplastic forming is especially suitable to titanium, which has the capability of being elongated 300% without local thinning under controlled temperature and strain rate. Superplastic forming can be combined with diffusion bonding techniques so that two titanium pieces can be mated along their edges in a die, heated to 925°C (1700°F) and pressurized to 2.07×10^6 N/m^2 (300 psi). The pieees simultaneously bond along their edges and expand into the die to complete the fabrication process.

Through recent developments in computer analysis techniques, increased freedom in compressor airfoil shape selection is also being exploited. Multiple-arc and supercritical compressor airfoil contours have been identified which operate transonically at 15% higher relative air Mach numbers than the JT9D-7A with the same efficiency. The airfoils are also capable of carrying higher aerodynamic loads at peak efficiency. This ability is being used to reduce compressor and turbine airfoil count and to reduce the through-flow gas velocity to improve efficiency.

Compressor and turbine research tests have identified a significant efficiency loss caused by flowpath air recirculating into and out of inner engine cavities beneath blade and vane root shrouds. In the turbine, vane inner shroud forward projections overlapped by blade shrouds were tested to isolate these cavities from the flowpath. Efficiency capability increased 1.0%. Compressor rig testing has shown both cavity size and shape to significantly impact compressor efficiency. As a result of the tests, small, smooth, low leak cavity designs with the potential for improving compressor efficiency by 0.5% are becoming possible.

These aerodynamic improvements, taken together, were estimated to reduce the amount of fuel burned by 5%.

Forced Exhaust Mixer

It has long been realized that engine thrust output could theoretically be increased without burning more fuel by forcefully mixing the fan discharge air with the turbine exhaust gases prior to discharge through a common nozzle. This approach could provide substantial fuel savings but has not been used in the past because the theoretical gains were offset by parasitic losses and weight associated with forced mixing.

Mixing now appears more attractive for conserving fuel as a result of recent tests of forced mixers that successfully combining high mixing efficiency, low parasitic loss, and short length. These tests include model and full scale tests of JT8D mixers and model tests of high bypass ratio (5 to 7) mixers. The results of these tests were used to arrive at the EEE mixer predictions.

Much remains to be accomplished before deciding on the exact mixer geometry and its ultimate performance potential. Model tests of various candidate geometries are required as an important step before finalizing a design approach and deciding on the mixer application to future powerplants. Integration of the long nacelle with the aircraft without incurring increased interference drag is also a big step in realizing the 3% fuel savings potential identified in this study program (fig. 15).

High Pressure Ratio

In order to take a full 15% advantage of fuel savings technology, a compressor system pressure ratio which is 50 percent higher than the JT9D-7A will be required (fig. 16). Higher pressure ratio was shown to provide significant fuel savings potential in the low energy consumption turbofan study. The question became how to produce the additional pressure with the same number of stages as the JT9D-7A to hold down cost. The straight forward solution was to use 25% higher compressor average diffusion factor combined with 28% higher compressor blade speeds than the JT9D-7A.

The higher airfoil loading capability derives from increased understanding of compressor design variables. Higher rotor speeds permit higher airfoil loadings. With a given compressor geometry, the peak pressure ratio increases with wheel speed. However, if the number of compressor blades are reduced, the achievable pressure ratio is also reduced. Thus higher speed can be traded for increased stage pressure ratio, or alternatively, for reduced airfoil count. The EEE high pressure compressor compared with the JT9D-7A in figure 17 represents a balance between increased stage pressure ratio, and lower airfoil count. The lower compressor blade count can give a 12% reduction in compressor module maintenance cost.

Advanced Hot-Section Materials

The high pressure ratio and high speed, high spool rotor system dictated the use of advanced, higher strength titanium and nickel base alloy compressor and turbine disks, single crystal HP turbine airfoils and a higher temperature combustor liner. High-strength blade and disk alloys are presently being developed to permit safe operation at higher speeds and temperatures of the EEE. A single crystal alloy for blades and a nickel superalloy (MERL 76) for the disk allow a 55% higher turbine wheel rim speed and an attendent 80% total blade and vane count reduction in relation to the 2-stage JT9D-7A turbine (fig. 18). High temperature titanium mid-stage disks and MERL 76 aft stage disks can also operate at the higher speeds and increased pressure levels in the compressor.

Current burner liners presently operate at about a 870°C (1600°F) maximum metal temperature. The energy efficient engine burner liner was calculated to require a metal temperature capability of 1040°C (1900°F) to permit 65% of the inlet air to be used for emissions and exit temperature profile control leaving a maximum of 35% for liner cooling. An advanced oxide dispersion strengthened material, which has the required operating temperature capability, is being considered as the primary design approach for the energy efficient engine.

Electronic Fuel Control

Current hydromechanical engine fuel controls are bulky - the JT9D-7A requires five control components to manage engine operation. Advances in digital electronic technology now make electronic fuel controls a practical alternative. An advanced, full authority digital electronic control, consisting of only two major components, the computer and a flow metering unit, will perform all of the necessary functions (fig. 19). This control will perform 60% more functions than the current hydromechanical controls. This additional capability can be used to have the unit continuously monitor the condition of the engine and give early warning of problems or situations which require maintenance action.

The payoff is a 33% reduction in control system weight and a 44% reduction in control maintenance cost. In-flight shut-downs due to control problems can be reduced by 80%. This control approach may also save fuel by eliminating the need for periodic ground run trimming of the engine and control.

Acoustically Treated Lightweight Nacelle

The nacelle of the future will require the latest light weight composite materials and lightweight structures to reduce weight by 15 percent relative to current configurations (fig. 20). Materials for the various applications within the nacelle will be selected from filament materials (boron, graphite, Kevlar and glass), matrix materials (epoxy, polyimide and aluminum) and composite honeycomb.

Stricter noise rules can be expected in future years. A noise goal of FAR 36 (1969) minus 10 EPNdB was established by NASA for this study. A fully treated nacelle, fan noise 3 EPNdB lower than present, and advanced acoustical treatment to attenuate fan noise by an additional 2 EPNdB are needed to meet this goal. The required noise reduction could be achieved by 1990 by directing research towards the definition of improved, low noise fan blading shapes, and by developing segmented liners with improved tone and broadband noise attenuation capabilities. FAR 36 (amended 1977) rules can be fully met with currently available acoustic technology.

Vorbix Combustor

The low emissions design concept is based on a combustor developed in the NASA-sponsored Experimental Clean Combustor Program (ECCP) which demonstrated significant reductions in exhaust emissions. It represents a major departure from conventional combustors in commercial engines. Two in-line burning zones are used. The front, or primary zone, is designed to the specific requirements of reduced carbon monoxide and unburned hydrocarbon emissions at very low power settings near idle. The aft, secondary zone is designed to control NOx. Swirlers are used to thoroughly mix the fuel and air leading to the acronym vorbix for vortex burning and mixing. The short length of the secondary zone minimizes the residence time at high temperature to cut NOx generation in half.

The vorbix concept has been tested in the JT9D as experimental hardware. The EEE emissions predictions were derived from the results of these tests by using emissions indices which correct for the different burner thermodynamic conditions with the higher pressure ratio cycle. Development margin and production tolerances were included in the estimates. The estimated EPA parameters are compared with the current JT9D-7A production combustor and the 1981 regulations in figure 21. Low power emissions were estimated to meet the regulations. NOx generation, estimated to be 43% lower than the JT9D-7A, needs to be reduced by an additional 30% to meet 1981 regulations. A technique to provide the additional reduction has not yet been identified.

The EEE combustor design concept is simplified substantially from the ECCP configurations. The throat between the two zones was removed and replaced with less costly and more maintainable straight inner and outer wall sections. The number of fuel nozzles were reduced 20 percent and clustered in groups of three to limit fuel supply tube case penetrations to 24 circumferential locations. Substantial additional development work is needed to verify the emissions characteristics of this more practical burner before it can be considered for commercial service.

ENGINE BENEFITS

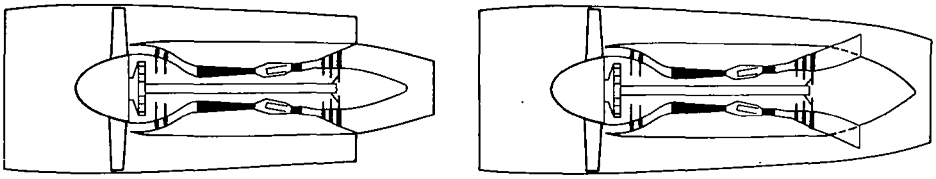
Improvements in component efficiencies, achieved by advancing technology and fully exploiting active clearance control, use of a high pressure ratio cycle and a mixed flow exhaust system can provide an engine cruise TSFC reduction of 15% relative to the JT9D-7A.

The lower TSFC can produce large fuel savings and reduced DOC. Improved performance retention can be achieved by advanced technology application of a rigid rotor support system in combination with a load sharing nacelle. With full application of key technologies identified in this study, over a 15% fuel savings, a 6 to 10% DOC reduction, and one-half of the present JT9D-7A performance deterioration rate are all possible.

A long nacelle, fully lined with low pressure loss acoustic treatment, has the potential of fully meeting future requirements. The staged vorbix combustor concept, a major departure from conventional configurations, shows promise for reducing exhaust emissions by 43 to 96%.

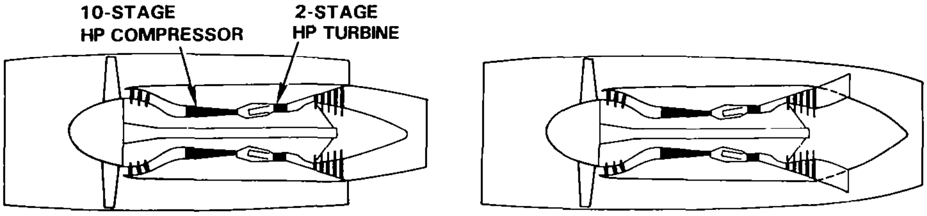
FUTURE PLANS

Pratt & Whitney Aircraft is presently embarking on an analytical and experimental program, the NASA sponsored Energy Efficient Engine Component Development and Integration Program, to complete the flight propulsion system preliminary design and to empirically verify the pertinent turbomachinery and mixer related technology benefits. Nacelle related benefits are also being pursued by NASA in other on-going technology programs such as the Energy Efficient Transport Project. The overall objective of this intensive effort is to provide needed technology by the mid 1980's to produce significant fuel savings in future commercial turbofan engines of the 1990's.



GEARED FAN
SEPARATE EXHAUST

GEARED FAN
MIXED EXHAUST



DIRECT DRIVE FAN
SEPARATE EXHAUST

DIRECT DRIVE FAN
MIXED EXHAUST

Figure 1.- Four study turbofan design configurations — different low spools and exhaust types were combined with a common high spool.

CRUISE TSFC	−12% MIN. (JT9D-7A REF)
DOC	−5% MIN. (JT9D-7A REF)
EXHAUST EMISSIONS	1981 EPA STANDARDS
NOISE	FAR 36 (1969) MINUS 10 EPNdB
PERFORMANCE DETERIORATION	IMPROVED (JT9D-7A REF)
THRUST GROWTH	W/O COMPROMISING OTHER GOALS

Figure 2.- Study goals — goals balance fuel savings technology with practicality.

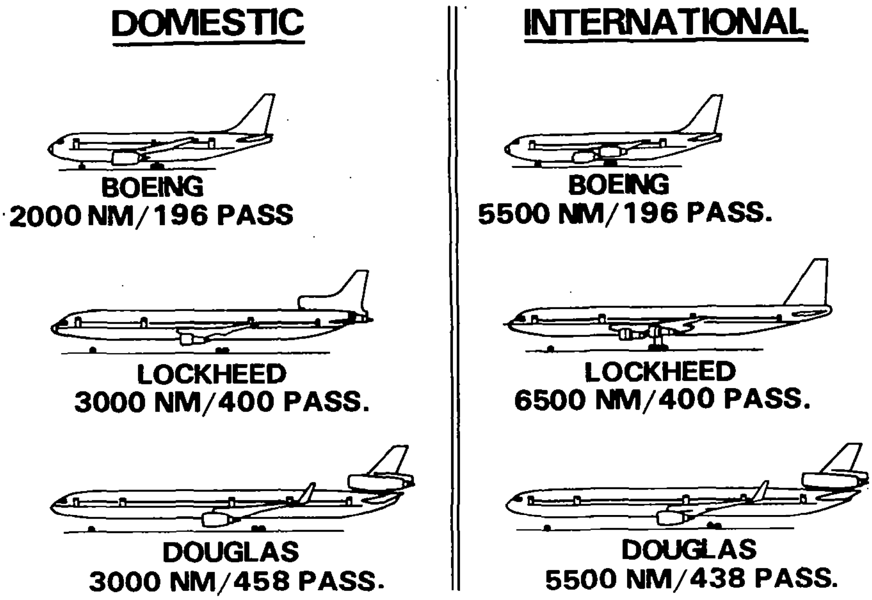


Figure 3.- Advanced study aircraft — wide spectrum selected for engine configuration evaluation.

2-STAGE HIGH PRESSURE TURBINE

AVERAGE MIXING ADVANTAGE = 2.5% FUEL BURNED
AVERAGE GEARING ADVANTAGE = 2.7% FUEL BURNED

FAN DRIVE	DIRECT		GEARED	
EXHAUST	SEPARATE	MIXED	SEPARATE	MIXED
BYPASS RATIO	7	7	9	9
REL TSFC (JT9D-7A REF)	−15%	−18%	−19%	−21%

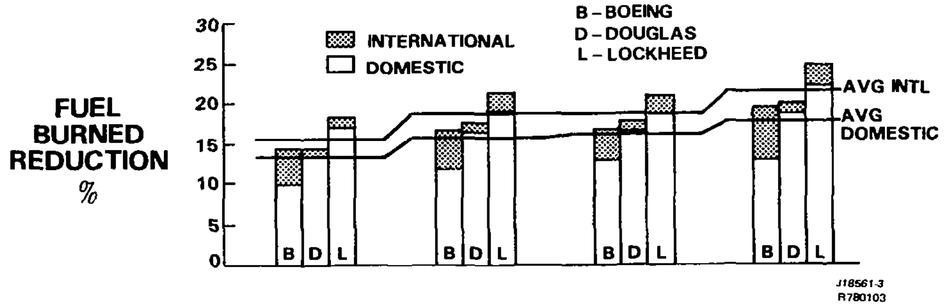


Figure 4.- Conceptual study fuel savings — exhaust mixing and low rotor gearing each improve fuel consumption by 2-½%.

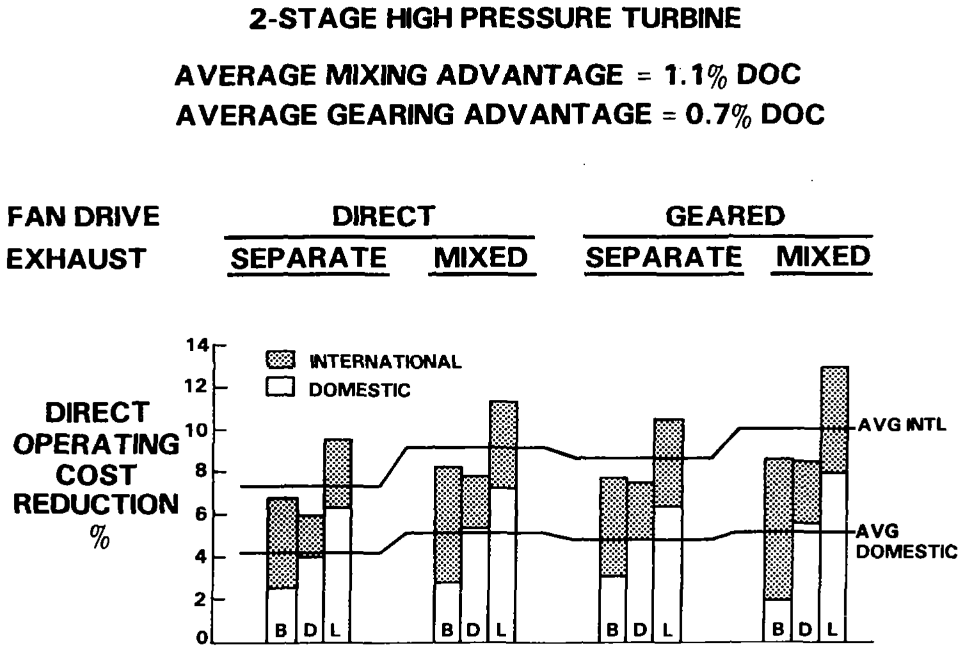


Figure 5.- Conceptual study DOC reductions — exhaust mixing and low rotor gearing each reduce DOC by 1%.

2-STAGE HIGH PRESSURE TURBINES

		DIRECT DRIVE		GEARED	
	STUDY GOAL	SEPARATE	MIXED	SEPARATE	MIXED
INSTALLED CRUISE TSFC	-12% MIN.(REL TO JT9D-7A)	-15%	-18%	-19%	-21%
DIRECT OPERATING COST (DOC)	-5% MIN. (REL TO JT9D-7A)				
DOMESTIC AIRCRAFT (AVG)		-4.3%	-5.2%	-4.9%	-5.3%
INTERNATIONAL AIRCRAFT (AVG)		-7.4%	-9.2%	-8.7%	-10.1%
EMISSIONS	1981 EPA	MEETS 1981 THC AND CO, EXCEEDS NO_X			
TOTAL NOISE					
(W/CURR TECH)	FAR 36 (1969) MINUS 10 EPNdB	MEETS FAR 36 (1977)			
(W/ADV TECH)		MEETS FAR 36 (1969) MINUS 10 EPNdB			
TSFC DETERIORATION at 4000 HRS	BETTER THAN JT9D-7A (2.8%)	1.5%	1.5%	1.2%	1.2%
THRUST GROWTH	NO COMPROMISING OTHER GOALS	PRESSURE RATIO AND TURBINE INLET TEMPERATURE SELECTED WITH THRUST GROWTH ALLOWANCE			

J18561-5
780902

Figure 6.- Conceptual study results against goals — relative capabilities led to selection of mixed exhaust type.

TWO-STAGE HPT

- 0.7% ADDITIONAL FUEL SAVINGS
- 3% HIGHER EFFICIENCY POTENTIAL
- SUBSONIC FLOW FOR REDUCED DEVELOPMENT RISK

ONE-STAGE HPT

- ADDITIONAL DOC BENEFIT
  - 1.3% DOMESTIC
  - 1.2% INTERNATIONAL
- 10% LOWER ENGINE MAINTENANCE COST
- 40% FEWER HPT AIRFOILS

Figure 7.- Relative advantages of one- and two-stage high pressure turbines - economic advantages led to the choice of the one-stage approach.

GEARED FAN ADVANTAGE

- 1.5% ADDITIONAL FUEL SAVINGS

DIRECT DRIVE FAN ADVANTAGES

- ADDITIONAL DOC BENEFIT
  - 1.0% DOMESTIC
  - 0.5% INTERNATIONAL
- 4% LOWER MAINTENANCE COST
- LIGHTLY STRESSED LP TURBINE PARTS
- FREE FROM GEAR INDUCED ROTOR VIBRATION
- POSITIVE FAILURE MODE PARTS CONTAINMENT

Figure 8.- Relative advantages of direct drive and geared fans — economic and operational advantages led to the choice of the direct drive fan approach.

CRUISE DESIGN POINT

OVERALL PRESSURE RATIO	38.6:1
BYPASS RATIO	6.5:1
FAN PRESSURE RATIO	1.74:1
TURBINE ROTOR INLET TEMPERATURE	1205°C (2200°F)

J18561-24
R780103

Figure 9.- Energy efficient engine cycle parameters — advanced cycle parameters provide fuel savings and reduced DOC.

PROPOSED EEE DESIGN INCORPORATES ADVANCED TECHNOLOGY COMPONENTS

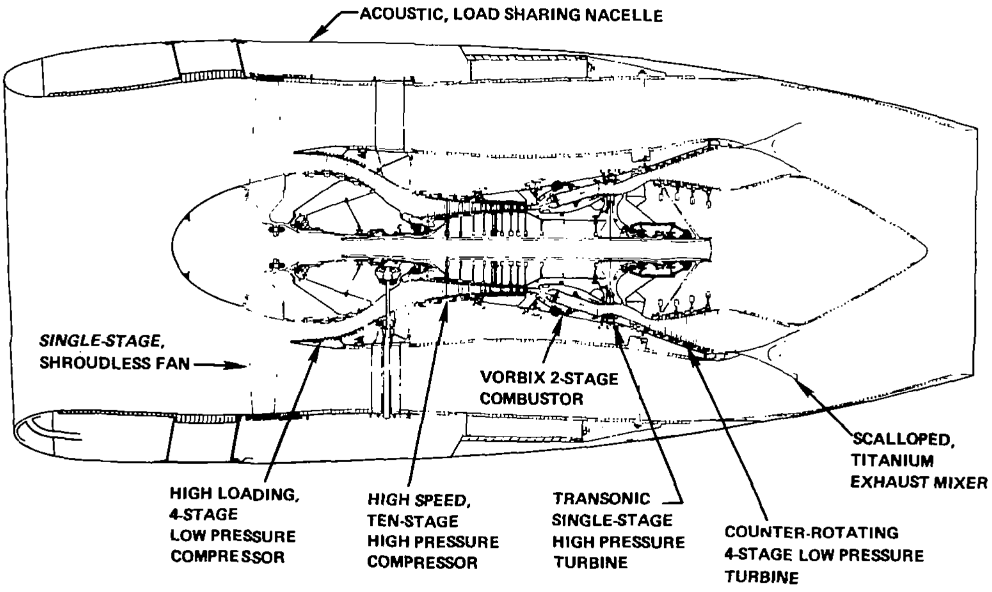


Figure 10.- Energy efficient engine preliminary design —high efficiency and low cost components provide fuel savings and reduced DOC.

- **ACTIVE CLEARANCE CONTROL & NACELLE LOAD SHARING**
- **ADVANCED INTERNAL AERODYNAMICS**
- **FORCED EXHAUST MIXER**
- **HIGH PRESSURE RATIO**
- **ADVANCED MATERIALS**
- **ELECTRONIC FUEL CONTROL**
- **ACOUSTICALLY LINED LIGHTWEIGHT NACELLE**
- **VORBIX COMBUSTOR**

Figure 11.- Critical propulsion technologies — successful development of key technologies is needed to realize projected fuel savings.

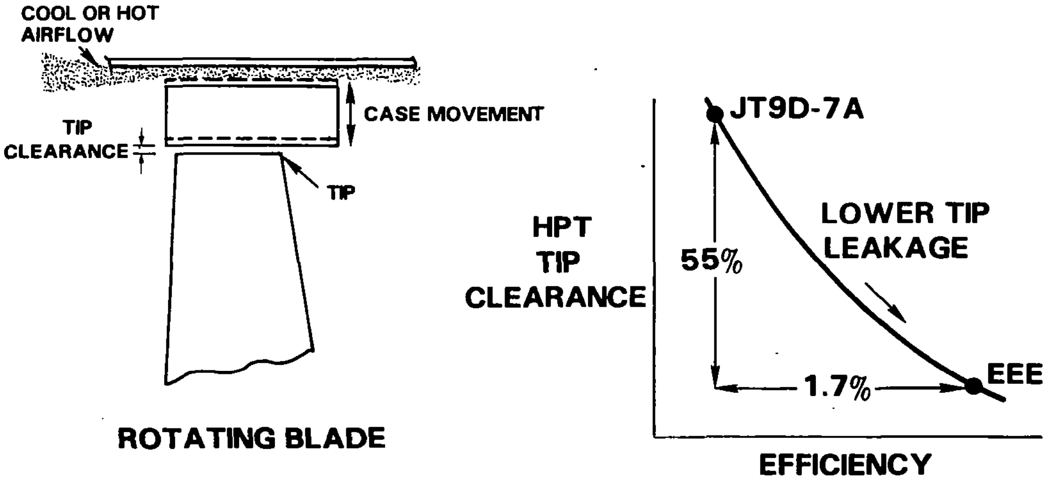


Figure 12.- Active clearance control — reduced blade tip clearances in compressor and turbine can provide a 3% fuel savings.

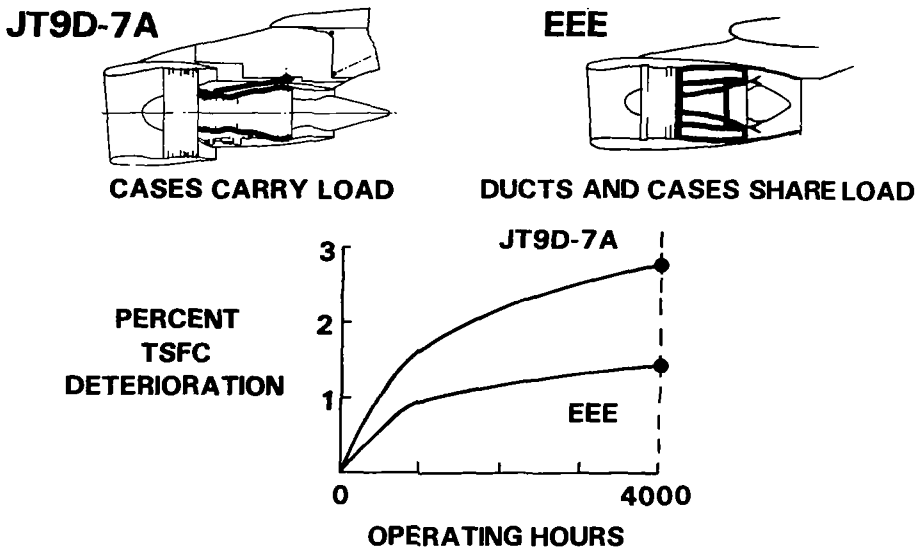


Figure 13.- Load sharing nacelle — nacelle load sharing design retains fuel savings over long-term operation.

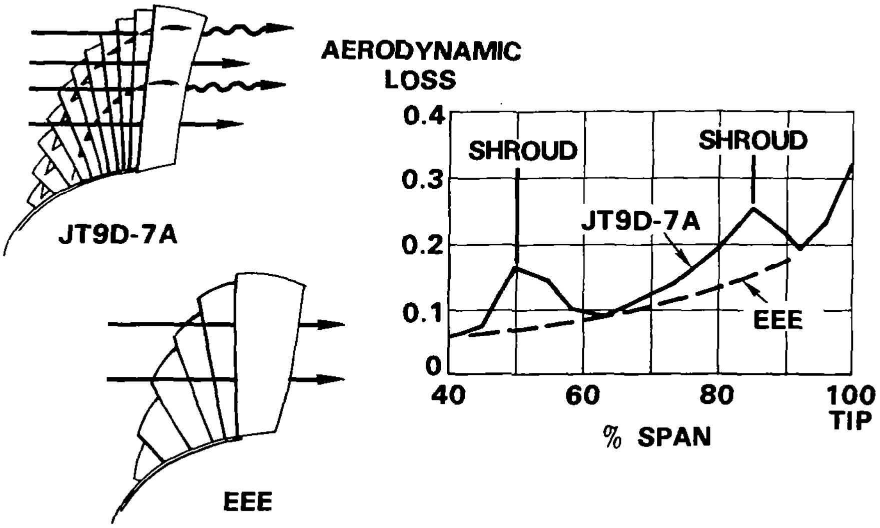


Figure 14.- Shroudless fan blades — shroudless fan blades have the potential for 2% efficiency improvement.

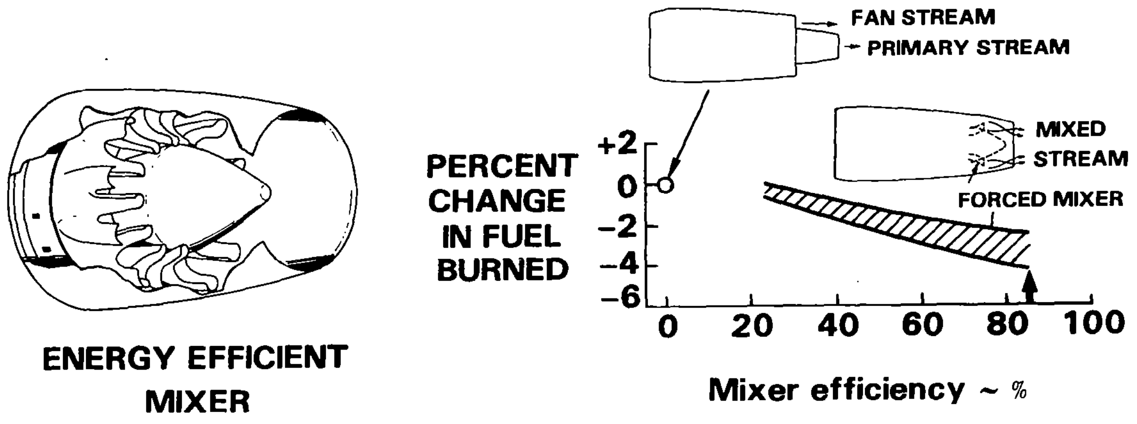


Figure 15.- Advanced exhaust mixer — shorter mixer, possible with advanced technology, reduces losses and weight for a 3% fuel savings potential.

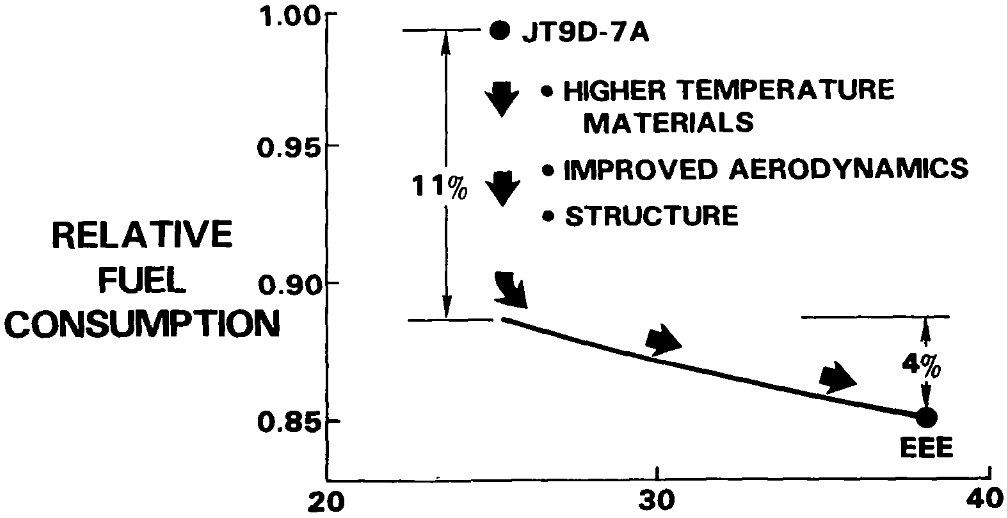


Figure 16.- High overall pressure ratio — high pressure ratio made possible by advanced technology provides an additional 4% fuel savings potential.

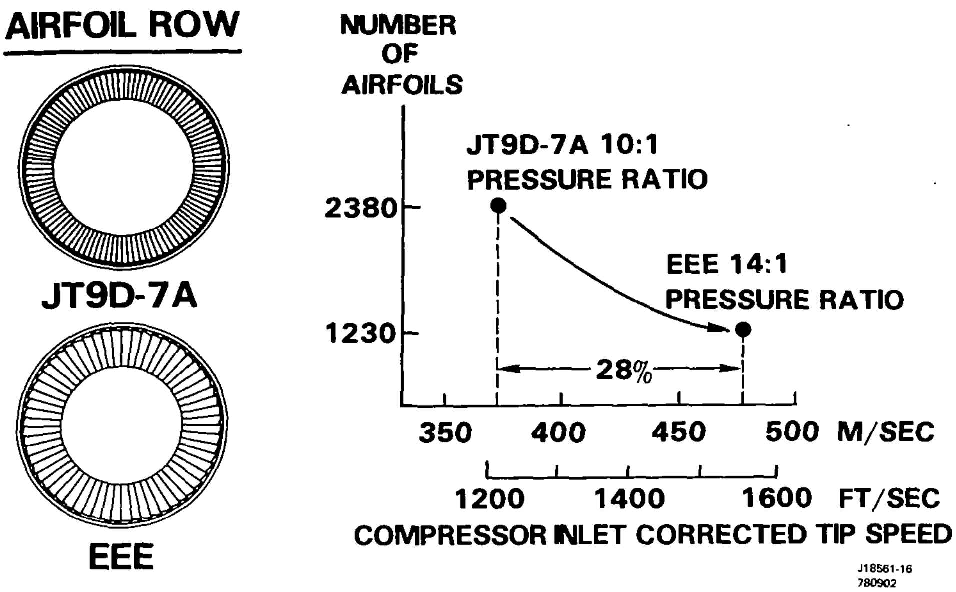


Figure 17.- High speed compressor — 48% fewer airfoils result in a 12% lower compressor maintenance cost.

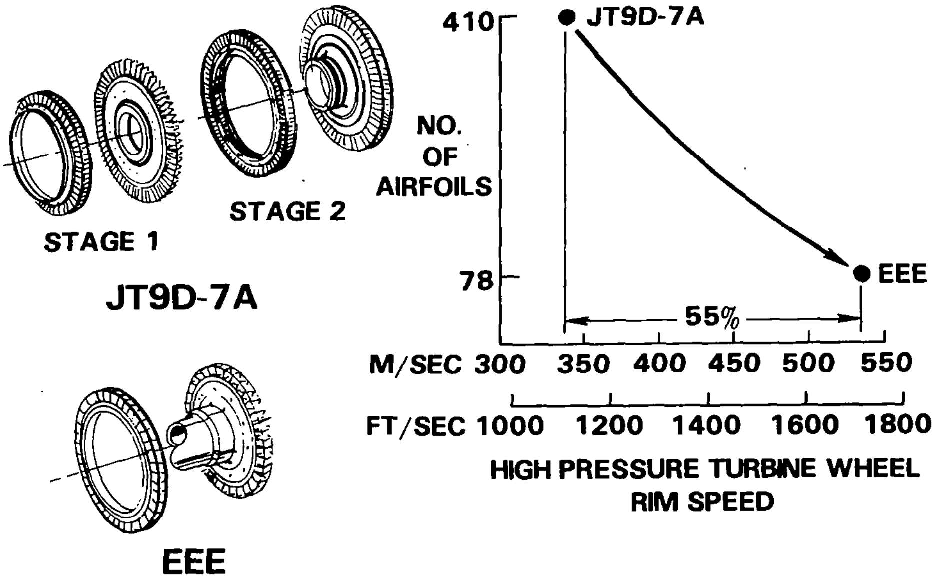


Figure 18.- High work turbine — high speed, single-stage high pressure turbine, with 80% fewer blades and vanes, has potential for a 30% lower module maintenance cost.

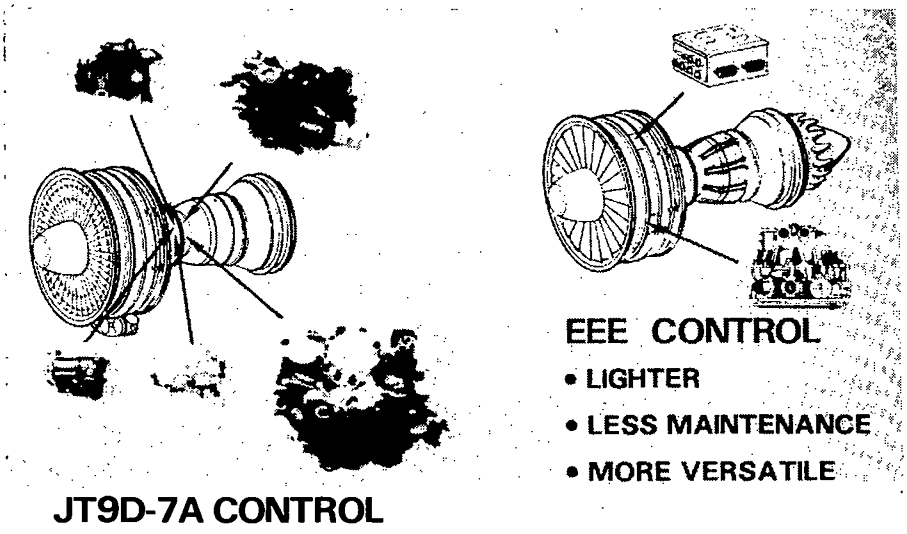


Figure 19.- Electronic fuel control — 2 major electronic control units are equivalent to 5 hydro-mechanical components.

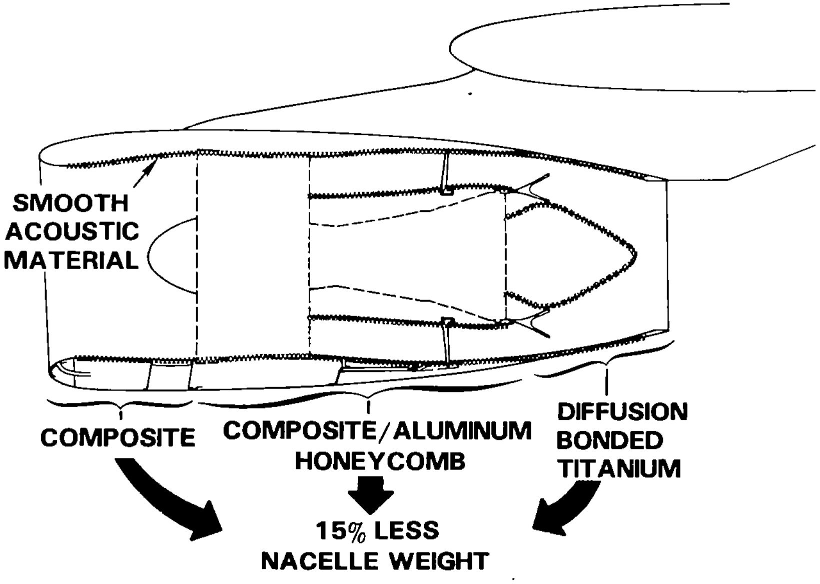


Figure 20.- Acoustically treated lightweight nacelle — 15% less weight and FAR36-10 EPNdB noise are possible through use of composites and improved acoustical technology.

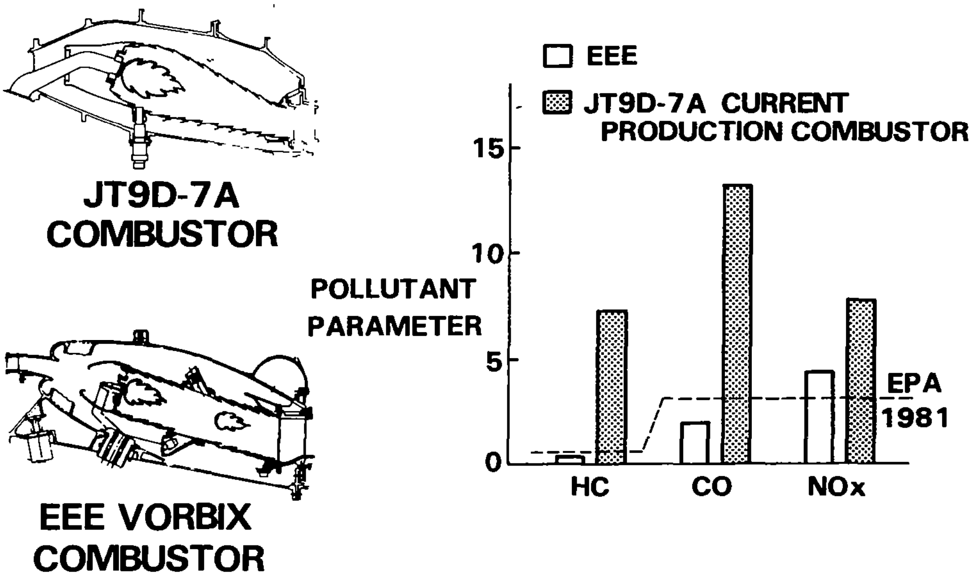


Figure 21.- Vorbix combustor — emissions reductions from 43 to 96% are projected with the two-stage vorbix combustor concept.