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Abstract

This paper summarizes the status of NASA's Energy Efficient Engine Project, a cooperative government-industry effort aimed at advancing the technology base for the next generation of large turbofan engines for civil aircraft transports. Results of recently-completed studies by General Electric and Pratt & Whitney Aircraft are reviewed. These studies involved selection of engine cycles and configurations that offer potential for at least 12 percent lower fuel consumption than current engines and also are economically attractive and environmentally acceptable. Emphasis is on the advancements required in component technologies and system design concepts to permit future development of these more energy-efficient engines.

Introduction

In response to the nation's growing energy problems, NASA initiated the Aircraft Energy Efficiency (ACEE) Program in 1976 to assist in the development of technology for more fuel-efficient aircraft for commercial airline use. A major propulsion element in this program is the Energy Efficient Engine (EEE) Project which is intended to lay the advanced-technology foundation for a new generation of turbofan engine. This project, planned as a seven-year (1977-83) cooperative government-industry effort, is aimed at developing and demonstrating advanced component and systems technologies for engines that could be introduced into airline service by the late 1980s or early 1990s -- depending on the evolving airline market needs.

NASA's Engine Component Improvement (ECI) Project, another major element of the ACEE Program, is intended to help improve the performance of current production engines (i.e., JT9D and CF6 engine families) by application of new component technologies. Performance improvements up to 5 percent are anticipated. However, studies[1-3] have indicated that application of advanced technologies to a completely new engine offers promise of significant reduction in fuel consumption. By optimizing the selection of engine pressure ratio, turbine temperature, and bypass ratio, along with improvements in component efficiency levels, reductions in SFC of about 10-15 percent below the levels of the current high-bypass-ratio turbofan engines can be achieved. As shown in Figure 1, these reductions are comparable to the improvements achieved when the first high-bypass-ratio turbofans were introduced into service.

In addition to fuel savings, new engines must offer potential for being economically attractive to the airline users and environmentally acceptable. Since these requirements often impose conflicting demands on the selection of the basic engine configuration and cycle conditions, NASA established a set of engine performance goals that attempt to strike an acceptable balance between these varying requirements. The EEE goals are listed in Figure 2. The goals address performance levels for fully-developed engines, but they are used in the EEE Project to aid selection of engine concepts that will serve as the focus for the development of appropriate component and system technologies within the project timeframe.

Project Approach

Parallel contracts have been awarded to General Electric Company and Pratt & Whitney Aircraft to develop advanced component technologies, experimentally verify component performance, and demonstrate technology readiness through full-scale tests of the high-spool core and the integrated core-low spool systems. The general schedule for the EEE Project is given in Figure 3 which shows the major project elements and the relative timing of each. Candidate engine configurations and cycle conditions were selected by each contractor during preliminary engine definition studies. Through refinement of the cycle parameters and the evaluation of the benefits and trade-offs of advanced technologies and their effect on SFC, DOC, fuel burned, noise, and emissions, each contractor has recommended an engine design which meets the aggressive goals of the program.

Engine Definition

Results of the preliminary engine definition studies are described in references 4 and 5 for General Electric and Pratt & Whitney, respectively. The studies included the participation of major airframe manufacturers (Boeing, Lockheed, and Douglas) to assess the aircraft installation effects associated with the various engine concepts. In addition, two airline operators (Eastern and Pan American) assisted NASA in evaluating the findings and recommendations from a potential user's viewpoint.

Engine Configuration Considerations

Four basic types of turbofan engines were considered:

1. Direct-drive fan with a separate core and fan stream exhaust
2. Direct-drive fan with mixed core and fan stream exhaust (long duct nacelle)
3. Geared fan with separate-flow exhaust
4. Geared fan with mixed-flow exhaust (long duct nacelle)

Both engine manufacturers recommended a direct-drive fan, mixed flow exhaust design for the EEE.

Tradeoff studies among the four engine configurations, each with cycle conditions optimized for minimum SFC and DOC, indicated a potential benefit in reduced SFC for engines with a mixed-flow exhaust. Similarly, the geared fan engines were lower in SFC than the direct-drive engines. Engines with a geared fan have a higher bypass ratio (8-10) and therefore, a larger fan diameter for a given core size compared to the direct-drive configuration. The added weight of a gearbox and the increased drag caused by a large fan more than offsets the SFC benefit, so the geared engine burns more fuel and has a higher DOC for a typical domestic mission than its direct-drive counterpart.

Weight is also a penalty for the mixed flow exhaust, long-duct nacelle engine. However, the 3 percent reduction in SFC of the mixed over the separate flow exhaust was enough to persuade both engine companies to select the mixed-flow configuration for further development and verification in the EEE program. With special attention paid to the integration of the engine and the airframe, the interference drag penalty can be minimized or it may even be possible to achieve a condition of positive interference. Even if the potential benefits of exhaust mixing are not realized, the other advanced engine components developed in parallel are still applicable to engines with separate-flow exhausts.

Cycle Selection

A wide variety of engine cycle combinations were assessed in the preliminary design studies. Increases in bypass ratio, pressure ratio, and turbine inlet temperature all lead to desirable improvements in thermodynamic and propulsive efficiencies, but these potential gains must be balanced by the associated detrimental effects of increased engine size, weight, and cost. Also, higher operating pressures and temperatures have historically led to increased performance deterioration and higher maintenance costs.

The cycle parameters selected by GE and P&WA for their energy-efficient engines are summarized in Figure 4. Also shown, for comparison, are the cycle conditions for the current production JT9D-7A and CF6-50C engines which were used as the reference engines in estimating performance improvements for the EEE design. Higher overall pressure ratio, higher bypass ratio, higher turbine inlet temperature, and a mixed-flow exhaust characterize the EEE cycle advances. In the GE design, the bypass ratio is increased about 60 percent and the pressure ratio across the high pressure compressor is nearly twice that of the reference engine. On the other hand, in the P&WA design, cycle advancements were in the overall pressure ratio (with an increase of about 50 percent) and turbine inlet temperature at takeoff (increase of about 150°F) over the reference engine.

Figures 5, 6, and 7 illustrate the effect on fuel burned and DOC of varying overall pressure ratio, turbine inlet temperature, and bypass ratio about the selected design cycle conditions.

The design overall pressure ratio offers a 3 to 4 percent fuel consumption improvement relative to current generation high bypass engines and results in near optimum direct operating cost for the domestic aircraft as shown in Figure 5. Although higher pressure ratio engines offer some further improvement in fuel consumption without severely affecting direct operating cost, thermal/structural analysis of the rear of the compressor section and the high-pressure turbine indicates that the selected overall pressure ratio level represents an aggressive design limit when taking into account overall performance, cost, and future thrust growth potential.

The design turbine rotor inlet temperature minimizes fuel consumption while leaving margin for growth in engine thrust. At higher temperatures, engine weight reductions are offset by increased specific fuel consumption (SFC) so that fuel burned remains constant over a large temperature range, as shown in Figure 6. Direct operating cost is adversely affected at higher temperatures, as shown, because of the required increase in the number of high cost, cooled turbine parts and decrease in hot section part lives.

The direct operating cost and fuel burned trends with bypass ratio are shown in Figure 7. As bypass ratio is increased, SFC decreases. Also, as bypass ratio is increased, the 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 and costs, as well as increased nacelle drag. Thus, direct operating cost minimizes at low bypass ratios (approximately 6) for each of the aircraft. This results in the shallow fuel burned trend with bypass ratios above 7 and an increasing direct operating cost penalty. The selected bypass ratio provides the best combination of direct operating cost and fuel burned.

The thrust selection was based on market forecasts which indicate that a significant portion of the transport aircraft market in the 1990s will likely require engines in the 30,000 to 50,000 pound thrust size. The use of the Energy Efficient Engine high-pressure core with various low-spool combinations can provide the thrust flexibility to meet this range of requirements.

Description of Engine Features

The energy efficient engine designs of General Electric and Pratt & Whitney are illustrated in the upper half of the cross-sectional drawing of Figures 8 and 9 respectively. For comparison purposes, the lower half of each figure shows each company's current production high bypass engine; the CF6-50C and JT9D-7A. In overall features, the two EEE designs are quite similar, but the individual components and technology approaches selected to meet the system requirements are considerably different. The basic design philosophy, shared by both General Electric and Pratt & Whitney in their approach to the Energy Efficient Engine is to achieve higher thermodynamic and propulsive efficiencies through higher cycle pressures and temperatures, but with a simplified, more rugged mechanical design compared to current high-bypass engines. Both of the proposed EEE designs offer the potential for significant reductions in fuel consumption, performance deterioration, and operating costs. Both designs are high-bypass, high-pressure ratio, two-spool, direct-drive turbofans with mixed-flow exhaust and long-duct nacelle. The high and low-spool rotors are co-rotating in the GE design and counter-rotating in the P&WA concept.

Particular attention has been directed toward reducing the causes of performance degradation found in current engines. Both the EEE designs feature a short, stiff, ruggedized construction to minimize the effects of engine bending forces encountered during flight. Cowl and nacelle load-sharing are used to stiffen the longitudinal axis of the engine. Also, to reduce maintenance and cost and to provide mechanical simplicity, the EEE configurations have a large reduction in number of airfoils -- primarily in the hot section for P&WA and in the compression system in the GE design -- as compared to current engines.

Active clearance control systems are incorporated to expand or contract the core case during operating transients. This is intended to maintain minimum clearances between the rotors and case during cruise and avoid rubs during transients. The active clearance control systems, coupled with the use of electronic digital control systems, permit design of much tighter clearances than in current engines and thereby increase the total system efficiency.

Although the general approaches to reducing performance degradation are similar, the specific design approaches proposed by GE and P&WA to achieve nacelle load-sharing and active clearance control are considerably different. Both approaches need extensive technology efforts to verify that the predicted performance benefits are achievable. A description of the engine components and technology features for each design follows.

General Electric - Figure 10 shows a layout of the General Electric EEE configuration. The fan is an advanced CF6 type design with midspan shrouds located near the trailing edge of titanium blades. A fan hub quarter stage is incorporated to permit lower fan tip speeds for higher efficiency and lower noise. A quarter stage booster provides high hub fan pressure ratio, good distortion attenuation, and tolerance to bypass variation without variable geometry. This configuration also offers a reduction in potential foreign object damage to the core by incorporating a unique, double core splitter to allow foreign objects to be centrifuged into the bypass stream. The fan frame features a composite construction with an advanced hybrid blade containment system of steel wrapped with Kevlar backing. Structural exit guide vanes made of composite material are also incorporated.

The high-pressure compressor is an advanced 10-stage, 23:1 pressure ratio machine with long chord blades and ruggedized construction to reduce performance deterioration with time. The design incorporates small stator cavities and close rotor tip clearances to reduce leakage losses. Unshrouded rotors are used throughout, and all stators are shrouded at the inner ends. Active clearance control is planned for the last five stages to reduce clearances at cruise. The inlet guide vanes and the first four vane rows are variable angle, activated by an electronic digital control system to achieve the desired compressor performance characteristics over the entire engine operating range.

The combustor is an advanced, extremely short, lightweight, double-annular design based on low emission combustor technology derived from the NASA Experimental Clean Combustor Program. The reduced length of the combustor and diffuser section is apparent by comparing it to that of the CF6-50 in Figure 8. This short combustor section is one of the three principle sources of length reduction in the EEE design; the others being the compactness of the compressor and the elimination of the long transition duct between the high- and low-pressure turbines. Scheduling fuel flow between the pilot zone of the outer annulus and the high power, primary zone of the inner annulus is accomplished with the engine digital control system.

The high pressure turbine is a two-stage, air-cooled configuration with moderate stage loading and high efficiency. Ceramic tip shrouds and an active clearance control system modulated by the engine digital control assures effective gas path sealing under all engine operating conditions. Directionally solidified Rene' 150 material is planned for the airfoils to extend turbine life, and the rotor incorporates Rene' 95 powdered metal disks with bore entry cooling. Blade cooling air is brought on board the rotor through a unique low radius inducer and impeller system to provide an efficient deterioration-resistant system while protecting the critical power shaft from excessive temperatures.

The low-pressure turbine is a moderately loaded, five-stage, close-coupled design requiring no airfoil cooling. Ruggedized blading utilizes integral, interlocking-tip shrouds to reduce the potential for damaging vibratory modes and improve performance retention. The vanes are grouped in multivane segments to minimize leakage paths and honeycomb seals, and shrouds are provided to accommodate relative rotor-to-stator excursions. An unsplit impingement cooled case is used to maintain roundness and improve clearance control.

The mixer design consists of 24 chutes contoured for effective mixing of the hot, high-velocity, core gas with the relatively low-velocity fan air to achieve a more uniform velocity at the nozzle throat, hence improving propulsive efficiency.

The engine nacelle is a thin, symmetric, long-duct design made of light-weight composites. Pylon or core mounted accessories allow the use of a thinner nacelle to reduce nacelle drag. Kevlar bulk acoustic absorbing material is integrated into the inner walls of the inlet, fan frame, fan-duct, core cowl, and nozzle, for sound suppression.

The bearing/shaft system is much simpler and stiffer than in the current CF6-50C engine. Being shorter, the number of bearings in the EEE design are reduced from 8 to 5 (3 on the low-spool shaft and 2 on the high-spool shaft) and the number of bearing compartments are reduced from 4 to 2. The core is straddle mounted between the two high-spool bearings to reduce out-of-round distortions caused by cantilivering the HP turbine beyond the rear bearing as in the CF6 engine. The hot bearing support strut through the combustor diffuser section in the CF6 has been eliminated in the EEE, leaving struts only in the cool sections. Elimination of the bearing compartment in the combustor region results in more accessible bearing compartments and a larger diameter, stiffer, high-spool shaft. These structural design features, along with core/fan frame load sharing, minimize gas path casing distortions for improved performance retention compared to current production engines.

Pratt & Whitney Aircraft - Figure 11 shows a layout of the P&WA EEE configuration. The fan is a single-stage design featuring shroudless, hollow-titanium blades with an aspect ratio of 2.8. Supercritical airfoil shapes are used for the fan inner stators to reduce the losses in the high subsonic Mach number range. The fan exit guide vanes are integrated with the duct structural struts to reduce engine weight and cost. Grooves over the rotor tip provide adequate blade clearance while allowing a smaller effective aerodynamic clearance.

A four stage, 1.77 pressure ratio low-pressure compressor supercharges the core and has supercritical airfoils which are canted to minimize losses and provide high surge margin. An improved cavity design drum rotor reduces circulation losses and the rotor case is grooved to reduce the effective clearance.

The high-pressure compressor produces a pressure ratio of 14 in ten stages. Variable stators are used in the first four stages. The mechanical construction features a drum rotor and stiff wall outer cases with abradable rub strips and rotor tip grooves (trenches) for improved clearance control. A hot/cold modulated active clearance control system is proposed for the last seven stages to pull the casing away from the rotor during takeoff and to maintain close running clearance during cruise. An improved cavity design reduces inner endwall losses by reducing the stator cavity recirculation zone. Multiple circular arc airfoils are planned for the supersonic and transonic front end stages and supercritical airfoils will be used in the high subsonic Mach number stages for improved aerodynamic performance.

The combustor is a low emissions, two-stage vorbix type design which is based on the technology demonstrated under the NASA Experimental Clean Combustor Program. It is, however, modified to reduce cost and weight and to improve durability. Staged fuel injection provides significant emissions reductions over the full range of engine operating conditions.

The engine design features an advanced, high rim speed, single-stage HP turbine with single crystal cast airfoils. In an effort to reduce the turbine maintenance costs, the proposed design has only 78 blades and vanes compared to 410 for the two-stage, JT9D-7A HP turbine. High efficiencies for a single-stage turbine are expected through the use of a large annulus area and a high rotor speed combined with a high rim speed, contoured endwalls, pre-swirled coolant flow injection, and active clearance control. Ceramic outer air seals and abrasive blade tips are also incorporated. The active clearance control system uses hot, high-pressure compressor discharge air on the turbine cases during takeoff to avoid a rub condition. Cooler, mid-compressor bleed air is then used during cruise, allowing the cases to cool and the clearances to close down.

The low-pressure turbine has four uncooled stages and rotates in the opposite direction from the high-pressure turbine to reduce the camber required in the first-stage airfoils and improve aerodynamic performance. Various design features such as flow guides, overlapping blade and vane platforms, and local endwall contouring are incorporated to reduce endwall losses. To reduce weight, the rear stage blades and vanes will be fabricated from titanium-aluminide.

The exhaust system incorporates an advanced design mixer featuring a 12-lobe scalloped configuration for increased mixing effectiveness and low pressure drop. A flight mixer would be made of titanium fabricated in one piece using a superplastic forming with diffusion bonding to reduce weight and fabrication cost.

Advanced lightweight composite materials will be used in a flight nacelle, and the engine/nacelle structure will be integrated to remove backbone bending and case ovalization loads from the engine. Removal of these loads is expected to significantly improve engine performance retention. Bulk absorbing acoustic treatment will be used in the inlet, fan-duct, core cowl, and nozzle for sound suppression.

The high-spool shaft is straddle mounted to reduce shaft bending for better clearance control, particularly in the HP turbine. Straddle mounting also eliminates the need for a bearing compartment underneath the hot combustor section allowing better accessibility to the bearing compartments and a larger diameter, stiffer shaft. The EEE design has only two bearing compartments compared to three in the JT9D. The low-spool shaft has three bearings compared to two in the JT9D for a total of five bearings in the EEE. An additional roller bearing has been added to minimize fan deflection. Special attention is paid to the structural load carrying member design to improve performance retention. The compressor case is double walled with the outer casing carrying the load, thus reducing the gas path inner casing distortion. In addition, cowl load sharing is used to minimize core engine casing distortion.

Benefits

The conceptual energy efficient engines described in this paper offer the potential for achieving, or exceeding, all the goals established for the EEE Project. The predicted benefits in SFC, DOC, and fuel burned for the two proposed engines are summarized in Figure 12. The values shown are representative of the projections of both the engine manufacturers and the airframe manufacturers for typical domestic and international airline missions. The current projections in SFC and DOC are 3-5 percentage points higher than the goals -- a necessary margin for an advanced technology program such as the EEE Project.

The proposed engines will incorporate a number of design features which are expected to reduce the rate of performance deterioration to approximately 50 percent that of current high-bypass-ratio engines.

The estimated environmental benefits of the energy efficient engine are expressed in terms of noise and emission levels. The noise goals for the EEE are FAR-Part 36 (as amended March 1977) with provisions for engine growth corresponding to future engine applications. The projected noise levels are shown in Figure 13 for approach conditions. Similar results apply to takeoff and sideline noise.

The emissions goals, consistent with the proposed 1981 EPA Standard, are also expected to be met or exceeded.

Concluding Remarks

The conceptual energy-efficient engine designs described in this paper offer potential for achieving all of the goals established for the EEE Project. However, extensive technology-development efforts are needed to translate these designs into practical hardware. The EEE Project will concentrate, over the next five years, on the primary technology development and demonstration efforts needed to achieve the predicted benefits of the various design approaches. While the EEE Project will not culminate in a prototype demonstration, technology-readiness should be adequately demonstrated at the end of the program in 1983 to impact decisions for development of new or derivative energy efficient commercial engines.

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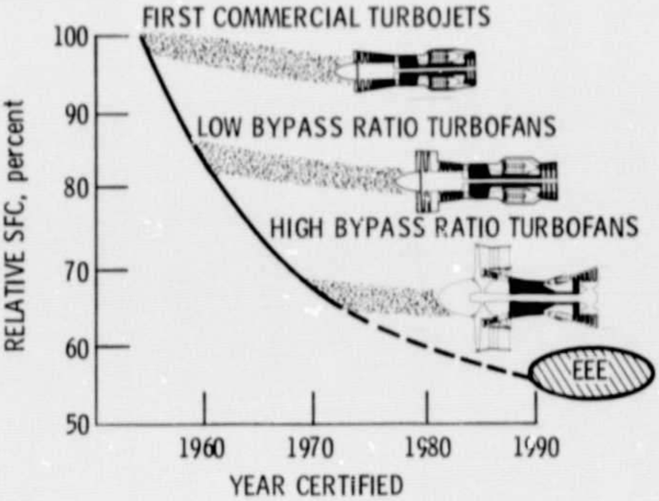

Figure 1. - Improvements in fuel efficiency.

GOALS FOR ENERGY EFFICIENT ENGINES

AT LEAST 12% LOWER
SPECIFIC FUEL CONSUMPTION (SFC)

AT LEAST 5% LOWER
DIRECT OPERATING COSTS (DOC)

AT LEAST 50% LOWER
PERFORMANCE DETERIORATION RATE

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

MEET FUTURE NOISE AND POLLUTION REGULATIONS

Figure 2. - Goals for energy efficient engines.

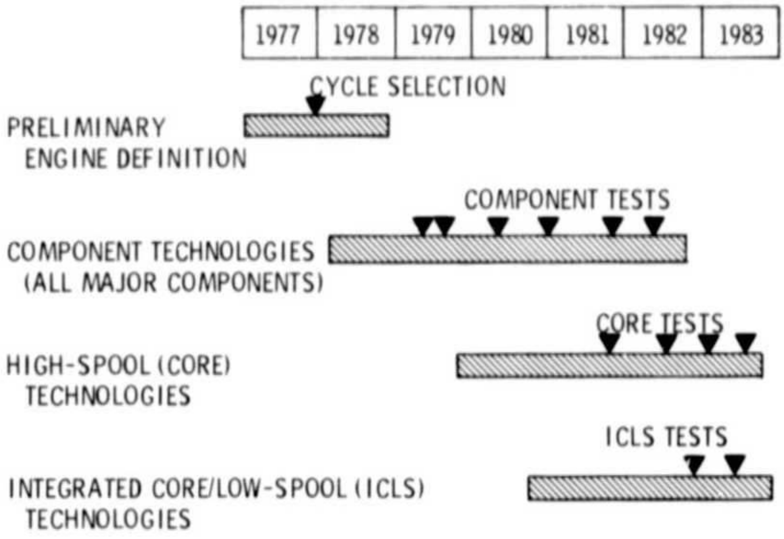

Figure 3. - Energy efficient engine project schedule.

	PRATT & WHITNEY		GENERAL ELECTRIC	
	JT9D-7A	EEE	EEE	CF6-50C
FAN DRIVE	DIRECT	DIRECT	DIRECT	DIRECT
EXHAUST CONFIGURATION	SEPARATE	MIXED	MIXED	SEPARATE
BYPASS RATIO	5.1	6.55	7.0	4.3
FAN PRESSURE RATIO	1.58	1.74	1.61	1.72
COMPRESSOR PRESSURE RATIO	10	14	22.2	12.9
OVERALL PRESSURE RATIO	25.4	38.6	36	32
TURBINE TEMPERATURE (^{0}F)				
MAX. CRUISE	1990	2200	2160	2080
HOT-DAY TAKEOFF	2285	2450	2440	2400
SLS THRUST (LBS)	44,265*	39,250	36,500	39,580*
RELATIVE ENGINE WEIGHT (LBS)	BASE	-1120	-1130	BASE

*SCALED VERSIONS OF REFERENCE ENGINES

Figure 4. - Cycles selected for energy efficient engines (maximum cruise conditions).

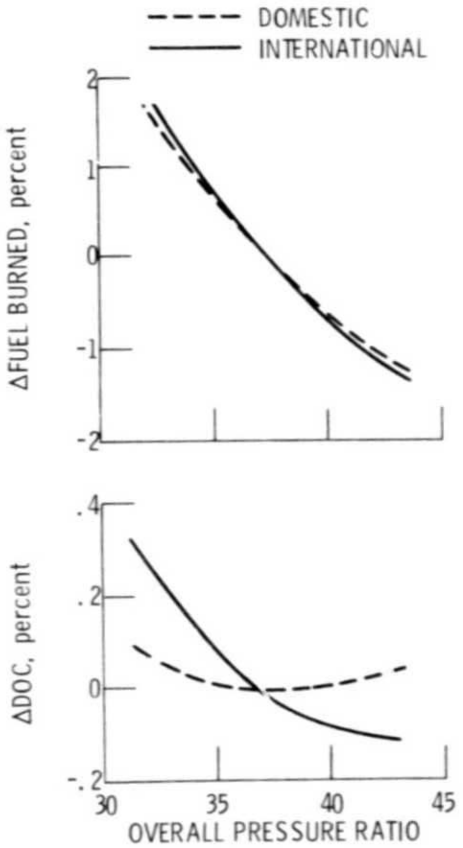

Figure 5. - Effects of overall pressure ratio.

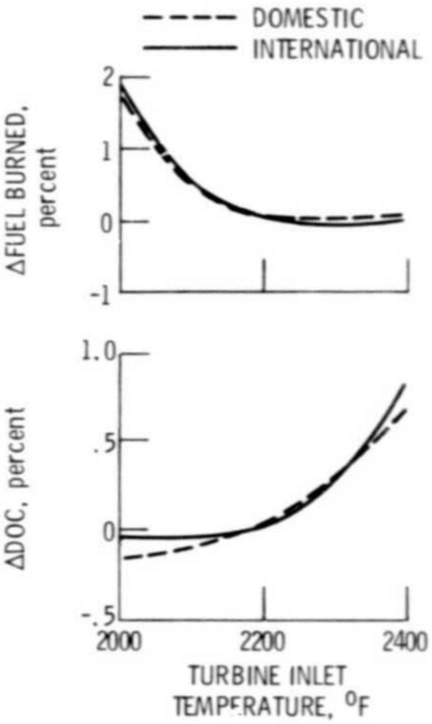

Figure 6. - Effects of turbine temperature.

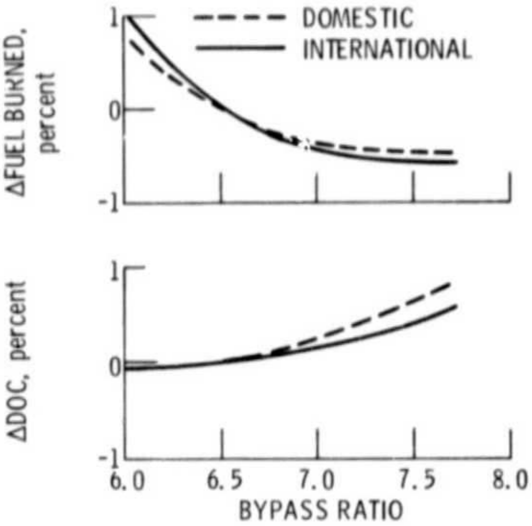

Figure 7. - Effects of bypass ratio.

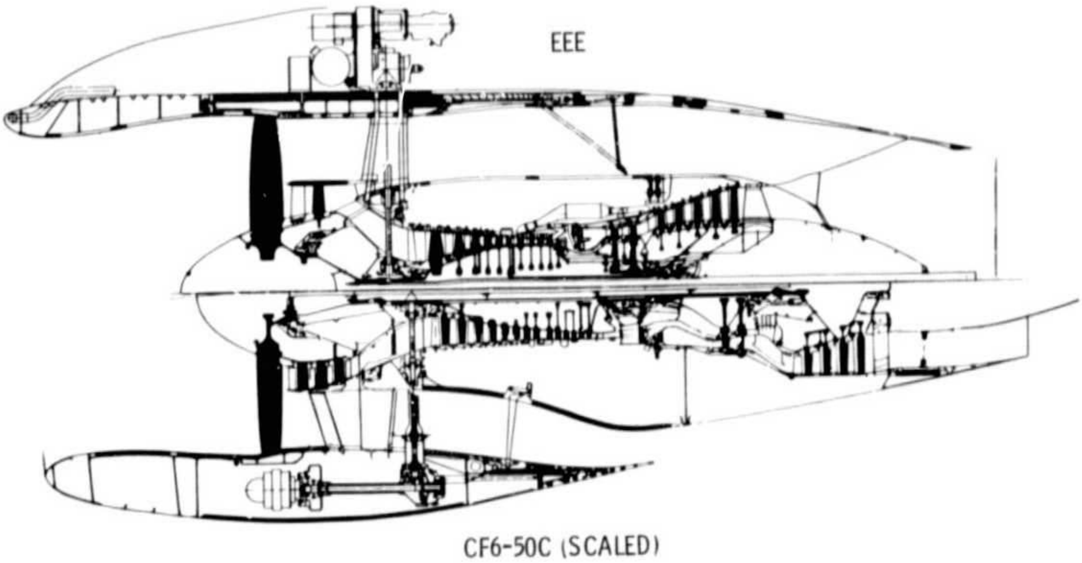

Figure 8. - Comparison of General Electric's engine configurations.

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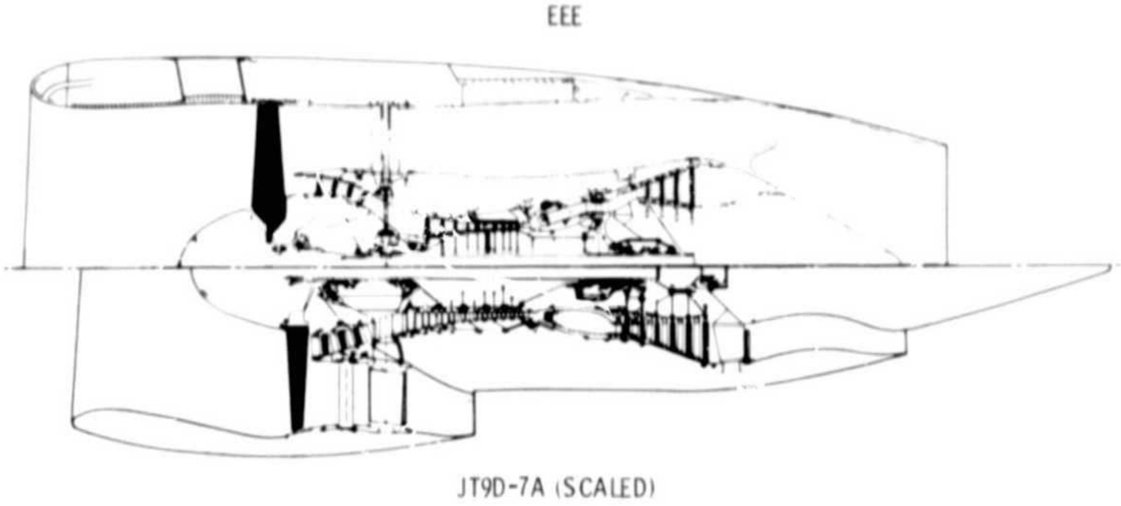

Figure 9. - Comparison of Pratt and Whitney's engine configurations.

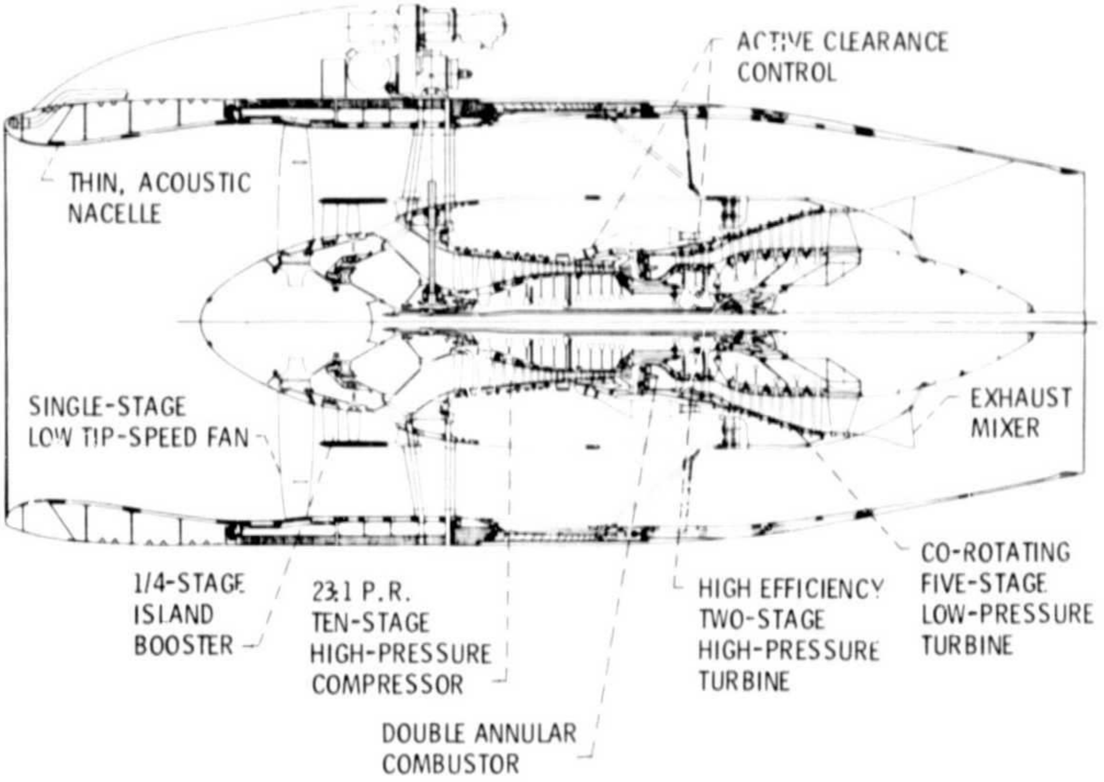

Figure 10. - General Electric's energy efficient engine configuration.

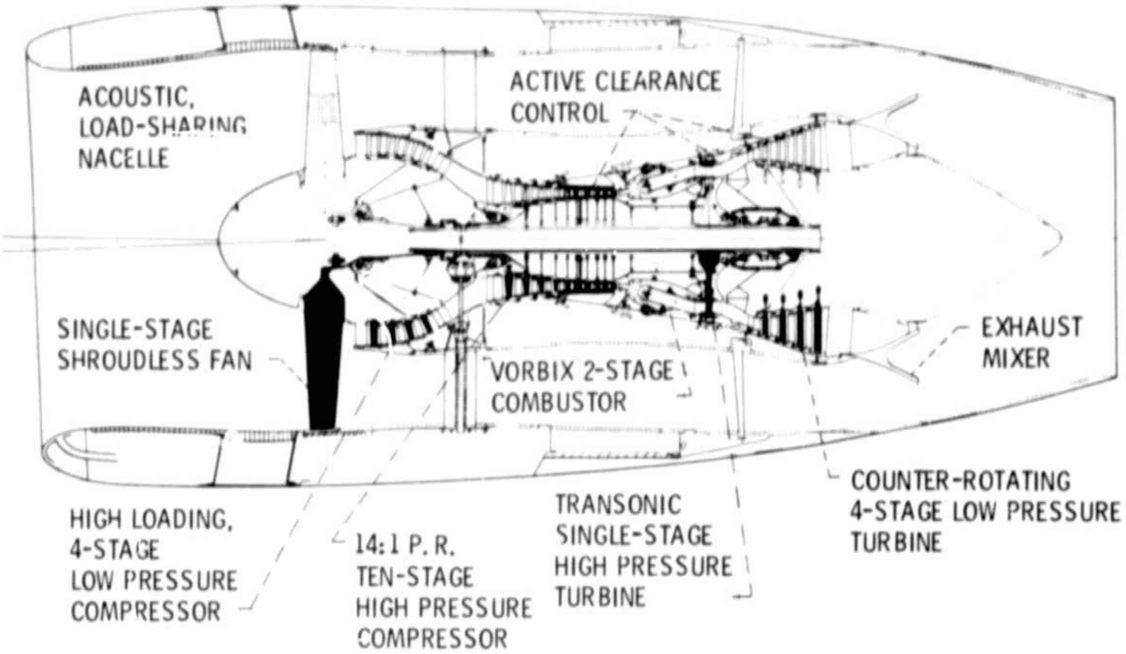

Figure 11. - Pratt and Whitney's energy efficient engine configuration.

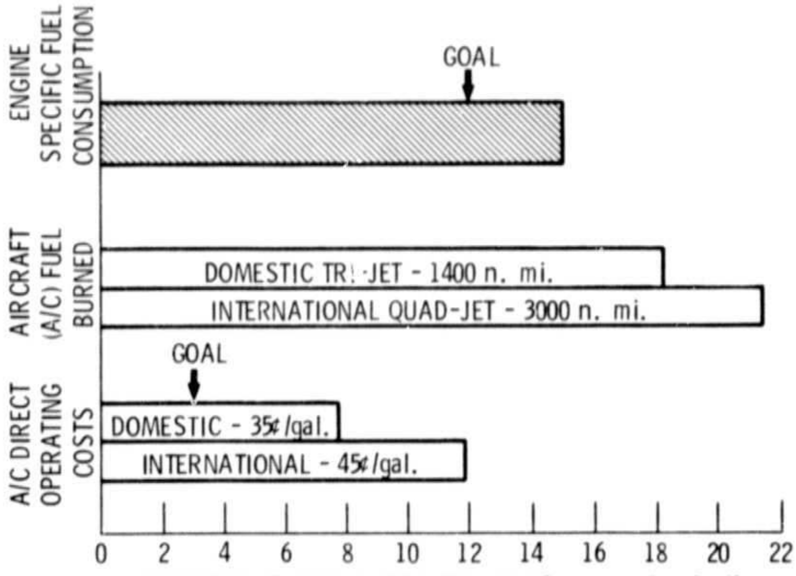

Figure 12. - Potential benefits of energy efficient engines.

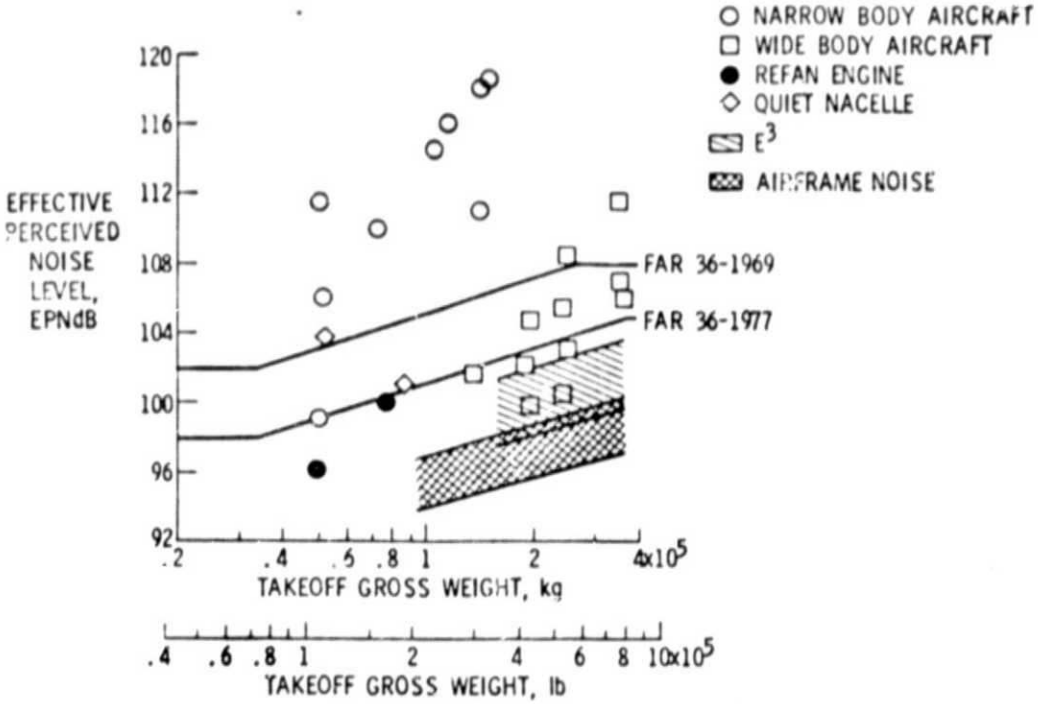

Figure 13. Estimated approach noise levels of aircraft powered by E^3 engine.