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Future Trends in Subsonic Transport Energy Efficient Turbofan Engines

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Details of the NASA sponsored General Electric Energy Efficient Engine (E^3) technology program are presented along with a description of the engine, cycle and aircraft system benefits. Opportunities for further performance improvement beyond E^3 are examined. Studies leading to the selection of the E^3 cycle and configuration are summarized. The advanced technology features, cycle and component performance levels are also presented. An evaluation of the benefits of the fully developed Flight Propulsion System (FPS) is made relative to the NASA program goals by comparing the FPS with the CF6-50C where both are installed in advanced subsonic transport aircraft. Results indicate that a mission fuel saving from 15 to 23 percent is possible depending on mission length.

INTRODUCTION

After the 1973 oil embargo, it became clear that efforts to develop a more fuel efficient air transport system needed to be accelerated. An overall plan to implement this, called the Aircraft Energy Efficient (ACEE) program, was developed by NASA. The Energy Efficient Engine (E^3) project is an important part of ACEE.

The current E^3 had its beginnings in earlier NASA study contracts such as Studies of Turbofan Engines Designed for Low Energy Consumption (STEDLEC) (Reference 1), Studies of Unconventional Engines Designed for Low Energy Consumption (USTEDLEC) (Reference 2) and Energy Efficient Engine - Preliminary Design and Integration (E^3 - PDI) (Reference 3). In addition, a compressor study called Advanced Multi-stage Axial Flow Core Compressor (AMAC) (Reference 4) influenced the core engine configuration of the current E^3. The timing and major contribution of these studies toward the E^3 is shown in Figure 1.

The STEDLEC study investigated the use of advanced engine technology in the choice of cycle and fan pressure ratios, materials and turbine inlet temperatures. Direct and geared (for high bypass flows) drive engines of up to 45:1 overall pressure ratio and turbine inlet temperatures up to 2800°F (1538°C) were evaluated in terms of increased fuel efficiency.

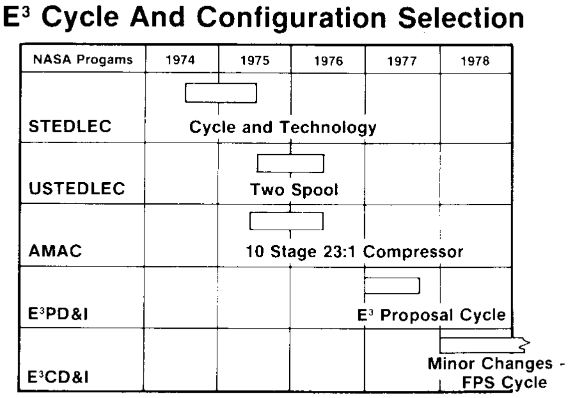

Figure 1 E^3 Cycle And Configuration Selection

USTEDLEC was essentially an engine configuration study in that gearing, triple spools, propfans, turboprops and exhaust gas regenerators were studied to see if there were fuel efficiency advantages in any unconventional arrangements of turbomachinery. Direct and geared drive two-spool engines and turboprops were identified as having high potential for advanced fuel efficient engines.

The AMAC study resulted in the selection of a 10 stage 23:1 pressure ratio core compressor coupled with a 2 stage turbine for the core of the General Electric E^3. This configuration was shown to offer both fuel efficiency and economic benefits over earlier core engine configurations studied.

In the most recent of the preceding E^3 studies, E^3 - PDI (Reference 3), the general configuration and cycle of the General Electric E^3 was selected. The cycle utilized projected advances in

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aerodynamic technology and the long duct mixed flow engine configuration to produce an estimated 14.4% reduction in installed specific fuel consumption (sfc) relative to a scaled CF6-50C at a maximum cruise rating condition. Figure 2 is a cross section of the engine resulting from this preliminary design study. Table 1 is a comparison between this advanced engine and the reference scaled CF6-50C.

Advanced E^3 PDI Study Engine

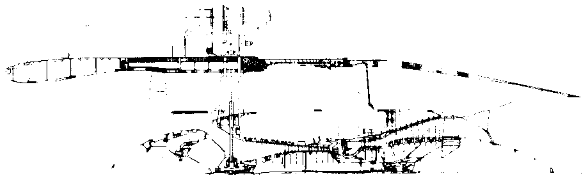

Figure 2 Advanced E^3 PDI Study Engine

Engine Cycle Comparison

	Ref. CF6-50C (Scaled)	Initial FPS Engine
Installed Fn @ M=.8 lbs (kN)	**8610 (38.3)**	**8610 (38.3)**
10668 m (35K), MxCl Hot Day		
Core Corr Flow - MxCl lb/sec (kg/sec)	**118.7 (53.8)**	**120.0 (54.4)**
Bypass Ratio - MxCl	**4.2**	**6.8**
Fan Pressure Ratio - MxCl	**1.76**	**1.65**
Overall Pressure Ratio - MxCl	**32**	**38**
ΔSFC - Uninstalled MxCr (Std) %	**Base**	**-13.7**
ΔSFC - Installed MxCr (Std) %	**Base**	**-14.4**

Table I Engine Cycle Comparison

Other NASA sponsored material studies (References 5 and 6), were also conducted during this period to determine possible system benefits of certain new materials installed in an advanced technology transport engine. Several of these concepts such as Near Net Shape - Rene' 95 powdered metallurgy disks, directionally solidified turbine blade alloys and ceramic HP turbine shrouds were eventually incorporated into the General Electric E^3.

The current General Electric E^3 work is being conducted under Energy Efficient Engine - Component Development and Integration contract NAS3-20643 to NASA-Lewis Research Center with Mr. Neal T. Saunders as the Lewis Project Manager. The purpose of the contract is to develop and evaluate technology advances identified in earlier studies. These advanced technology features are then to be demonstrated in a series of component tests culminating in the running of a core engine and an Integrated Core/Low Spool (ICLS) engine in 1982 to demonstrate the complete engine system.

ENERGY EFFICIENT ENGINE PROGRAM

There are well-defined NASA goals for the current E^3 program. In terms of a completely installed Flight Propulsion System (FPS) on an advanced technology subsonic transport aircraft, the FPS is to show, as a minimum, the following benefits relative to a CF6-50C reference engine:

- 12% reduction in installed specific fuel consumption (sfc)
- 5% reduction in direct operating cost (DOC)
- 50% reduction in sfc deterioration in service

Other goals are:

- Meet FAR 36 (March 1978) acoustic standards with provisions for growth
- Meet Proposed EPA (1981) emissions standards for new engines

The program is structured into four major technical tasks as follows:

Task I	-	Preliminary Design of a fully developed FPS based on Task II, III and IV results
Task II	-	Preliminary and Detailed Design and testing of the individual components
Task III	-	Testing and Evaluation of the core engine
Task IV	-	Testing and Evaluation of the ICLS

The timing of the major elements of the various tasks is shown in Figure 3.

E^3 Program Milestones

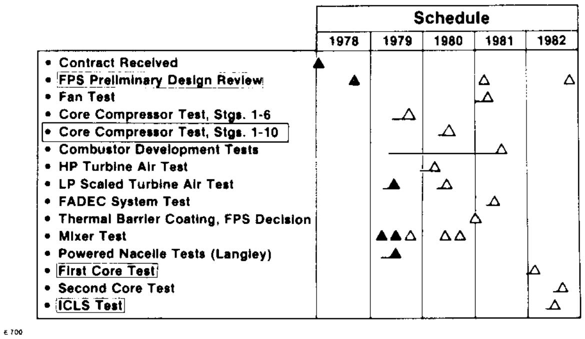

Figure 3 E^3 Program Milestones

FPS TECHNOLOGY GOALS

12% SFC Reduction

Table II is a comparison of the major cycle and system parameters for the General Electric FPS and the reference CF6-50C. A visual comparison of the two engines is given in Figure 4. Besides the obvious difference of a separate versus mixed flow exhaust, the FPS utilizes a higher overall pressure ratio, lower fan pressure ratio and a higher bypass ratio in conjunction with higher component efficiencies.

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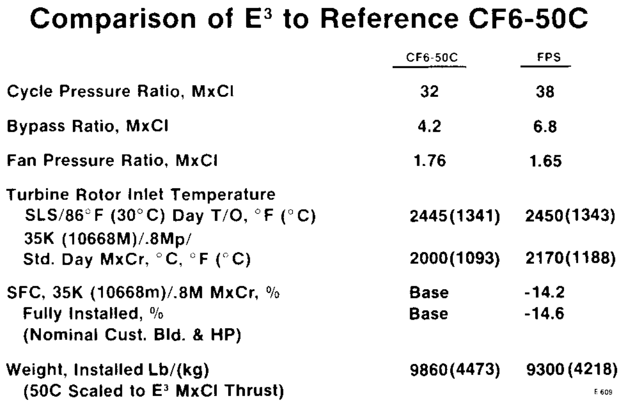

Comparison of E^3 to Reference CF6-50C

	CF6-50C	FPS
Cycle Pressure Ratio, MxCl	32	38
Bypass Ratio, MxCl	4.2	6.8
Fan Pressure Ratio, MxCl	1.76	1.65
Turbine Rotor Inlet Temperature		
SLS/86°F (30°C) Day T/O, °F (°C)	2445(1341)	2450(1343)
35K (10668M)/.8Mp/ Std. Day MxCr, °C, °F (°C)	2000(1093)	2170(1188)
SFC, 35K (10668m)/.8M MxCr, %	Base	-14.2
Fully Installed, % (Nominal Cust. Bld. & HP)	Base	-14.6
Weight, Installed Lb/(kg) (50C Scaled to E^3 MxCl Thrust)	9860(4473)	9300(4218)

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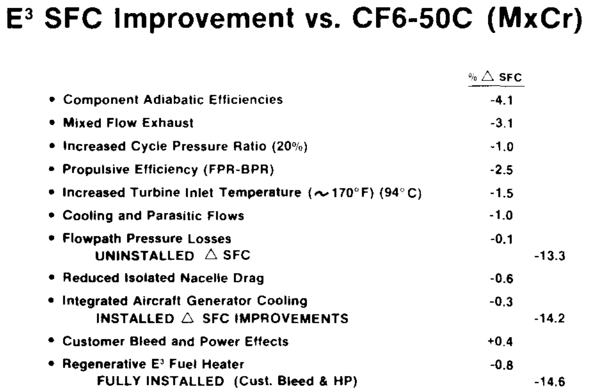
Table II Comparison Of E^3 FPS And CF6-50C Component Efficiencies



E^3 SFC Improvement vs. CF6-50C (MxCr)

	% △ SFC	
• Component Adiabatic Efficiencies	-4.1	
• Mixed Flow Exhaust	-3.1	
• Increased Cycle Pressure Ratio (20%)	-1.0	
• Propulsive Efficiency (FPR-BPR)	-2.5	
• Increased Turbine Inlet Temperature (~170°F) (94°C)	-1.5	
• Cooling and Parasitic Flows	-1.0	
• Flowpath Pressure Losses	-0.1	
UNINSTALLED △ SFC		-13.3
• Reduced Isolated Nacelle Drag	-0.6	
• Integrated Aircraft Generator Cooling	-0.3	
INSTALLED △ SFC IMPROVEMENTS		-14.2
• Customer Bleed and Power Effects	+0.4	
• Regenerative E^3 Fuel Heater	-0.8	
FULLY INSTALLED (Cust. Bleed & HP)		-14.6

Table III E^3 SFC Improvement vs. CF6-50C

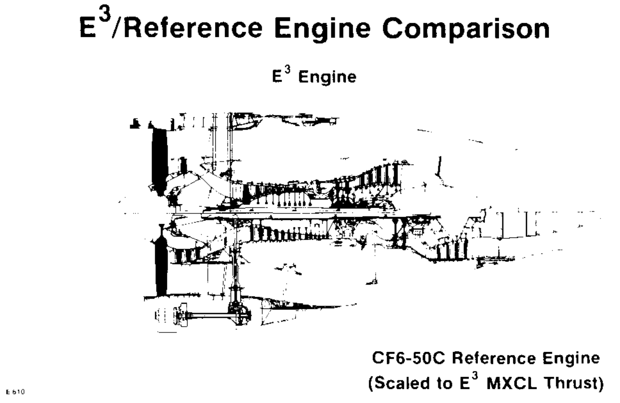
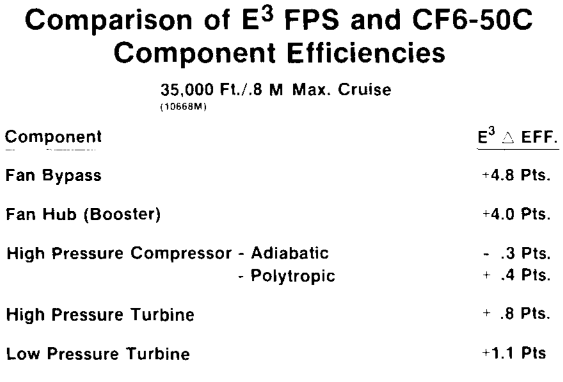


Figure 4 E^3/Reference Engine Comparison



Comparison of E^3 FPS and CF6-50C Component Efficiencies

35,000 Ft./.8 M Max. Cruise
(10668M)

Component	E^3 △ EFF.
Fan Bypass	+4.8 Pts.
Fan Hub (Booster)	+4.0 Pts.
High Pressure Compressor - Adiabatic	- .3 Pts.
- Polytropic	+ .4 Pts.
High Pressure Turbine	+ .8 Pts.
Low Pressure Turbine	+1.1 Pts

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Table IV Comparison Of E^3 FPS And CF6-50C Component Efficiencies

The 14.6% projected reduction in sfc for a fully installed (customer bleed, power extraction, and ram recovery) FPS comes from many sources as shown in Table III. Component adiabatic efficiency improvements are the single largest source of sfc improvements. Individual component improvements are given in Table IV. The levels of improvement were estimated by taking current technology levels of component performance and comparing them with the projected performance levels of the FPS with FPS levels of aerodynamic loading.

The largest improvements were made in the fan and fan hub regions. Fan tip speeds were set at the most efficient levels that would provide adequate stall margin and specific flow. The blade shrouds were placed in the minimum performance loss position on the blade. Fan tip clearance reductions from current levels were possible due to the improved fan casing deflection control achieved by use of stiffer, lighter composites and structural integration into the fan frame. To provide the required core supercharging, a quarter stage booster was added and loading on the fan hub reduced. A side benefit of the booster configuration is that about 40% of the booster air is bypassed into the fan duct resulting in removal of the blade tip boundary layer air from the core supply along with debris that might enter the fan hub region. The quarter stage operation also permits proper matching of the booster to core air requirements by permitting excess air to bypass the core entrance. This eliminates any variable geometry bypass provisions normally required with close coupling of booster and core compressor.

The choice of the 23:1 pressure ratio 10 stage compressor (Figure 5) had a significant effect on the overall FPS configuration and fuel efficiency potential. Its short length permitted a stiffer, less deflection prone engine to be designed with just two major frames. In addition, the work extraction from the core turbine reduces fan turbine inlet temperatures. When compared to the 14 stage CF6-50C, the projected polytropic efficiency of the E^3 compressor is higher although the pressure rise is over 50% greater.

In addition to the attention given to reduction of aerodynamic losses in all the components, a large improvement in component efficiencies resulted from a reduction in blade tip and seal clearance losses. The reductions came about in three major ways:

- Matching of materials and thermal response
- Low deflection engine mounting system
- Active Clearance Control system (ACC)

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The ACC system is employed over the last 5 stages of the core compressor, the high pressure turbine and the low pressure turbine. A schematic of the aft core compressor ACC system is shown in Figure 6.

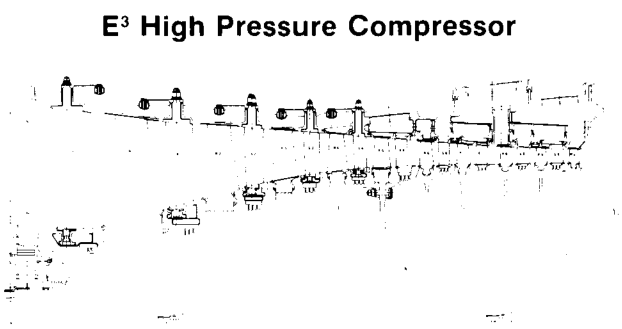

Figure 5 E^3 High Pressure Compressor

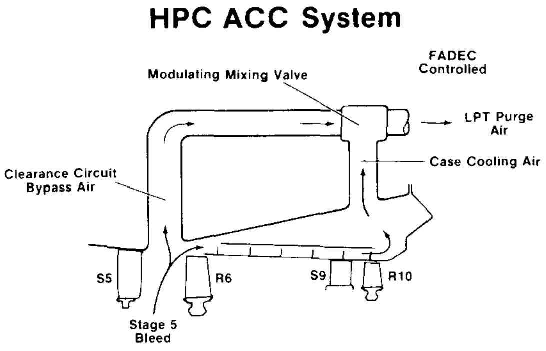

Figure 6 High Pressure Compressor ACC System

In operation, a modulating valve varies the amount of cooling air permitted to pass along the outer surface of the aft inner casing. This modulated cooling varies the radial expansion of the casing and can then alter the running clearances of the blades and vane shrouds. The modulation itself is governed by the engine control. During periods of higher than normal engine deflection or transient tip clearance closure, the casing is not cooled and thereby, becomes hotter and expands. This combination of heating or cooling allows engine build-up clearances to be minimized and reduces excess running clearances during climb and especially cruise.

The ACC system for the turbines is similar in operation except that controlled fan air is allowed to impinge directly onto the turbine cases. Operation of the ACC on a typical turbine stage is shown in Figure 7. Table V illustrates the expected performance benefit for each component due only to the ACC system. The gains are substantial, especially for the core turbine. A second major benefit of the ACC system is that deterioration due to inadvertent tip rubs will be reduced since the clearances can be opened up during periods of high maneuver loads or nacelle aerodynamic loads.

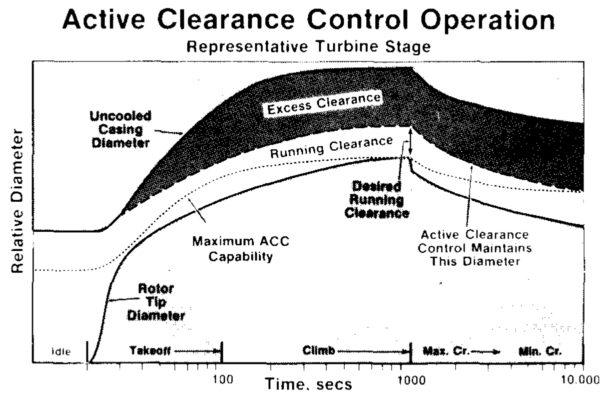

Figure 7 Active Clearance Control Operation - Representative Turbine Stage

Estimated Active Clearance Control Performance Improvement

	Eff - %	SFC - %
• HPC	.5	.3
• HPT	1.6	1.0
• LPT	.4	.2
	Total	1.5

Table V Estimated Active Clearance Control Performance Improvement

The other significant contribution to FPS fuel efficiency is the mixed flow exhaust system. The core exhaust is mixed with fan air by a mixer (Figure 8) to produce additional thrust. Besides improving overall engine efficiency, the mixer also provides these benefits:

- Core thrust spoiling during reverse mode
- Reduction of jet exhaust velocity and noise

A mixing effectiveness goal of 75% at maximum cruise thrust has been established for the FPS. Scale model testing is in progress and results, to date, indicate achievement of approximately two-thirds of the projected 3.1% cruise sfc improvement.

The propulsive efficiency improvements over the CF6-50C are the result of the higher bypass flow ratio and the lower fan pressure ratio. At maximum climb, for instance, the fan bypass ratio of the FPS is 60% higher than that of the CF6-50C. The increase in propulsive efficiency coupled with the increased pressure ratio and cruise turbine inlet temperature produces a 5% reduction in sfc as compared to the CF6-50C. Currently, the uninstalled FPS sfc, as shown in Table III, is estimated to be 13.3% lower than the uninstalled CF6-50C.

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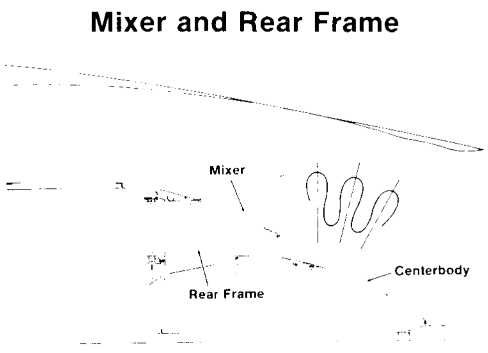

Figure 8 Mixer and Rear Frame

Nacelle drag improvements over the CF6-50C were accomplished by reducing the maximum nacelle diameter, relative to the fan diameter, increasing the nacelle slenderness ratio and reducing the frontal area. The nacelle diameter was reduced by integrating the fan casing and frame directly to the outer nacelle walls and through extensive use of lighter and stiffer composite materials. Frontal area was also reduced by installing the accessory gearbox within the core cowl volume instead of the fan case.

When the reduced nacelle drag and benefits due to elimination of fan air cooling of current technology constant speed drives for the FPS Variable Speed Constant Frequency (VSCF) aircraft generator are combined, the FPS installed sfc benefit relative to the CF6-50C is 14.2 percent, as shown in Table III.

If a fully installed FPS (customer bleed, power extraction and ram recovery) is considered, an advanced fuel heater/regenerator system increases the net sfc benefit to the 14.6% shown on Table III. A schematic of the fuel heater/regenerator as installed on the FPS is given in Figure 9.

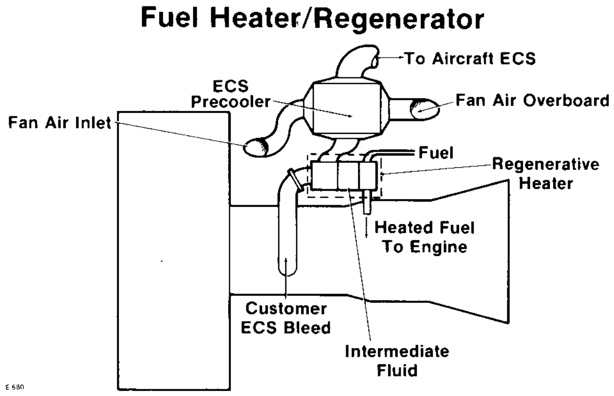

Figure 9 Fuel Heater/Regenerator

The regenerator takes advantage of the heat in the Environmental Control System (ECS) air that is normally lost to the engine cycle. By transferring the excess heat to the fuel, low grade heat is added to the engine in the thermodynamically most desirable location, the combustor. Also, the current requirement for fan air to cool the ECS air is reduced, and at most mission power settings, eliminated. Table III shows +0.4% sfc penalty for E^3 relative to the CF6-50C for customer bleed at constant thrust. This penalty is exceeded by the benefits of the regenerator.

The individual control functions that must be maintained for the FPS to achieve fuel efficient operation through wide variation of altitude and thrust have been increased significantly as shown in Figure 10.

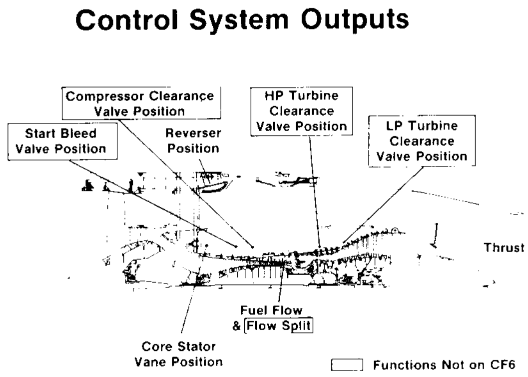

Figure 10 Control System Outputs

Because of the number of controlled functions required, increased power management complexity, and more convenient aircraft interfaces, a Full Authority Digital Electronics Control (FADEC) has been selected for the General Electric E^3. A schematic of the FADEC control function, Figure 11, illustrates the initial concept of reliability through the use of an active standby FADEC. As experience with and reliability of the FADEC grow, more economical methods of ensuring essential reliability would be utilized. Other control functions, not now envisioned, could also be added due to the inherent ability of a digital control to be programmed to accept new duties.

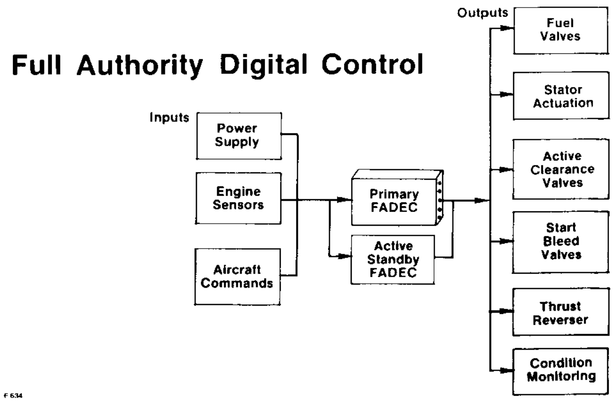

Figure 11 Full Authority Digital Control

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5% DOC Reduction

Integration of the E^3 FPS with advanced subsonic transport study aircraft has been evaluated by aircraft companies to determine total system benefits. The three subcontractors (Boeing, McDonnell Douglas, Lockheed) evaluated the General Electric FPS on their advanced study aircraft.

The study aircraft characteristics are shown in Table VI. The aircraft were representative of the technology level expected to be available in the mid to late 1990's and included advanced features such as:

- Extensive use of structural composites
- Active control systems
- Low drag, high lift devices
- High aspect ratio supercritical airfoils
- Recirculating ECS air systems
- Wind Load alleviation

Aircraft/Engine Integration Studies

Aircraft Being Evaluated

• Boeing	Domestic Twin	196 PAX/2000 Miles (3219 km)
• Douglas	Domestic Trifan	458 PAX/3000 Miles (4828 km)
• Lockheed	Domestic Trifan	500 PAX/3000 Miles (4828 km)
• Lockheed	Intercontinental Quad Fan	500 PAX/6500 Miles(10460 km)

Table VI Aircraft/Engine Integration Studies

The FPS was compared with a scaled CF6-50C on an equivalent advanced aircraft with the results shown in Figures 12 and 13. Block fuel savings ranged from 15 to 23% with DOC reductions of from 5 to 12% depending on the mission and aircraft. Higher benefits are available if the deterioration rate reduction goal is considered. The subcontractor results confirmed that the DOC goal can be met with the FPS design.

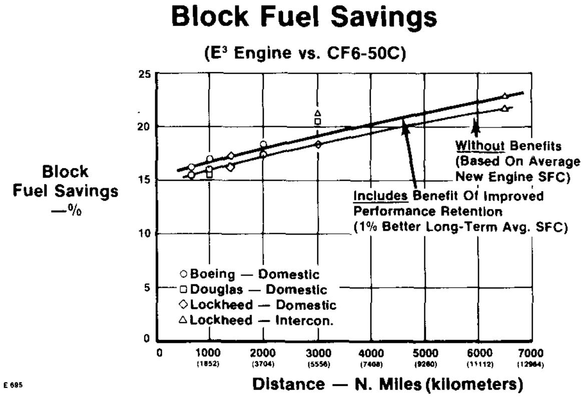

Figure 12 Block Fuel Savings

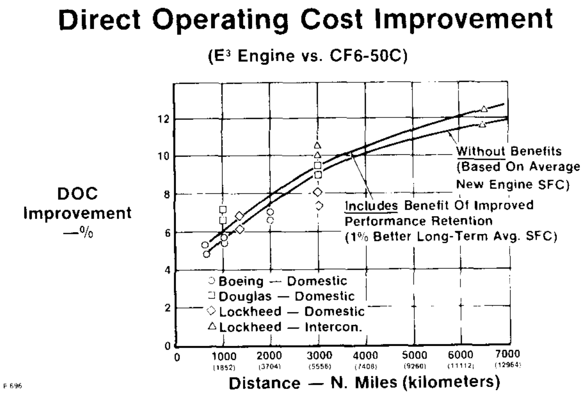

Figure 13 Direct Operating Cost Improvement

50% Deterioration Reduction

Over a long period of service, engine performance deteriorates with a consequent rise in SFC. Figure 14 illustrates the typical trend shape of the deterioration curve for a current CF6-50C along with a projected General Electric FPS curve. Achievement of the deterioration goal for the FPS would reduce engine fuel consumption by approximately 1% over the life of the engine.

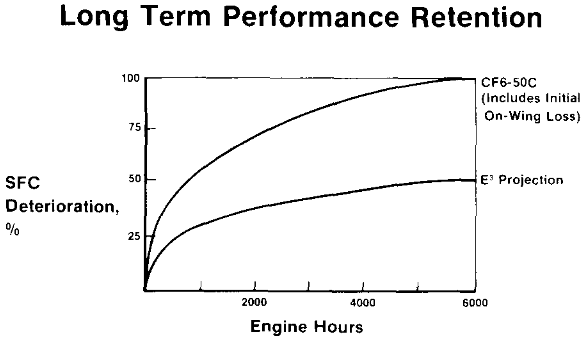

Figure 14 Long Term Performance Retention

Three major areas of deterioration which have been identified in current engines are:

- Clearances
- Leakages
- Erosion

Table VII shows the amount of deterioration associated with each of these areas for the CF6-50C and an estimate of losses that would be experienced by the FPS over the same engine life. The FPS, by design intent, will achieve a deterioration rate of less than 50 percent of the CF6-50C.

The improved engine stiffness, mounting system and ACC will provide a reduction in engine clearance sfc loss due to inadvertent rubs. Leakage improvements will come from reduced casing to stator shroud deflection and improved variable vane trunnion configurations. The improved variable vane bearing supports will reduce the leakage of compressor

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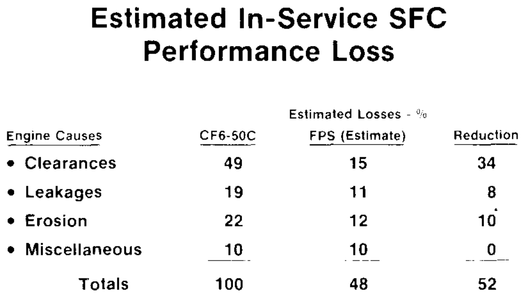
air into the core cowl region. Erosion will be reduced through the debris separation provided by the quarter stage design. The larger chord, thicker airfoils of the core compressor will also be less susceptible to damage.



Estimated In-Service SFC Performance Loss

Engine Causes	CF6-50C	Estimated Losses - % FPS (Estimate)	Reduction
• Clearances	49	15	34
• Leakages	19	11	8
• Erosion	22	12	10
• Miscellaneous	10	10	0
Totals	100	48	52

Table VII Estimated In-service SFC Performance Loss

Meet FAR 36 (1978) Acoustic Standards

An important design consideration is that the FPS should be able to meet anticipated environmental requirements. Many advanced design features were incorporated in the FPS to permit it to meet the NASA acoustics goal. Sound reduction has been achieved in two ways as shown in Figure 15. Modern bulk absorber acoustic treatment has been applied to the maximum extent practicable and source noise reduction has been incorporated into the design and the cycle. A primary noise reduction feature is the high bypass ratio and mixed exhaust which results in a significantly lower exhaust jet noise than in current engines. Estimates of the FPS noise on the advanced study aircraft, are shown in Table VIII. A design goal for the FPS was to satisfy the FAR 36 (1978) with a suitable margin.

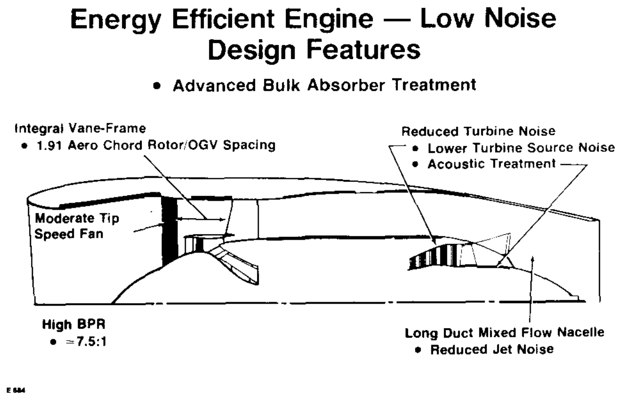
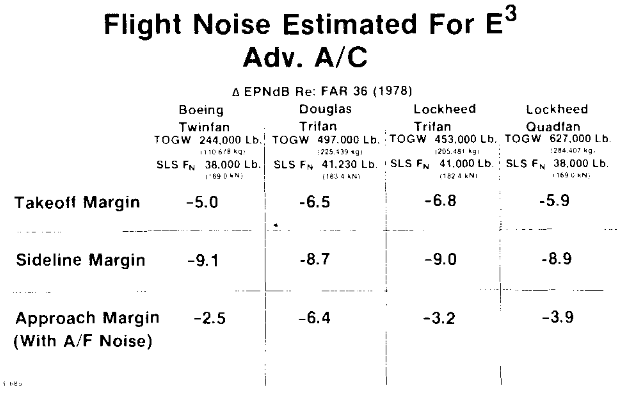


Figure 15 Energy Efficient Engine - Low Noise Design Features



Flight Noise Estimated For E^3 Adv. A/C

Δ EPNdB Re: FAR 36 (1978)

	Boeing Twinfan TOGW 244,000 Lb. (110,678 kg) SLS F_N 38,000 Lb. (169.0 kN)	Douglas Trifan TOGW 497,000 Lb. (225,439 kg) SLS F_N 41,230 Lb. (183.4 kN)	Lockheed Trifan TOGW 453,000 Lb. (205,481 kg) SLS F_N 41,000 Lb. (182.4 kN)	Lockheed Quadfan TOGW 627,000 Lb. (284,407 kg) SLS F_N 38,000 Lb. (169.0 kN)
Takeoff Margin	-5.0	-6.5	-6.8	-5.9
Sideline Margin	-9.1	-8.7	-9.0	-8.9
Approach Margin (With A/F Noise)	-2.5	-6.4	-3.2	-3.9

Table VIII Flight Noise Estimated For E^3 Advanced Aircraft

Meet Proposed EPA (1981) Emissions Standards

The double annular combustor selected for the General Electric FPS (Figure 16) was derived from an earlier NASA sponsored study called the Experimental Clean Combustor Program (ECCP) (Reference 7). The FPS features a short burning length and a relatively high space rate yet is projected to meet all requirements with margin except for nitrous oxide (NOx). Estimated emissions levels, relative to the 1982 EPA goal, are shown in Figure 17. At a 6 percent idle thrust setting, the predicted NOx levels would be considered marginal for a production engine.

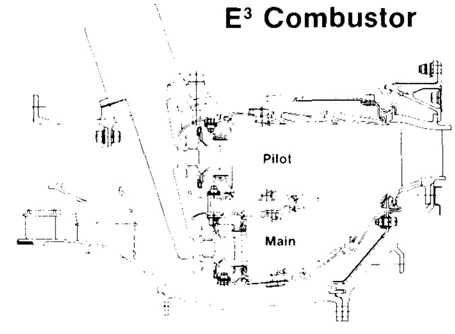


Figure 16 E^3 Double Annular Combustor

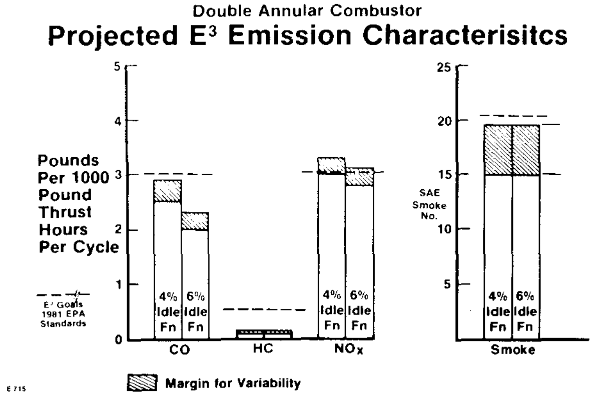


Figure 17 Projected E^3 Emission Characteristics

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FUEL EFFICIENCY BEYOND E^3

The E^3 engine provides a substantial improvement in fuel efficiency relative to the current generation of high bypass engines. Figure 18 shows the trend of U.S. commercial transport engine fuel efficiency with the E^3 objective performance level projected for the late 1980's time period. Although the E^3 is not the ultimate 0.8 Mach cruise transport turbofan engine, the trend line suggests that additional fuel efficiency improvements will be substantially smaller. Extrapolation of the trend line would indicate that expected improvements relative to E^3 might be in the order of 5 percent.

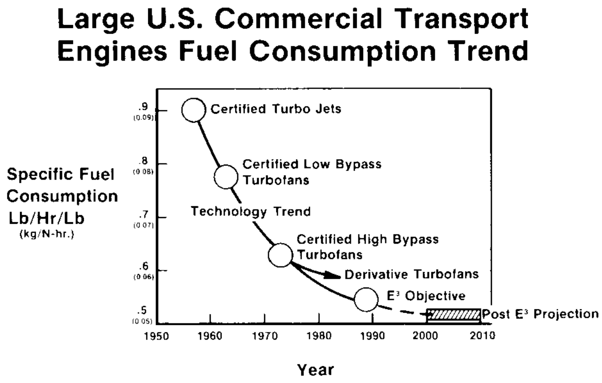

Figure 18 Large U.S. Commercial Transport Engines Fuel Consumption Trend

Recognizing the uncertainty of long range predictions, it is never-the-less of interest to estimate fuel efficiency potential beyond E^3 with continuing advances in engine technology. Using the E^3 objective as a baseline, assumptions were made as to the nature and magnitude of engine improvements which may be achieved for the generation following E^3.

Assumptions

The E^3 objective is a result of comprehensive NASA studies of low energy consumption engine concepts and represents an aggressive design for the goals and missions evaluated. These studies evaluated engine performance parameters which included fan pressure ratio, cycle (overall) pressure ratio, component efficiency levels, firing temperature and exhaust system design. The studies concluded that the design fan pressure ratio of 1.65 is near optimum when considering all design constraints and that the benefits of a mixed flow exhaust system for fuel efficiency and environmental requirements dictate its use on future engines.

With the expectation that technology advances will be made in component efficiencies and material technology, a projection is made for performance improvement of mixed flow engines using some simplified assumptions. These assumptions have been simplified to minimize the scope of the study and are not intended to define the optimum engine with respect to all design constraints.

A range of cycle pressure ratios (CPR) and high pressure turbine (HPT) rotor inlet temperatures (T41) are examined at a constant fan pressure ratio of 1.65 and a constant uninstalled thrust (gross thrust minus ram drag). The constant 1.65 fan pressure is assumed for simplification and it is recognized that it is not necessarily optimum for the engines examined. Performance improvements of 1% in rotating component efficiencies, +100°F (+55.5°C) increase in metal temperature capability, and a mixer effectiveness improvement from 75% to 80% are assumed as technology advancements. The matrix of cycle pressure ratios is achieved by variation in core engine boosting with the core compressor pressure ratio the same as the E^3 objective engine. With this approach, the bypass ratio, fan size, and core size is a result of sizing the engine at the same thrust. Cycle pressure ratios are examined in the range of 38 to 60 with HP turbine inlet temperatures increased up to +400°F (+222.2°C) above the E^3 objective. Cooling for both turbines is adjusted for levels of compressor discharge temperature (T3) and turbine inlet temperatures. Table IX summarizes the assumptions used in this projection.

Post E^3 Projection Assumptions

Mixed Flow Engine - Mixing Effectiveness Improved (75% to 80%)	+5%
Same Fan Pressure Ratio As The E^3 Objective	1.65
Each Rotating Component Efficiency Is Improved Above The E^3 Objective	+1%
Improved Metal Temperature Capability	+100°F (+55.5°C)
Cycle Pressure Ratio Range Examined	38 to 60
Core Compressor Pressure Ratio Is The Same As The E^3 Objective. Cycle Pressure Ratio Variations Are Achieved By Boosting The Core.	
Range Of T41 Increase	+200°F To +400°F
Cooling For HP And LP Turbines Is Adjusted For T3 Levels And Increased Metal Temperature Capability.	(+111.1°C to +222.2°C)
All Engines Are Sized At the Same Uninstalled Thrust (Gross Thrust Minus Ram Drag) With No Customer Bleed Or Power Extraction And 100% Ram Recovery.	

Table IX Post E^3 Projection Assumptions

Projection Results

The results of the projection are presented in Figures 19 through 24. Data is shown for uninstalled sfc and the effects of customer bleed and power extraction for the CPR/T41 matrix examined. Figures 19 and 20 present the uninstalled sfc improvement in two steps. The first step, Figure 19, shows the max cruise sfc for a cycle pressure ratio and HP turbine rotor inlet temperature matrix with all the assumptions except the +100°F (+55.5°C) increased metal temperature capability. The sfc improvement is seen to be about 3.5 percent. The second step, Figure 20, shows the max cruise sfc for the CPR/T41 matrix with the addition of the increased metal temperature capability. This resulted in an additional 1.5% sfc improvement. From Figure 19, it is seen that without the metal temperature improvement, the E^3 design cycle pressure ratio and T41 are still essentially optimum with the projected cooling technology. The increase in sfc exhibited with higher cycle pressure ratios and T41 levels is a result of increased LP turbine cooling flow requirements. Improvement in metal temperature capability reduces the cooling flow requirements and shifts the CPR/T41 matrix with the minimum sfc occuring in the CPR region of 45 to 50, with the best T41 between +200°F (+111.1°C) and +300°F (+166.7°C) above the E^3 objective. Again, at higher CPR/T41 levels, the penalty is shown for increased LP turbine cooling.

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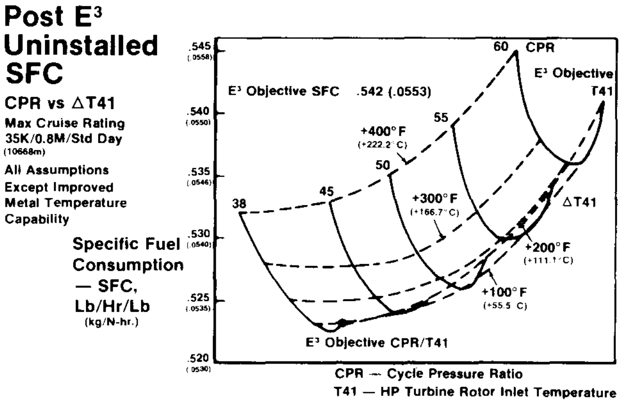

Figure 19 Post E^3 Uninstalled SFC - All Improvements Except Metal Temperature Capability

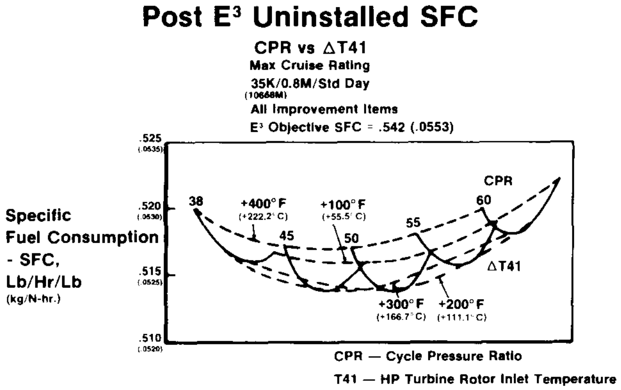

Figure 20 Post E^3 Uninstalled SFC - All Improvements

Sizing each engine at the E^3 uninstalled thrust level provides an indication of the relative effect of CPR and T41 on fan size and core size. Figure 21 shows the change in corrected fan flow, corrected core flow and bypass ratio for ΔT41 values of +200°F (+111.1°C) and +400°F (+222.2°C) over the range of cycle pressure ratios examined. It shows that both CPR and T41 have an effect on core size, but only the CPR significantly affects the fan size. Increasing the CPR at a given T41 reduces the fan diameter and the nacelle drag.

Engines of the same uninstalled thrust size but with different fan and core sizes will experience different penalties for nacelle drag, compressor customer bleed, and power extraction. Evaluation of the engines shown in Figure 20 for installation effects will indicate the effect on the shift in the CPR and T41. Figure 22 shows the relative penalty in sfc and net thrust loss on three engines when bleed and power extraction are applied. Three engines at CPR=38 and ΔT41 levels of +200°F (+111.1°C), +300°F (+166.7°C) and +400°F (+222.2°C) are examined for the same level of bleed and power extraction. Bleed and power extraction are applied while holding the design T41 level constant on each engine. The results show the +400°F (+222.2°C) engine experienced a higher net thrust loss and a higher sfc penalty relative to the +200°F (+111.1°C) engine. The higher net thrust loss results in a higher nacelle drag to net thrust ratio (FD/FN).

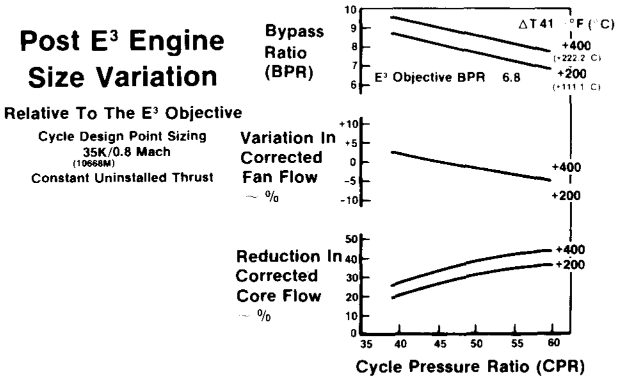

Figure 21 Post E^3 Engine Size Variation

The total installed sfc penalty is shown to be comprised of two effects. One is the increased drag component and the other is the effect of bleed and power extraction on the engine cycle. This illustrates the inherent penalty of higher temperature engines (smaller cores) to compressor bleed and power extraction.

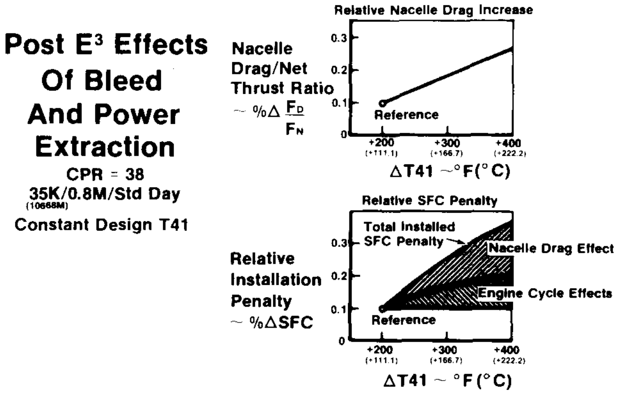

Figure 22 Post E^3 Relative Installation Penalty

Using the 38/+200°F (+111.1°C) engine as a reference for the matrix, Figure 23 shows the relative penalty for the CPR/ΔT41 matrix over the +200°F (+111.1°C) to +400°F (+222.2°C) range. Note that lines of constant bypass ratio have been added for reference only. The data indicates that the relative installation penalty is lowest for the engine with the higher CPR and the lowest ΔT41 increase.

The higher CPR minimizes the nacelle drag loss effect, and the lower temperature core minimizes the cycle effect loss. The lowest penalty effect of this matrix is the CPR=60/ΔT41=+200°F (+111.1°C) engine. The best engine, however, is the one with

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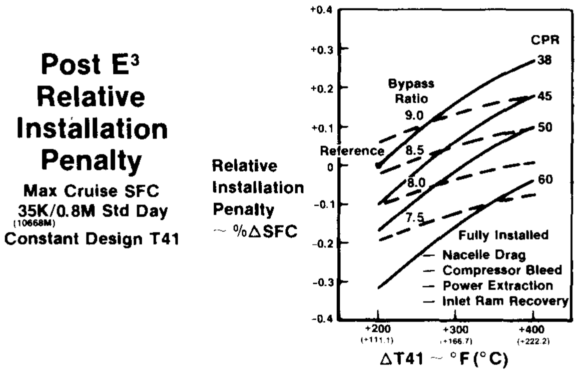

Figure 23 Post E^3 Effects Of Bleed And Power Extraction

the lowest fully installed specific fuel consumption. Figure 24 presents the installed sfc for the matrix of engines examined and the minimum is a +200°F (+111.1°C) engines with a CPR=50. These data can be compared with Figure 20, which shows the uninstalled sfc minimum is in the 45 to 50 CPR range and between +200°F (+111.1°C) and +300°F (+166.7°C) in ΔT41. From Figures 20 and 24, the range of sfc improvement relative to the E^3 objective is shown to be -5.2% uninstalled and -5.8% fully installed.

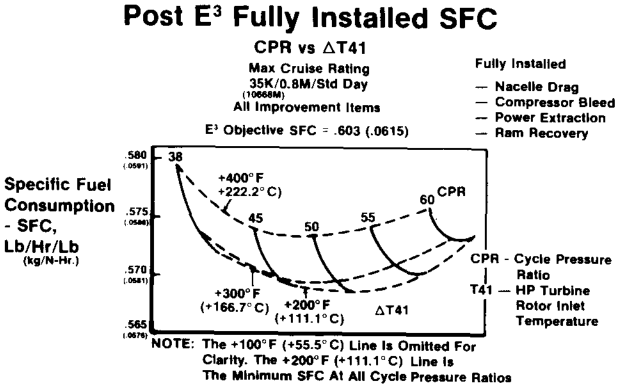

Figure 24 Post E^3 Fully Installed SFC

These data trends are influenced by cooling flow assumptions used in the analysis. The limitation on CPR and T41 for an optimum engine are significantly affected by cooling requirements of the LP turbine. In addition, other factors which influence the optimum engine definition are the design fan pressure ratio, which affects the sfc, and the engine weight, which affects the mission fuel consumption. Tradeoffs of core compressor bleed penalties must be weighed against reduced core weight on an aircraft.

CONCLUSIONS

The advanced system design and technology that is being developed and demonstrated in the current Energy Efficient Engine Program will provide the basis for more fuel efficient, environmentally compatible turbofan engines that can be operational in the late 1980's and early 1990's. These advanced turbofan engines could reduce fuel burned in future commercial transports by 15 to 23 percent and will reduce Direct Operating Cost (DOC) by 5 to 11 percent.

The E^3 represents a technically aggressive design for the next generation of transport engines, with a substantial payoff in fuel efficiency. However, the opportunities for turbofan engine fuel efficiency improvement beyond E^3 appear to be substantially reduced. Extrapolation of the fuel consumption trend curve of Figure 18 suggests an sfc improvement in the order of 5% could be expected. From the projection of continuing improvement in component efficiency and metal temperature capability presented, the 5% could be achieved where 3.5% results from component efficiency improvement and 1.5% is achieved with increased metal temperature capability. Even with the +100°F (+55.5°C) increase in metal temperature capability beyond E^3 technology, cycle pressure ratios greater than the 45 to 50 range do not appear to be beneficial.

ACKNOWLEDGEMENT

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