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Energy Efficient Engine Program Contributions to Aircraft Fuel Conservation

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ENERGY EFFICIENT ENGINE PROGRAM CONTRIBUTIONS TO AIRCRAFT FUEL CONSERVATION

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BACKGROUND

Because of the 1973 OPEC oil embargo, the price of jet fuel nearly tripled and the Energy Crisis started. During the next couple of years, NASA performed several studies to establish energy/transportation research programs to substantially reduce fuel consumption by transport aircraft. One such program was the JT8D-Refan Program. In January 1975, however, NASA was specifically requested by the Senate Committee on Aeronautical and Space Sciences to establish a research program that would have the reduction of future aircraft fuel consumption as its prime objective. NASA assembled a task force consisting of NASA, Department of Transportation, Federal Aviation Administration, and the Department of Defense with assistance from engine and airframe manufacturers, airlines and several advisory boards. The task force produced a report outlining this plan which was called the Aircraft Energy Efficiency (ACEE) program (see Reference 1 for an overview of the entire ACEE Program).

The six basic elements of the plan are shown in Figure 1. Of these six, three are airframe related and three are propulsion related. The three airframe elements were composite structures for lighter weight, the Energy Efficient Transport with advanced aerodynamics and active controls for both weight and drag reduction, and laminar flow control for drag reduction. The three propulsion elements were Engine Component Improvement, a near term program to improve efficiency and identify sources of deterioration in then production engines; the Energy Efficient Engine, a late 1980's advanced technology turbofan and subject of this presentation; and the Advanced Turboprop, with the greatest fuel savings potential but a much higher risk effort. The total program goal was to establish technology for a 50% fuel reduction for transport aircraft by 1985. The plan was approved by the Senate in November of 1975.

The Energy Efficient Engine (EEE) used fuel efficiency as a prime objective but also factored in direct operating cost and environmental acceptability. The EEE would be a "clean sheet of paper" design with 1985 being the target date for introduction. The main objectives of the EEE program were:

- At least 12 percent reduction in specific fuel consumption with at least a 50 percent reduction in performance deterioration rate
- Improve direct operating costs by at least 5 percent
- Meet future environmental regulations such as the FAA 1978 FAR-36 noise and EPA 1981 emissions standards

ENERGY EFFICIENT ENGINE PROGRAM OVERVIEW

Figure 2 shows the program schedule as it is ultimately being completed, but it can be used to generally outline the program. The program is primarily a $200+M contracted effort with both General Electric and Pratt & Whitney originally having essentially parallel contracts.

The program consisted of three main activities. These were Propulsion System Definition, Component Technologies, and Systems Integration. Propulsion System Definition implemented the original "clean sheet" design of a paper engine, references 2 and 3. The activity defined the overall engine cycle and the technologies required to achieve it. These paper engines, called Flight Propulsion Systems (FPS) were to represent the fully developed, production versions of the EEE. As component technologies and test results became available from the rest of the effort, these FPS propulsion systems were updated and new performance and fuel benefits calculated.

The most aggressive technologies identified in the initial FPS design were developed during the Component Technology effort. The technologies were evaluated through sub-scale and full-scale rig tests for verification.

The System Integration involved both core and integrated core/low spool turbofan engine testing. By having this element, it was possible to evaluate the interactions and the operability of the advanced technology components in a complete system.

Completion of all component and system activities coupled with the final update of the FPS computer models would define the actual level of fuel savings achievement of the EEE. Technology readiness was provided by the testing and it was then up to industry to incorporate this technology into production engines.

As mentioned, these were originally essentially parallel contracts. In 1982, funding for EEE was reduced and the program had to be descoped by about $19M. General Electric, however, was well along and the vast majority of their systems integration costs had already been accrued. It was therefore decided to complete the General Electric program and terminate the System Integration effort in the Pratt & Whitney program. Later in 1982 and 1983 some of the funding was restored to be used as "seed" money for a follow-on to the EEE. As a result, the component technology activities have been expanded for both contractors. These efforts primarily include shroudless, hollow fan technology and additional testing of the EEE compressors. At this time, no funding for a follow-on turbofan program appears available and the technology efforts will be ending in 1985.

Figures 3 and 4 are cut-away type drawings of the two EEE FPS engines. Figure 3 is the General Electric EEE which consists of a single stage fan and quarter stage open booster driven by a five-stage low pressure turbine; a core consisting of a 10-stage 23:1 pressure ratio high pressure compressor, dual annular combustor for low emissions, and two-stage high pressure turbine; daisy-type mixer; and long duct nacelle. In addition, an electronic engine mounted fuel control, Kevlar fan containment, and bulk acoustic treatment are all used. The fan uses wide rotor and stator spacing for reduced noise.

Figure 4 is the Pratt & Whitney EEE FPS which consists of a single-stage fan and four-stage low pressure compressor driven by a five-stage low pressure turbine; a core consisting of a 10-stage 14:1 pressure ratio high pressure compressor, two zone low emission combustor, and single-stage high pressure turbine; a daisy-type mixer; and long duct nacelle.

Although the configurations of the two engines are different, the cycles are quite similar with ∼38:1 overall pressure ratio, ∼1350°C (2450 °F) turbine rotor inlet temperature, and ∼6.8:1 bypass ratio.

These two "paper" engines really represent the output of the EEE program with their component performance and technology assumptions proven by the EEE testing.

MAJOR TECHNOLOGY DEVELOPMENTS FOR FUEL EFFICIENCY

Because the subject is primarily fuel efficiency, only those technologies which contributed significantly to reduced fuel consumption have been selected for this review. Full description of the EEE will be available when the final reports for the contracts are completed.

Fan

Highlighted in figure 5 is the General Electric EEE fan (ref. 4). This single-stage fan consists of 32 low aspect ratio blades follow by a quarter-stage booster for the core. The design bypass ratio is 6.8 at a 1.65 pressure ratio and 400 m/sec (1315 ft/sec) tip speed. Fuel efficiency technologies include the reduced number of blades with .55 span, aft-mounted dampers to reduce losses. The quarter stage booster achieved a 1.67 pressure ratio for the core with moderate hub loading. The result was a fan with 89.2 percent bypass and 89.5 percent core efficiencies.

The quarter-stage open booster also provided a second fuel savings technology which is a centrifugal cleaning action on the core flow. With this design, most dust and dirt are thrown outward and not ingested by the core. This greatly reduces foreign object ingestion and thus erosion effects on the compressor blade leading edges.

Finally, an integral vane-frame with wide spacing between the rotor and stator vanes was used for reduced weight and reduced noise generation.

Compressors

Shown in figure 6 are both high pressure compressors. One of the fuel saving technologies for the EEE is to provide better active and passive tip clearance control. Significant gains were made on tip clearance control by using a short stiff core design. The shorter compressors were obtained by providing higher pressure ratio per stage thereby reducing the total number of stages. The General Electric approach, reference 4, shown on the left side of figure 6, is a 10-stage 23:1 pressure ratio design. This high pressure ratio was achieved through high speed rather than high loading. Endwall contouring was used to minimize wall losses. To avoid problems of comparing efficiencies for compressors with different pressure ratios, polytropic efficiency is quoted. For this compressor, a 90.5 percent polytropic efficiency was obtained. For improved durability, the front stages use a low aspect ratio blade design improving foreign object ingestion tolerance.

On the right in figure 6, is the Pratt & Whitney 10-stage 14:1 pressure ratio compressor, reference 5. This highly loaded compressor uses advanced aerodynamics and controlled diffusion airfoils for a very high 91.5 percent polytropic efficiency. It uses only half the number of blades of the existing JT9D engines. Eliptic leading edges were used for improved erosion resistance. This compressor is lower in pressure ratio so that it could be driven by a single-stage turbine.

Both compressors use active clearance control on the last several stages. The active clearance control was used to minimize clearances during cruise, maximizing efficiency, but would allow maximum clearance during take-off to reduce chances for tip wear, reference 6. This helps maintain their high efficiency over the life of an engine.

Turbines

The EEE represented Pratt & Whitney's first opportunity to use a single-stage high pressure turbine, reference 5. The main features of this turbine are shown in figure 7. This turbine used advanced transonic aerodynamics to yield a high efficiency design for a single stage of 88.5 percent. This high efficiency coupled with the reduced weight and parts count had a significant impact on reducing direct operating cost for the Pratt & Whitney EEE. To permit higher temperatures with reduced cooling, single crystal airfoils and ceramic coated outer air seals were used. Active clearance control was also used to maintain tight clearances for the cruise portion of operation.

Not shown is the General Electric two-stage high pressure turbine which achieved a 92.5 percent efficiency. Ceramic tip seals, active clearance control and advanced aerodynamics were used to achieve this high efficiency.

Both low pressure turbines used advanced aerodynamics and active clearance control to achieve high efficiencies.

In summary, for all the turbines, at least one point improvement in efficiency was obtained over mid 1970's technology.

Mixers

Both EEE engines used mixers and long duct nacelles, references 5 and 7. In both cases the mixers contributed about 1/5 of the total fuel savings benefits for the EEE. Both EEE's "daisy-type" exhaust gas mixers are shown in a side view in the upper left of figure 8, General Electric's reference 8, is the upper and Pratt & Whitney's is the lower. The upper right of figure 8 shows the progression of mixer experience from the $\sim$1:1 bypass engine through a series of three model tests. In the end, both mixer designs provided about the same benefit. For $\sim$7:1 bypass ratio turbofan engines, these mixers provide about 3 percent fuel savings benefit.

The bottom left section of figure 8 gives the overall design characteristics for both mixer designs. Both are scalloped 18 lobe designs. The main difference is the penetration of the lobes into the fan stream. Higher penetration yields better mixing but also higher pressure losses.

Exhaust gas mixers require the use of long duct nacelles. Nacelle locations were evaluated in model tests where installations with a net benefit were found thereby avoiding the penalty normally associated with such nacelles.

INTEGRATED SYSTEM EVALUATION

As stated earlier the General Electric contract was not terminated when funding was cut back. Therefore, General Electric's EEE went through the systems integration evaluation which included both core engine tests and fully integrated core and low spool (ICLS) turbofan tests. These engine configurations had full aerodynamic equivalency with their corresponding parts of the EEE FPS. The hardware was also flight weight in the gas path but other hardware such as engine cases, gearbox, etc., was boilerplate. Also, for the turbofan configuration, a bell-mouth inlet was used for the ground test and the nacelle had only interior aerodynamic surfaces.

Figure 9 is a photograph of the turbofan engine in the test stand at General Electric's Peebles, Ohio, test site. All the fuel saving component technologies were included in this engine and exercised during the ground testing. While on test, this unique engine achieved over 162,360 N (36,500 lb_f) thrust. When the engine data is corrected for installation, instrumentation, and flight vs. ground effects, the research engine is projected to have a cruise specific fuel consumption of 0.056 kg/hr-N (.55 lbm/hr-lb_f), uninstalled. Corrected for installation, the projected cruise specific fuel consumption would be 13.5 percent better than the baseline average production CF6-50C. That would make this set of research hardware the world's most fuel efficient turbofan engine.

FUEL SAVINGS SUMMARY

Figure 10 summarizes the results of the program. If all the EEE technologies were applied to a new engine and the cycle and configuration of that engine optimized for today's $0.264/liter ($1.00/gallon) fuel prices, the benefits of the EEE would be 17-19% in fuel savings. If the commercial fleet could obtain half this benefit, it would translate in to nearly 4 billion liters (1 billion gallons) of jet fuel saved each year. (Currently more than 38 billion liters (10 billion gallons) of jet fuel are burned each year.) A ten percent reduction in direct operating cost would also be realized along with acoustic and environmental improvements.

The fuel savings are achieved through the four main areas shown in the pie chart in figure 10. Improved components using advanced aerodynamics, active clearance control, reduced gas-path leakage, higher temperature materials, and reduced cooling flows account for about half of the fuel savings. The higher pressure, temperature, and bypass ratio cycle accounts for approximately a quarter of the benefit. The efficient mixed flow exhaust accounts for about a fifth and the improved nacelle installation, the remainder.

TECHNOLOGY APPLICATION

As the EEE program was progressing, both General Electric and Pratt & Whitney saw immediate benefit for the EEE technology. So even before the EEE contracts are officially complete, we find application of the EEE technologies occuring. Without getting into specific details, figure 11 indicates the numbers of technology applications as applied to new and derivative high bypass turbofans of both companies. What counts as a technology for figure 11 would be items like fan and compressor tip trenches, high compressor blade loading, improved compressor aerodynamic design tools, compressor vane uncambering at endwalls, etc. Tables I and II provide the complete list that went into figure 11.

It can be claimed that approximately half of the fuel savings benefits of the PW2037 are attributable to the EEE program. As both companies develop engines such as the PW4000 and the CF6-80C2, substantial portions of their fuel savings benefits can be attributed to technology developments initiated by the EEE. General Electric has also identified a substantial number of technologies that are appropriate for their military products and are incorporating them.

THE FUTURE

When funds were restored in 1983, it was decided to use some of the funds to evaluate turbofan engine technologies and cycles of the future building upon the EEE. The studies would have an output similar to the initial EEE study, that is a definition of a complete turbofan propulsion system, but for the years 2000-2010. The studies would try to answer if turbofan technology is an area of "diminishing returns" and, if not, establish the basis for a follow-on program after EEE.

Figure 12 is the result of the Pratt & Whitney study called the "Target Engine". Pratt & Whitney used technology extrapolations and limited parametric cycle analyses to arrive at this conceptual engine. The Target Engine has a gear-driven swept blade $\sim$12:1 bypass ratio fan and separate flow exhaust. (A mixer benefit at $\sim$12:1 bypass ratio could not be identified.) The other major impact is the high, $\sim$60:1, cycle pressure ratio which requires small and high temperature rear stages of the high pressure compressor. Because of the improved (approximately one point polytropic) compressor efficiency, only a modest rise in turbine rotor inlet temperature of approximately one hundred degrees is required.

The basic technologies required are advanced, controlled diffusion, higher efficiency compressor; low pressure drop diffuser-combustor; high annulus-speed-squared, full three-dimensional design turbines; closed-loop active clearance control; composite integrated structures; short, shock-free integrated fan cowl; a swept, shock-free fan; and high efficiency reduction gear.

When this type of engine is evaluated, the potential fuel savings is 15.5 percent in cruise specific fuel consumption over the EEE. This translates to a 24 percent savings in fuel burned for a 3700 km (2000 nautical mile) mission 500 passenger quadjet. These benefits are split roughly equally between thermal efficiency improvements and propulsive efficiency improvements. Because of the contributions of the swept fan to the efficiency improvements, some preliminary design studies have been started using EEE funds.

To put all the EEE and the future into one perspective, figure 13 is provided. This figure shows the trend of uninstalled, bare specific fuel consumption starting with the JT3 type turbojet as a function of year of initial certification. The next spot on the curve is the JT3D/JT8D type engines with about a 15 percent improvement. The next spot, the first JT9D/CF6 type high bypass engines, again made a substantial improvement on the order of 19 percent over the previous engines. Next comes the PW2037 with an improvement on the order of 12 percent over the JT9D/CF6. The PW2037 represents the first significant use of EEE technology.

Two spots for EEE are shown. The higher is about 15 percent below the JT9D/CF6 spot and represents the final results for the EEE FPS engines. The lower spot represents application of EEE technologies but with some re-optimization of the engine configuration such as the number of compressor and turbine stages. It is about 18 percent below the JT9D/CF6 spot. The Turbofan Future Potential spot represents the results of the Target Engine study just shown, again showing that substantial gains are still possible. This is very important because it is not clear that turboprops will be available in the high thrust size normally filled by turbofans during this time period.

Finally, are two spots for advanced propfan type turboprop systems which include advanced technology cores. The higher spot uses an EEE technology core and low pressure turbine and the lower spot uses the advanced Target Engine core and low pressure turbine technologies. Thus even the propfan gains substantially from turbofan core technology developments.

CONCLUSIONS

The EEE program was highly successful and provides an excellent technology base for much improved turbofan engine fuel efficiency. As a result, both General Electric and Pratt & Whitney are rapidly translating these technologies into their products making the EEE program a great success.

Although no funding has been identified, a follow-on turbofan research program could obtain substantial additional fuel savings benefits. The core portion of these technologies would have direct application to propfan turboprop propulsion systems providing substantial benefit to them also.

TABLE I

PW E^3 TECHNOLOGIES - APPLICATION TO COMMERCIAL ENGINES			
TECHNOLOGY	JT9D-7R4	PW2037	PW4000
COMPRESSOR INTERMEDIATE CASE WITH THROUGH STRUTS			X
FAN AND COMPRESSOR TIP TRENCHES	X	X	X
REDUCED LPC INNER CAVITY VOLUMES	X	X	X
LOW CX/U L C		X	X
DRUM COMPRESSOR ROTORS WITH INTEGRAL KNIFE EDGES		X	X
COMPRESSOR AIRFOILS WITH ELLIPTICAL LEADING EDGES		X	X
MINI SHROUDED HPC		X	X
DOUBLE WALL COMPRESSOR ACTIVE CLEARANCE CONTROL		X	
CONTROLLED DIFFUSION COMPRESSOR AIRFOILS		X	X
INCREASED COMPRESSOR STAGE LOADINGS		X	X
TANGENTIAL COMPRESSOR BLADE ATTACHMENTS		X	X
CANTED COMPRESSOR EXIST GUIDE VANE/DIFFUSER		X	
TWO BEARING HIGH SPOOL WITH DAMPING AND SPRINGS		X	X
NON-METALLIC TURBINE OUTER AIRSEAL		X	X
FULL RING TURBINE SIDEPLATES		X	
IMPROVED TURBINE FEATHERSEAL SLOTS		X	X
THERMAL BARRIER COATING ON TURBINE VANE PLATFORMS	X	X	X
IMPROVED GASPATH STATIC SEALS	X	X	X
TURBINE AIRFOIL INTERNAL TRIP STRIPS	X	X	X
TURBINE AIRFOIL INTERNAL TURNING VANES	X	X	X
3-D DESIGN TURBINE VANES			X
IMPROVED SUCTION SIDE FILM COOLING			X
HIGH AN^2 TURBINE		X	X
THIN TURBINE AIRFOIL TRAILING EDGES			X
HIGH STAGE LOADING TURBINE AIRFOILS		X	X
HIGH REACTION HP TURBINE		X	X
LOW CX/U TURBINE		X	X
TURBINE AIRFOILS WITH ELLIPTICAL LEADING EDGES		X	X
TWIST RESTRAINED HP TURBINE VANES		X	X
BOLTLESS TURBINE DISK SIDE PLATE			X
LP TURBINE FLOW GUIDES	X	X	X
LOW LOSS CONTOUR TURBINE EXIT GUIDE VANE		X	X
THREE BEARING LOW SPOOL		X	X

TABLE II

GE E^3 TECHNOLOGIES - APPLICATION TO COMMERCIAL/MILITARY ENGINES						
TECHNOLOGY	CF6-80C2	CFM 56-3	F110	GROWTH F404	T700	GE27
IMPROVED COMPRESSOR AERODYNAMIC DESIGN TOOLS	X	X	X			
COMPRESSOR VANE UNCAMBERING AT ENDWALLS	X					
IMPROVED BETWEEN SHINGLE SEALS FOR SHINGLE COMBUSTOR LINERS			X	X		
REDUCED THROUGH-FLOW VELOCITY HP TURBINE DESIGN	X	X		X		X
HIGH STAGE REACTION HP TURBINE		X				
IMPROVED HP TURBINE FLOWPATH OVERLAPS	X	X				X
HP TURBINE CONVERGED STATOR BANDS	X	X				X
HP TURBINE IMPROVED AIRFOIL SURFACE VELOCITY DISTRIBUTIONS	X	X		X		X
CERAMIC HP TURBINE SHROUDS			X	X	X	
LIGHTWEIGHT RADIAL STRUTTED TURBINE FRAME WITH POLYGONAL CASING	X					
IMPROVED LP TURBINE FLOWPATH OVERLAPS	X					X
IMPROVED LP TURBINE AIRFOIL SURFACE VELOCITY DISTRIBUTIONS	X					X
FADEC FAULT INDICATION AND CORRECTIVE ACTION SYSTEM				X		

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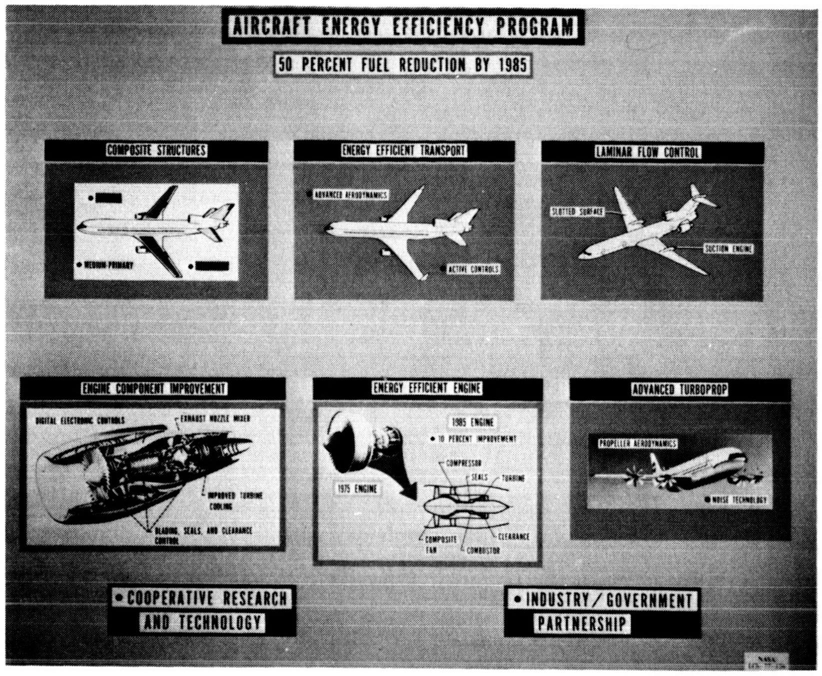


Figure 1. - Overview of aircraft energy efficiency program.

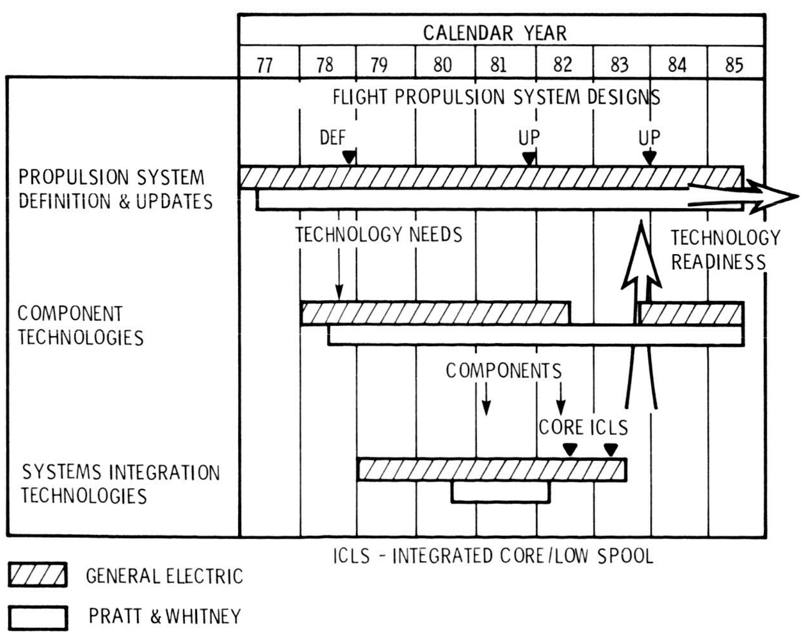


Figure 2. - Energy efficient engine program.

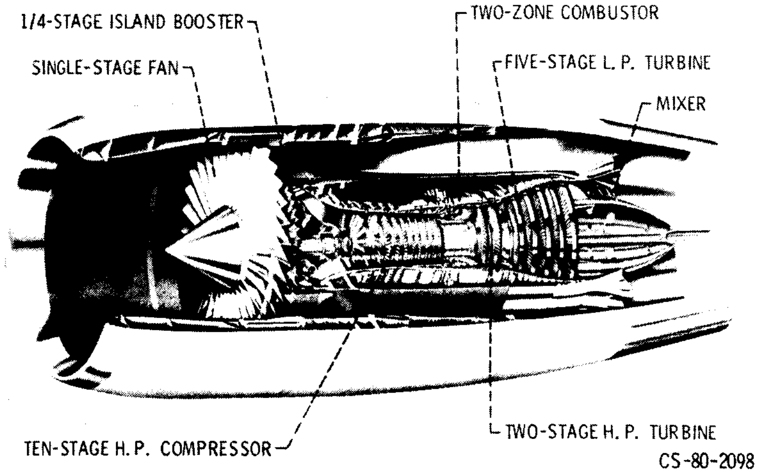


Figure 3. - Energy efficient engine, General Electric configuration.

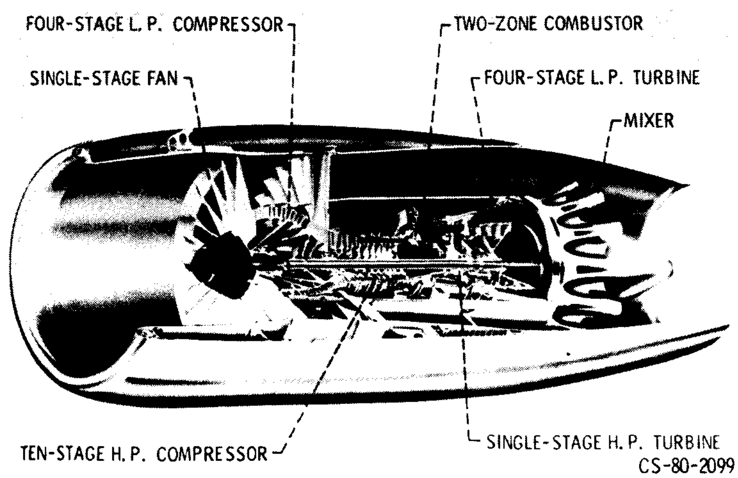
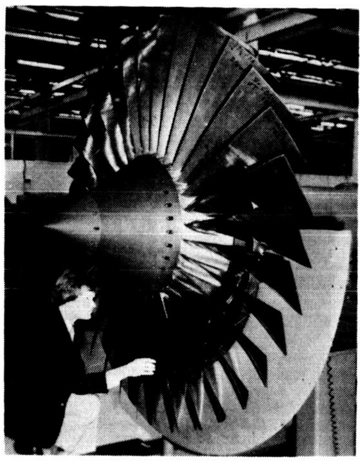
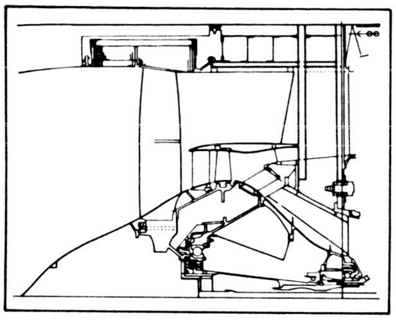


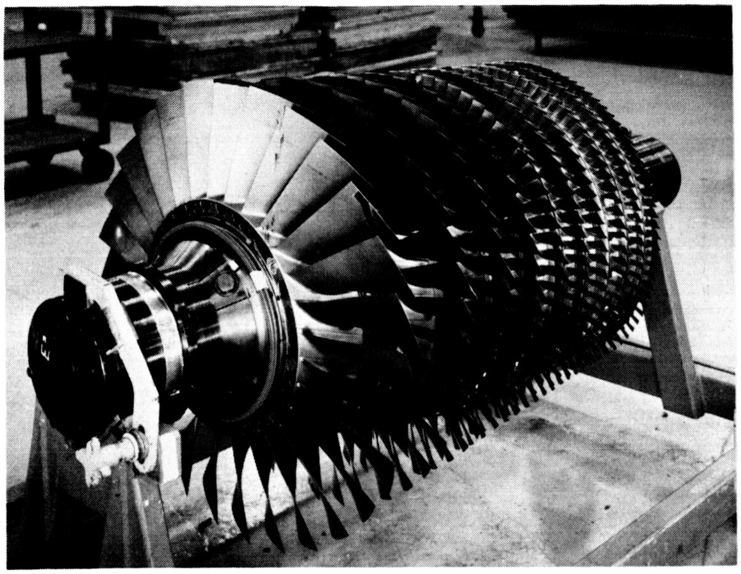
Figure 4. - Energy efficient engine, Pratt & Whitney configuration.



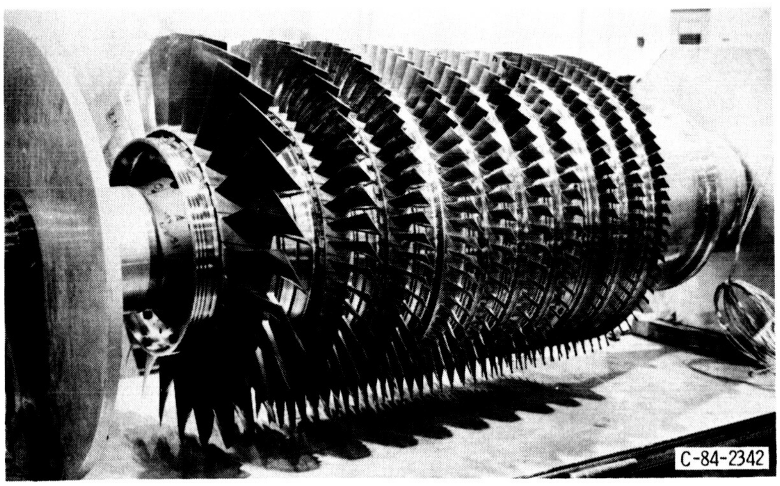


- 32 BLADE / 6.8 BYPASS RATIO / 1.65 PRESSURE RATIO
- 0.55 SPAN, AFT MOUNTED LOW LOSS SHROUD
- 89.2 BYPASS, 89.5 CORE EFFICIENCY
- QUARTER STAGE BOOSTER / FOD SEPERATION
- INTEGRAL STATOR-FAN FRAME / WIDE ROTOR-STATOR SPACING

Figure 5. - EEE fan technology.

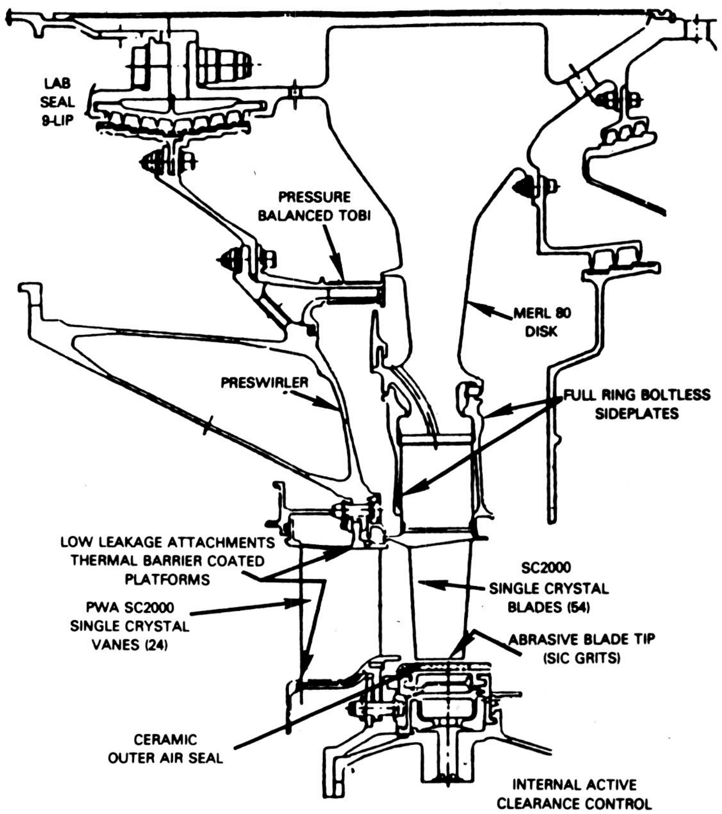


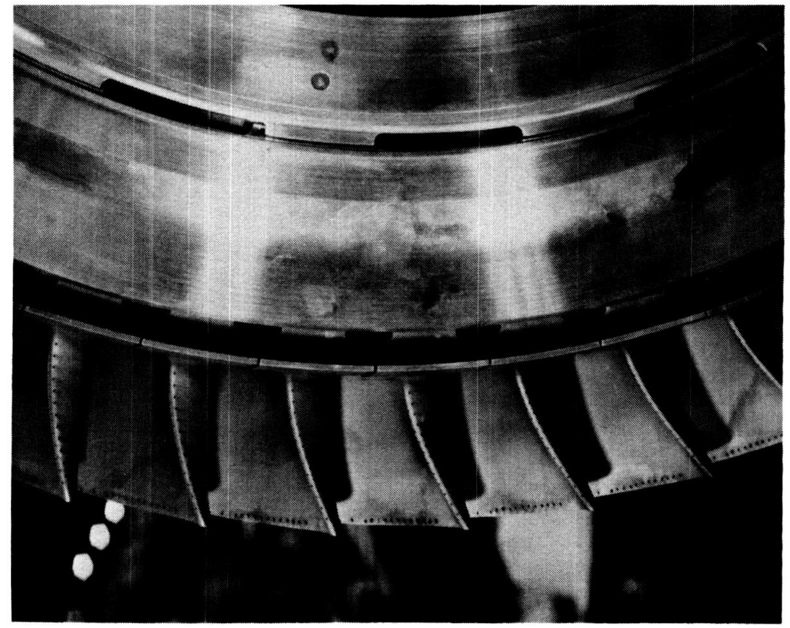
(a) General Electric. 10-stage; 23:1 pressure ratio; High speed, endbend treatment; 90.5 poly. eff.



(b) Pratt & Whitney. 10-stage; 14:1 pressure ratio; High loading controlled diffusion; 91.5 poly. eff.

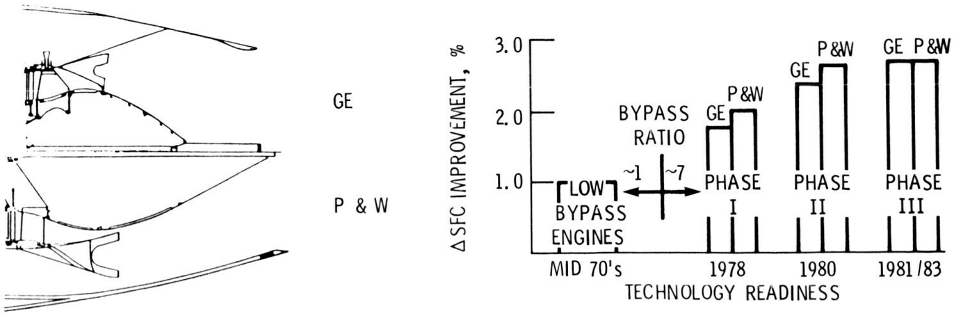
Figure 6. - EEE compressor technology; Active and passive clearance control; short, stiff rotor; low aspect ratio blades.





- ACHIEVED 88.5 PERCENT EFFICIENCY
- SINGLE STAGE / REDUCED NUMBER OF AIRFOILS
- LOW-LOSS TRANSONIC AERODYNAMIC DESIGN
- IMPROVED COOLING EFFICIENCY / EFFECTIVENESS

Figure 7. - EEE single-stage high pressure turbine.



FEATURES	GE	P & W
● NUMBER OF LOBES	18	18
● PENETRATION, %	45	75
● MIXING LENGTH, L/D	.52	.61
● MIXING EFFECTIVENESS, %	79	85

NEW E^3 TECHNOLOGY

- SHORT EFFICIENT MIXERS COMBINING HIGH MIXING EFFECTIVENESS WITH LOW PRESSURE LOSS
- MIXERS AT HIGH BYPASS RATIOS
- REDUCED WEIGHT MIXER DESIGNS

Figure 8. - EEE exhaust mixer technology.

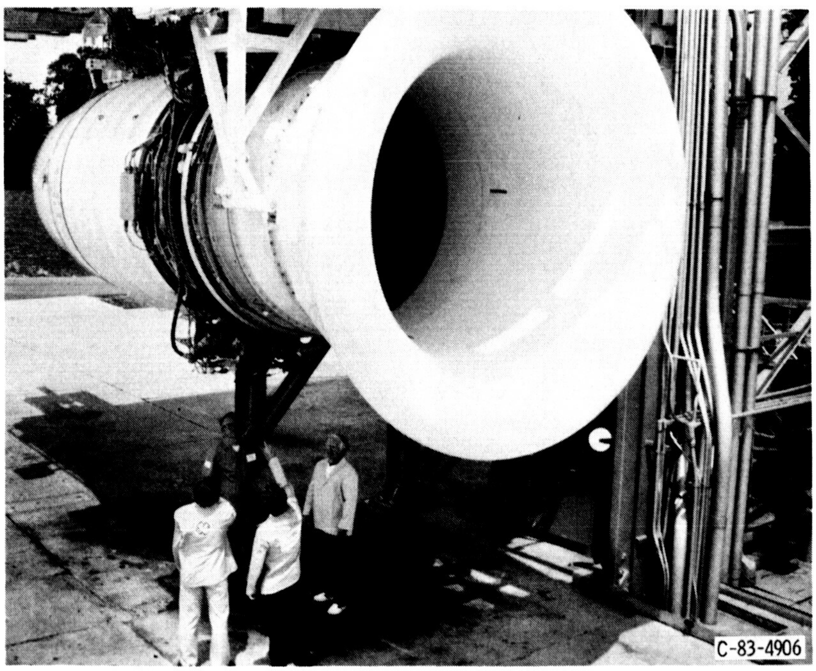


Figure 9. - EEE experimental engine on test stand.

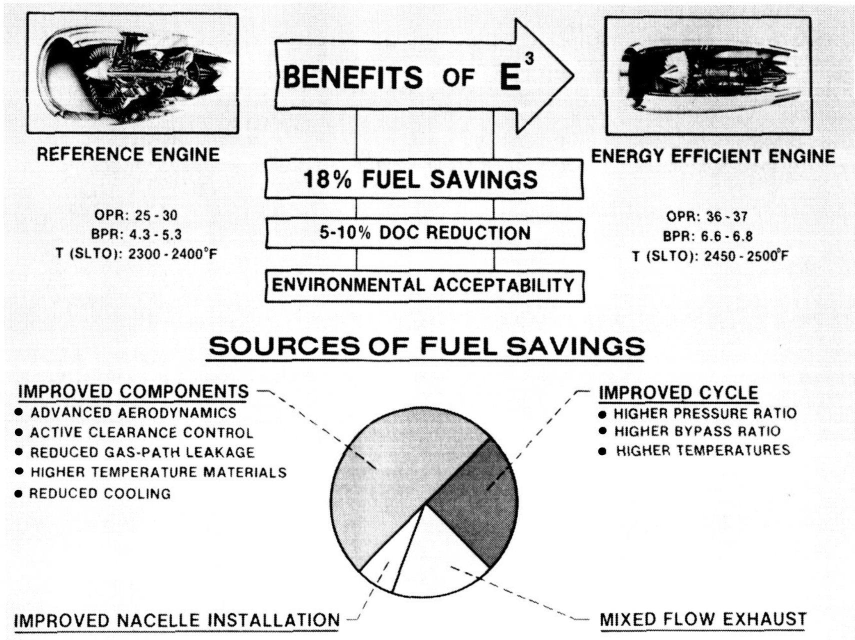
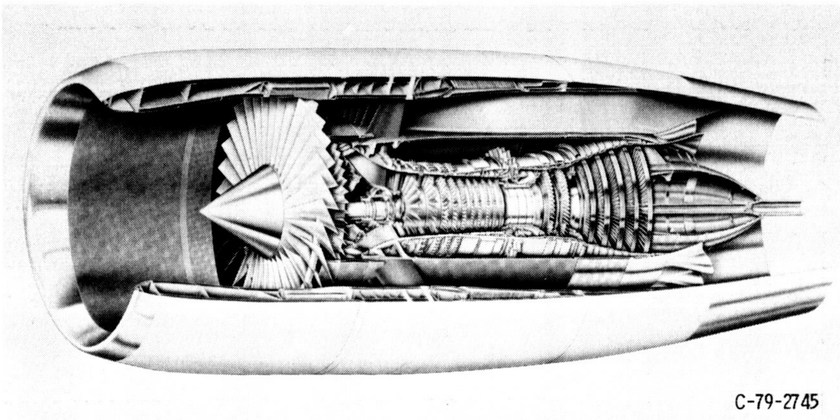
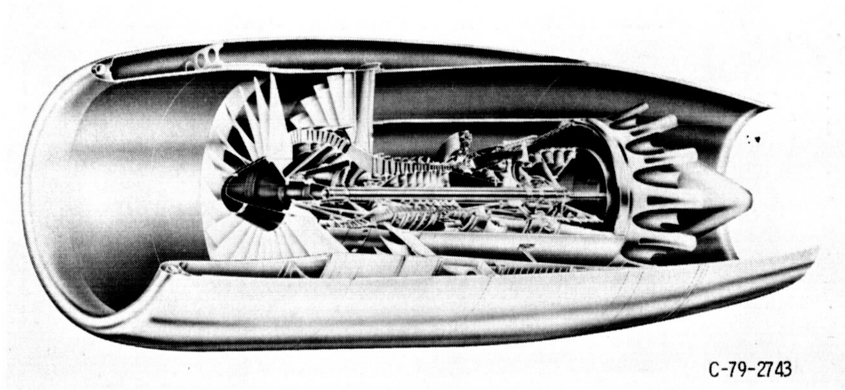


Figure 10. - EEE benefits summary.



APPLICATION	CF6-80C2	CFM56-3	MILITARY
NUMBER OF TECHNOLOGIES	9	6	15

(a) General Electric.



APPLICATION	JT9D-7R4	PW 2037	PW 4000
NUMBER OF TECHNOLOGIES	7	28	30

(b) Pratt & Whitney.

Figure 11. - Commercial & military application of energy efficient engine technology.

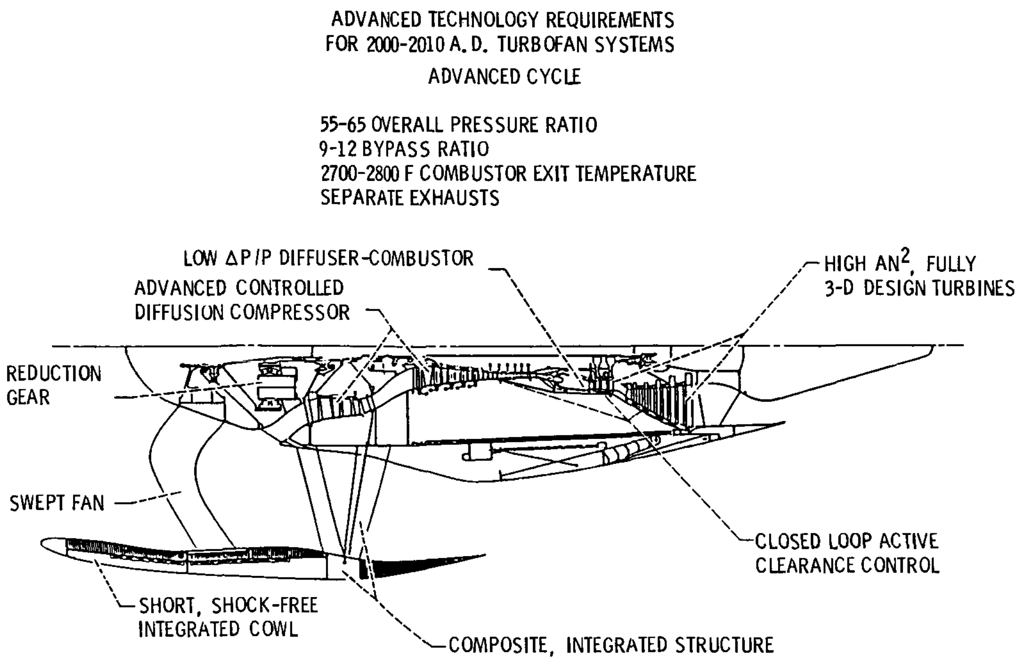


Figure 12. - Advanced turbofan research requirements and benefits. Potential fuel savings over EEE -15.5% SFC, -24% fuel burned.

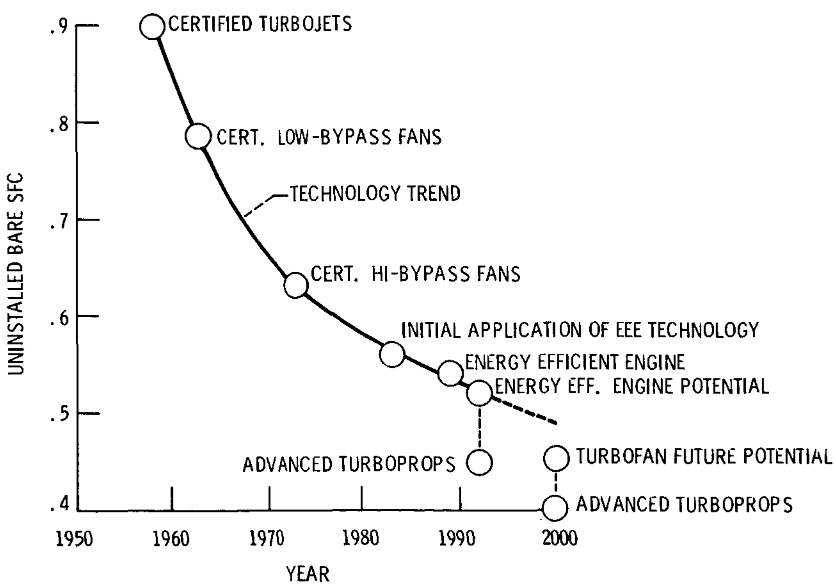


Figure 13. - Turbofan technology trend.

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16. Abstract

Significant advances in high bypass turbofan technologies that enhance fuel efficiency have been demonstrated in the NASA Energy Efficient Engine (E^3) Program. This highly successful second propulsion element of the NASA Aircraft Energy Efficiency Program included major contract efforts with both General Electric and Pratt & Whitney. Major results of these efforts will be presented including highlights from the NASA/General Electric E^3 research turbofan engine test. Direct application of all the E^3 technologies could result in fuel savings of over 18% compared to the CF6-50 and JT9D-7. Application of the E^3 technologies to new and derivative engines such as the CF6-80C and PW 2037, as well as others, will be discussed. Significant portions of the fuel savings benefit for these new products can be directly related to the E^3 technology program. Finally, results of a study looking at far-term advanced turbofan engines will be briefly described. The study shows that substantial additional fuel savings over E^3 are possible with additional turbofan technology programs.

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