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16. Abstract

The preliminary design of General Electric's Energy Efficient Engine (E^3) was reported in detail in 1980. Since then, the design has been refined and the components have been rig-tested. The changes which have occurred in the engine and a reassessment of the economic payoff are presented in this report.

All goals for efficiency, environmental considerations, and economic payoff are being met. The E^3 Flight Propulsion System has 14.9% lower sfc than a CF6-50C. It provides a 7.1% reduction in direct operating cost for a short haul domestic transport and 14.5% reduction for an international long distance transport.

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FOREWORD

This report presents an update of the preliminary analysis and design of an advanced Flight Propulsion System (FPS) conducted by the General Electric Company. This work was performed for the National Aeronautics and Space Administration (NASA), Lewis Research Center, under Contract NAS3-20643 as part of the Aircraft Energy Efficiency (ACEE) Program, Energy Efficient Engine (E^3) Project. Mr. Carl C. Ciepluch is the NASA E^3 Project Manager; Mr. Peter G. Batterton is the NASA Assistant Project Manager. Mr. Roger Chamberlin is the NASA Project Engineer responsible for the effort associated with the Flight Propulsion System - Preliminary Analysis and Design Update reported here. Mr. Raymond W. Bucy is Manager of the E^3 Project for the General Electric Company. This report was prepared by Mr. E. Marshall Stearns.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACC	Active Clearance Control
ACEE	Aircraft Energy Efficiency
CDP	Compressor Discharge Pressure
DOC	Direct Operating Costs
E^3	Energy Efficient Engine
ECS	Environmental Control System
EPNdB	Effective Perceived Noise in Decibels
FADEC	Full Authority Digital Electronic Control
Fn	Engine Thrust
FPS	Flight Propulsion System
HP	High Pressure
HPC	High Pressure Compressor
HPT	High Pressure Turbine
ICLS	Integrated Core/Low Spool
IGV	Inlet Guide Vane
LCF	Low Cycle Fatigue
L/D_{MP}	Length/Diameter at the Mixing Plane
LP	Low Pressure
LPT	Low Pressure Turbine
LPTR	Low Pressure Turbine Rotor
M	Mach Number
N2	Low Pressure Rotor Speed
Over'N Gov.	Overspeed Governor
RPM	Revolutions Per Minute

LIST OF ACRONYMS AND ABBREVIATIONS (Concluded)

SFC, sfc	Specific Fuel Consumption
SLS	Sea Level Static
STD	Standard
W_{25}	Compressor Inlet Airflow
° C	Degrees Celsius
° F	Degrees Fahrenheit
$\Delta P/P$	Normalized Change In Pressure
η	Efficiency

1.0 SUMMARY

The Energy Efficient Engine (E^3) program is a part of the National Aeronautics and Space Administration (NASA) Aircraft Energy Efficiency program. The objective of this program is to substantially improve the efficiency of commercial transport aircraft which would enter service in the late 1980's to the early 1990's.

The engine designed to achieve the program objectives is called the Flight Propulsion System (FPS). It requires technology advanced beyond engines currently in service. To evaluate the advancements, the E^3 program includes rig tests of each component, a core engine test, and a nonflight turbofan engine test.

The General Electric engine is unique, having a high bypass ratio, a high core pressure ratio, and a short compact configuration. Engine features include:

- A 10 stage, 23:1 pressure ratio compressor
- A double annular combustor for low emissions
- A two-frame, five-bearing design
- Spring mounted bearing supports with viscous damping on the front support
- A full authority digital electronic control
- A mixer to combine fan and core exhaust flows
- Case cooling systems to actively control blade tip clearances in the compressor, high pressure turbine, and low pressure turbine
- Composite materials and advanced manufacturing techniques
- Component efficiency levels above previous state of the art.

The FPS engine is shown in Figure 1.

The component test program has been completed. Test performance results are compared to goals in Table 1. The rig goals were internal goals intended to assure that, with some additional development beyond the current E^3 program, the FPS performance could be achieved. The data in Table 1 is for the maximum cruise thrust flight point. The test performance of the fan, combustor, high pressure turbine, and low pressure turbine met or exceeded FPS requirements. The final compressor configuration will be tested in the core. This compressor should have improved performance.

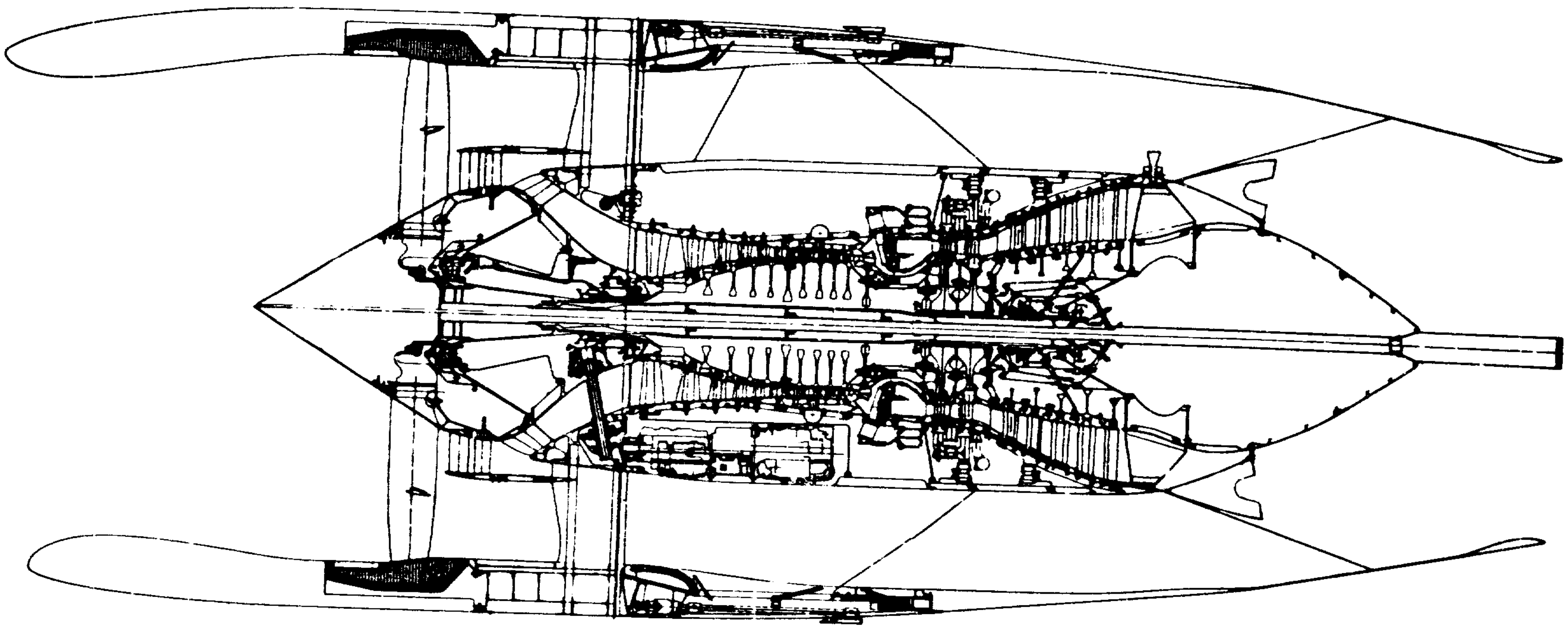

Figure 1. E^3 FPS Engine.

Table 1. Component Test Results.

	FPS Requirements	Rig Test Goal	Rig Test Results
Fan Efficiency	0.887	0.877	0.892
Fan Hub and Booster Efficiency	0.892	0.882	0.895
Compressor Efficiency	0.861	0.851	0.849 (not final configuration)
Combustor Pressure Drop, %	5	5	4.8
Combustor Emissions	EPA Proposed 1981 Standards	EPA Proposed 1981 Standards	Met Goal
High Pressure Turbine Efficiency	0.924	0.919	0.925
Low Pressure Turbine Efficiency	0.917	0.911	0.916 demonstrated 0.918 For FPS variation
Mixer, SFC Improvement	3.1%	3.1%	2.6% demonstrated

Fuel prices have increased from the 7.9¢ to 13.2¢ per liter (30¢ to 50¢ per gallon) range used initially in the E^3 program to about $0.396 per liter ($1.50 per gallon) in the current market. The higher fuel price has substantially increased the economic payoff due to the more fuel-efficient E^3.

E^3 direct operating cost is now 7.1% to 14.5% lower than a typical current production engine, the CF6-50. This range covers a spectrum of aircraft size and flight lengths.

NASA established specific performance, economic, and environmental goals for E^3. The General Electric FPS meets these goals. These goals and the current status are shown in Table 2.

The E^3 FPS Preliminary Analysis and Design report was issued in June 1980. The material in this report updates the 1980 report and is presented in an addendum to that report.

Table 2. E^3 FPS Program Goals and Status.

FPS Characteristic	NASA Goal	FPS Status
• Installed Specific Fuel Consumption (sfc)	Minimum 12% Reduction From CF6-50C(1)	14.5% Reduction(1) 14.9% Reduction(2)
• Direct Operating Cost (DOC)	Minimum 5% Reduction from CF6-50C on Equivalent Aircraft	7.1% to 14.5% Reduction Depending on Aircraft and Distance
• Noise	Meet FAR 36 (1978) Provisions For Growth	Meets With Margin
• Emissions	Meet EPA Proposed 1981 Standards	Meets Goal
• Performance Retention	Minimum 50% Reduced Deterioration From CF6-50C Levels	Projected to Meet

(1)Using E^3 ground rules which specify maximum cruise thrust at M = 0.8, 10,668 m (35,000 ft) with zero bleed and power extraction.

(2)Maximum cruise thrust at M = 0.8, 10,668 m (35,000 ft) with bleed and power extraction, using the bleed air/fuel heater system.

2.0 INTRODUCTION

The objective of the E^3 Program is the development of technology to improve the energy efficiency of propulsion systems for subsonic commercial aircraft introduced in the late 1980's and the early 1990's. The need for E^3 type programs was established by shortages of petroleum-based fuels. Since the E^3 program was launched, fuel shortages and escalated fuel prices have made improved aircraft energy efficiency essential. The E^3 program is a major element of the NASA Aircraft Energy Efficiency Program.

The following technical goals were established by NASA for the fully developed E^3 Flight Propulsion System:

- Fuel Consumption - Minimum of 12% reduction in installed sfc compared to a CF6-50C at maximum cruise thrust, M = 0.8 at 10,688 m (35,000 ft) altitude on a standard day with no bleed or power extraction.
- Direct Operating Cost - Minimum of 5% reduction from CF6-50C on equivalent aircraft.
- Noise - Comply with FAR 36 (1978) with provisions for growth.
- Emissions - Comply with EPA Proposed 1981 Standards for new engines.
- Performance Retention - Minimum of 50% reduction in the rate of performance deterioration in service as compared to the CF6-50C.

To meet and demonstrate the program goals, the E^3 program is structured into four major technical tasks.

- Task 1 addresses the design and evaluation of the E^3 Flight Propulsion System (FPS). The FPS is an engine, including the nacelle, intended to achieve program goals in commercial service. The design is executed in sufficient depth to evaluate performance, cost, weight, installation considerations, and economic payoff. The information developed in Task 1 establishes the design and performance requirements for hardware to be tested in component rigs, a core engine, and a turbofan engine. The initial function of Task 1, establishment and evaluation of the FPS design, has been completed. The Flight Propulsion System is continually being upgraded and modified as technology evolves, as new ideas develop, and as test results become available.

- Task 2 consists of the detailed design, fabrication, and rig testing of each engine component and includes supporting technology efforts. Task 2 has been completed.

- Task 3 involves the design, fabrication, and test evaluation of a core test vehicle, consisting of the compressor, combustor, and high pressure turbine. Design and part fabrication have been completed. Buildup and test preparations are underway. Core testing is scheduled for the third quarter of 1982.

- Task 4 integrates the core with the low pressure components to make the Integrated Core/Low Spool (ICLS) turbofan test vehicle. Design of the low pressure components has been completed, and most fabrication has been completed. Testing is scheduled for the first half of 1983.

The analysis and design of the Flight Propulsion System as of November 1978 was reported in Reference 1. Since that time, no fundamental changes have been made. However, the design has matured and significant refinements have been incorporated. Also, fuel price has dramatically increased, substantially changing the economic benefit of E^3 technology.

This report is presented as a supplement to Reference 1. It presents the changes in the FPS design, reassesses the economic payoff, and reevaluates the FPS against the program goals.

3.0 DESIGN

The engine uses a fan and single stage booster, driven by a five-stage low pressure (LP) turbine. The booster is untrapped, meaning booster flow passes into both the fan duct and the core. A 10-stage compressor with variable vanes is driven by a two-stage high pressure (HP) turbine. The combustor uses a double-annular configuration to retain short length while achieving low emissions. Active clearance control is used to provide tighter compressor, HP turbine, and LP turbine clearances at cruise, and to reduce deterioration occurring due to rubs during transient conditions. A mixer combines the fan and core flows before expanding them through a single exhaust nozzle. This provides higher thrust and lower SFC. A digital electronic control manages the large number of variable functions. To achieve goal fuel consumption, the engine uses a high bypass ratio, high cycle pressure ratio, advanced aerodynamics, advanced structural design, and advanced materials. The FPS is very short, has very high life, and is capable of 20% thrust growth within the same flowpath.

3.1 FAN

The fan uses 32 solid titanium fan blades, an untrapped quarter-stage booster under an island, hybrid aluminum/Kevlar containment, and an integral outlet guide vane/front frame made of composite materials. Fan tip diameter is 211 cm (83 inches). The fan cross section is shown in Figure 2.

The aerodynamic design point is maximum climb, but efficiency goals are specified for the maximum cruise power setting at Mach 0.8, 10,688 m (35,000 ft). Fan parameters for maximum climb, maximum cruise, and takeoff power conditions are:

Parameter	MxCl	MxCr	Takeoff
Fan Presssure Ratio (Bypass Flow)	1.65	1.61	1.50
Fan + Booster Pressure Ratio (Core Flow)	1.67	1.63	1.51
Bypass Ratio	6.8	6.90	7.3

Rig testing of the engine fan has been completed. Stall margin was very good, 15% to 16% at takeoff. Efficiency was above rig goals and exceeded FPS (fully-developed fan) levels. Table 3 compares the demonstrated fan performance with that which has been used for the FPS.

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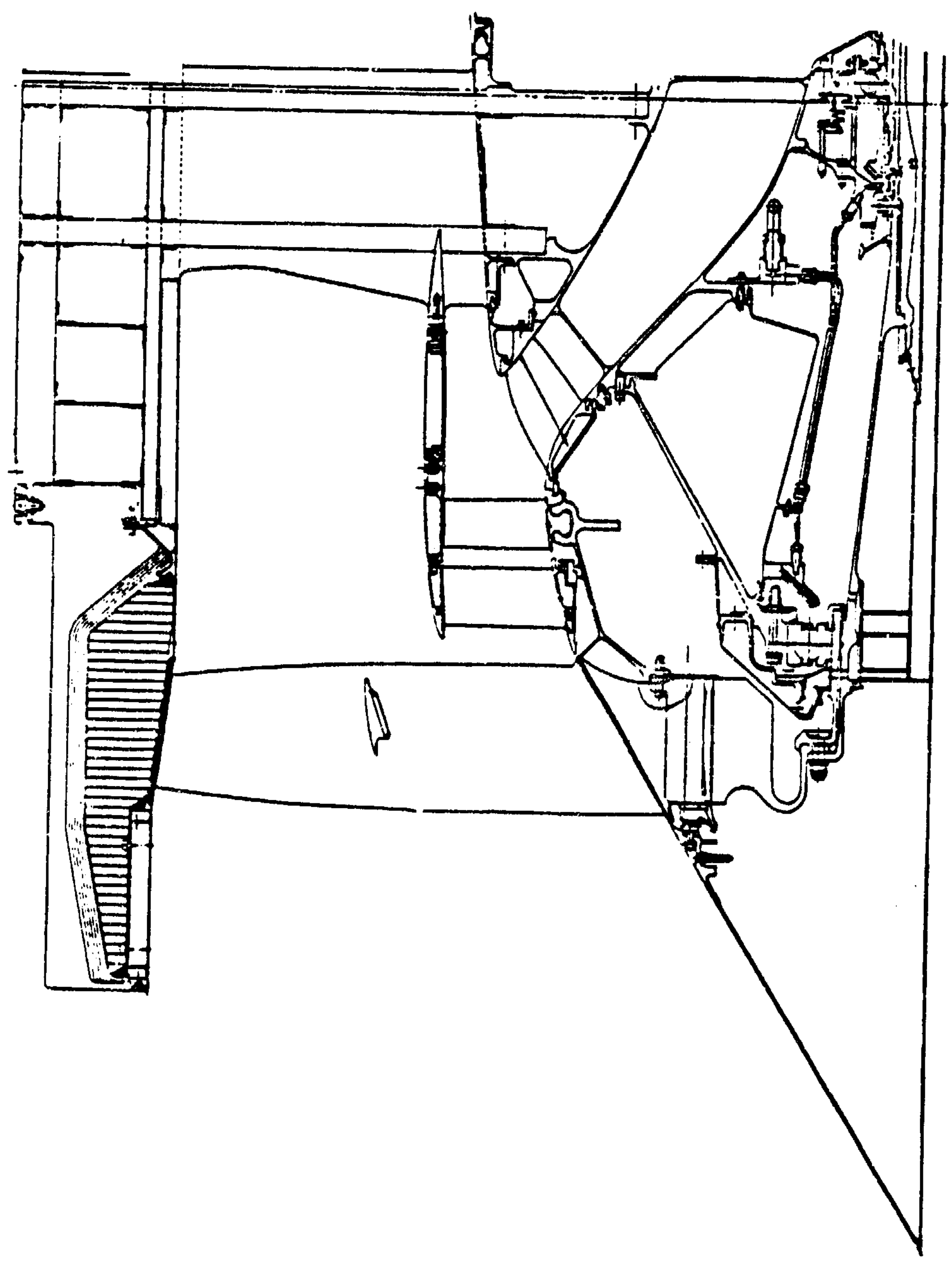


Figure 2. E^3 FPS Fan.

Table 3. E^3 Fan Performance.

	FPS Requirements			Rig Goal	Rig Results		
	Max. Climb	Max. Cruise	Takeoff	Max. Cruise	Max. Climb	Max. Cruise	Takeoff
Fan Bypass $\eta^{(1)}$	0.879	0.887	0.900	0.877	0.886	0.892	0.893
Fan Hub + Booster $\eta^{(2)}$	0.885	0.892	0.897	0.882	0.892	0.895	0.898

(1) Using momentum averaged exit conditions to include significant radial profile effects in the bypass duct.

(2) Using mass averaged exit conditions.

3.2 COMPRESSOR

The compressor achieves a 23:1 pressure ratio in 10 stages. Because of the high pressure ratio, high aerodynamic loading, and high speed, it is one of the most technically challenging designs that General Electric has built. The IGV and Stators 1 through 4 are variable. The forward rotor spool is made of titanium, the aft spool is made of a nickel alloy (René 95), and the casing is made of steel. Control of compressor blade tip clearance is achieved by modulating the split between the Stage 5 bleed air flowing through the compressor casing and that bypassing the casing. The air is then used for LP turbine cooling and purge. Customer bleed is provided from Stage 5 and from the compressor discharge. Start bleed is currently provided from Stage 7. However, compressor and high pressure turbine rig performance in the start region were significantly better than earlier predictions. The better start region performance may likely permit starting with substantially reduced seventh stage bleed, substitution of fifth stage bleed, or possibly complete elimination of bleed. The need for start bleed will be determined in core vehicle tests, and a decision on FPS start bleed will be made following these tests.

Since the design was reported in Reference 1, there have been some refinements in the mechanical design of the compressor. The rotor bolt joint was moved from Stage 5 to Stage 6. The design details of the compressor aft casing have changed. The aft flange diameter was reduced, the Stage 7 bleed air manifold was made integral with the case, and casing shapes, webs, flanges, and bleed ducting are different. A current cross section is shown in Figure 3.

Three different compressor configurations have been rig tested, and a fourth will be run in the core test vehicle. The rigs used engine hardware and provided both mechanical and aerodynamic evaluations.

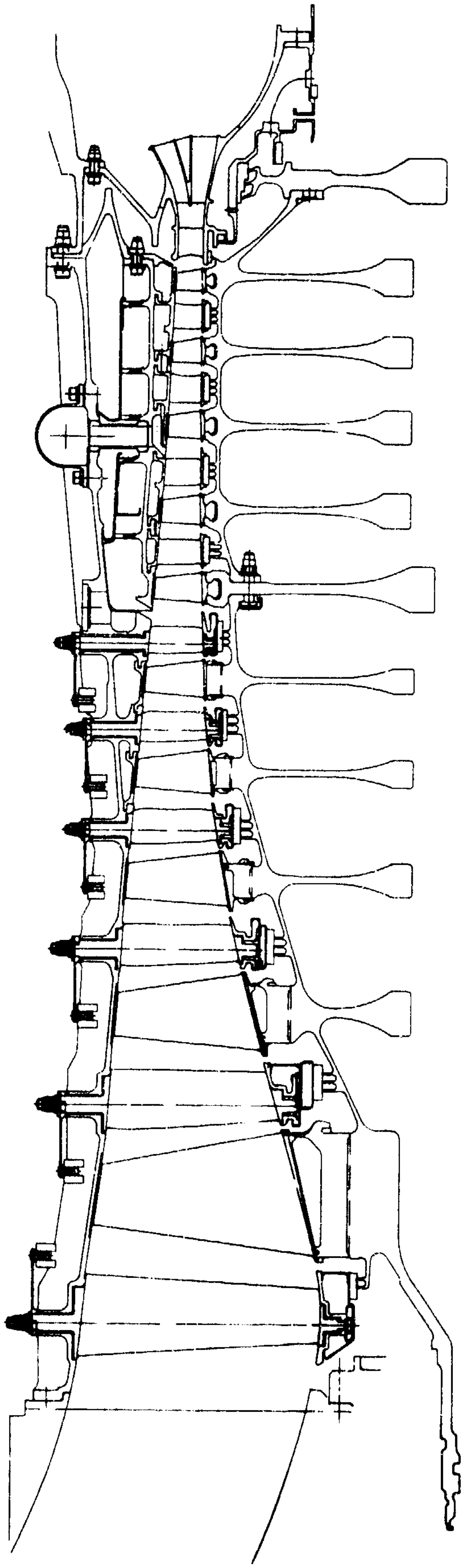


Figure 3. E^3 High Pressure Compressor.

The first configuration was comprized of Stages 1 through 6. It met its efficiency goal but lacked stall margin. The design change resulting from these tests was an increase in camber at the rotor hubs.

The second configuration was a full 10-stage compressor. Because rotor blades with recambered hubs could not be obtained in time, the camber of the stator hubs in Stages 1 through 6 was increased to provide a similar effect. Test data showed that this corrected the hub flow as intended. Stages 7 through 10 used the original design cast stators and alternate, increased camber, rotor blades. The blades were selected to favor stall margin in the low speed start region. Testing revealed that Stages 7 through 10 pulled more flow than desirable.

The third configuration was a 10-stage compressor with the lower camber, original design, blades in Stages 7 through 10, intended to reduce rear block flow capacity. Also, the more desirable overcambered hub rotor blades were included in Stages 1 through 6 rather than the overcambered stator hubs. The flow capacities of the front and rear of the compressor were properly matched and the overcambered forward rotor hubs worked as intended. Efficiency was still slightly below the goal level. Compressor rig results, rig goal and FPS requirements are shown in Table 4.

Table 4. Compressor Performance.

	FPS Requirements			Core Goal	Rig Results		
	Maximum Climb	Maximum Cruise	Takeoff	Maximum Cruise	Maximum Climb	Maximum Cruise	Takeoff
Compressor, η	0.857	0.861	0.871	0.851	0.847*	0.849*	0.855*

*Most recent rig test results. The final configuration will be evaluated in the core test vehicle.

The compressor for the core test vehicle incorporates additional changes. Hub camber was increased in Stators 7 through 9 to strengthen hub flow, and the original design aft rotor blades were staggered closed 2°. This is expected to further improve stall margin and efficiency. The core test vehicle will be run in the third quarter of 1982.

3.3 COMBUSTOR

The E^3 combustor uses staged combustion zones to achieve low emissions from idle to high power. A double annular configuration is used to allow staging with a very short combustor. A split duct diffuser expands compressor discharge flow. Shingled combustor liners are used to achieve very high life.

Only the pilot zone is used for starting, ground idle, and approach power setting. Both zones are used at all other power settings.

Two test rigs were used for the E^3 combustor. A sector of the combustor was used for ignition, ground start, altitude relight, and idle emissions testing. This rig used simple, film cooled, single-wall construction. Further development of overall combustion system performance was completed on a full annular rig which used the same construction as the sector rig. This testing covered ignition, exit temperature profiles, emission, and metal temperatures. The flight design combustor for the core engine was evaluated in the full annular rig stand.

Design refinements evolved prior to and during the test period. The centerbody was changed from shingle construction to an impingement cooled design. Thermal barrier coating was added to the centerbody. The centerbody was shortened and the tip region was slotted to reduce thermally induced hoop stresses. The dilution air and film cooling holes were tuned. The current FPS combustor is shown in Figure 4.

The combustor performance required for the FPS was achieved by the core engine combustor during rig testing. The required pressure drop is 5%, and 4.8% was demonstrated. The required efficiency of 99.5% was exceeded.

The core combustor met CO and HC emissions goals in rig testing but did not meet the NO_x goal. However, an earlier rig configuration met all emissions goals. By incorporating features from that rig, the FPS combustor will meet all emissions goals.

The emissions goals are the very stringent EPA Proposed 1981 Standards. While these standards have not been adopted, they have been retained as E^3 goals.

Requirements, rig tests, and FPS projections for emissions at 4% and 6% idle power settings are presented in Table 5. As shown in the table, emissions can be significantly reduced by increasing the idle power setting. In doing so, however, fuel consumption and braking increase. In order to meet emissions goals, only the pilot dome is fired during landing approach. This might be undesirable for safety considerations.

3.4 HIGH PRESSURE TURBINE

The E^3 high pressure turbine (HPT) provides an advancement in turbine aerodynamic, cooling and mechanical design technology from current production

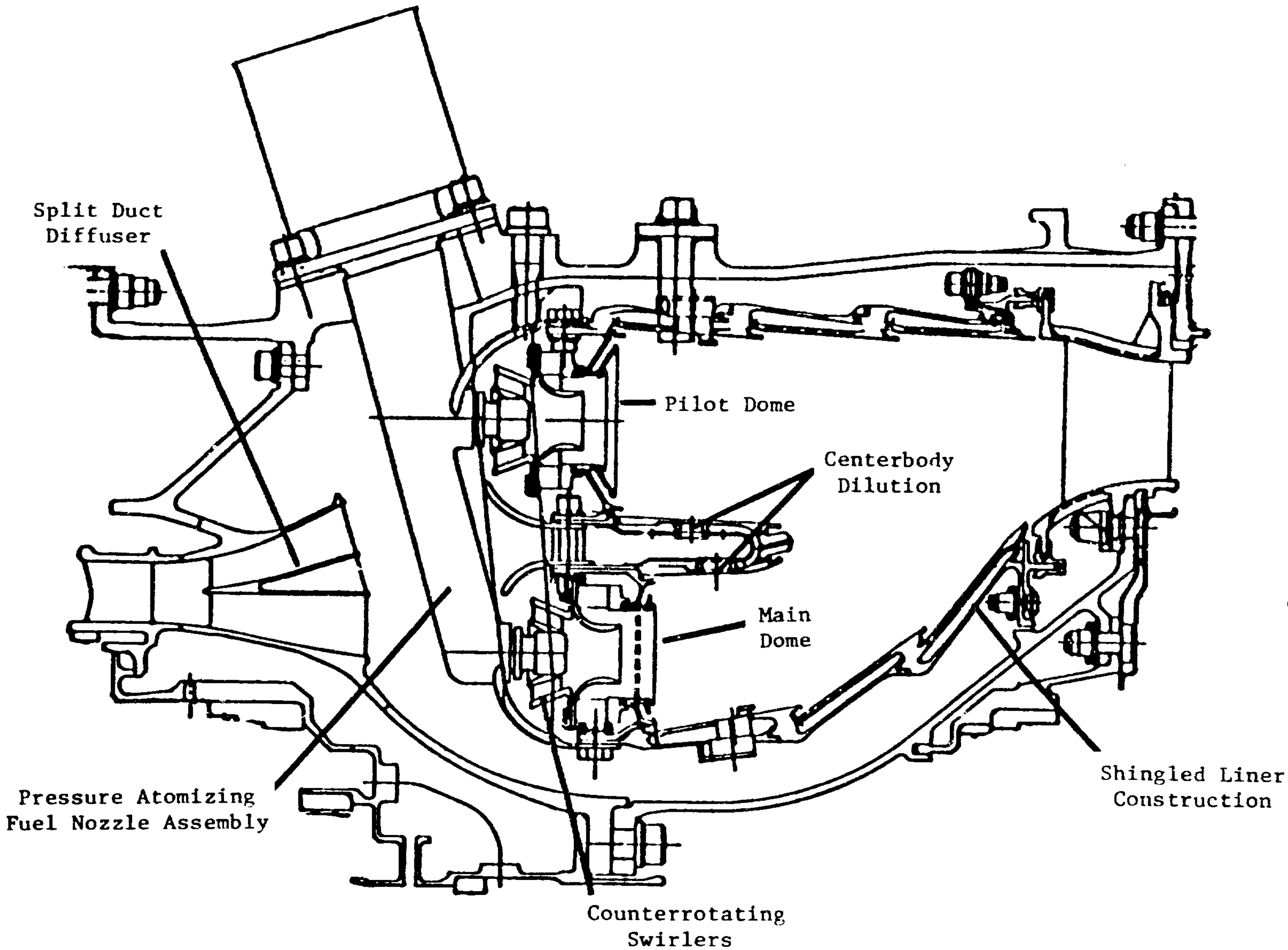


Figure 4. E^3 Combustor.

engines such as the CF6-50C. Moderate stage aerodynamic loading, efficient use of cooling air, low wheel space windage, and advances in flowpath contouring, vector design, and airfoil design produce very high efficiency. The high wheel speed of this turbine plus extended life requirements dictated a very "clean" structural design. Consequently, the load carrying portions of the disks have no boltholes or cooling passages.

Table 5. E^3 FPS Emissions.

	Pounds/1000-pound Thrust-Hour-Cycle				
		Core Engine Combustor Rig Results		FPS Prediction	
	FPS Requirement and Rig Goal	4% Idle Thrust	6% Idle Thrust	4% Idle Thrust	6% Idle Thrust
CO	3.00	2.45	1.58	2.45	1.58
HC	0.40	0.22	0.11	0.22	0.11
NO_x	3.00	4.97	4.66	2.98	2.79

The HPT retains the same configuration as the preliminary design described in Reference 1. However, the mechanical and cooling detail designs have since been executed for the core and ICLS test vehicles. The core turbine is an FPS design with the structure sized for growth thrust levels. The details of the completed design have changed extensively from the preliminary design. These changes are discussed below.

Active clearance control is used to reduce blade tip clearances during cruise and to open clearances during flight conditions where rubs occur. Clearances are controlled by impinging fan air on the HPT case. During the takeoff and early climb segments of the flight, the impingement air is shut off so clearances will be large enough to accommodate thermal excursions and engine deflections. During cruise, impingement air is turned on to contract the casing, reducing clearances.

An active clearance control heating circuit has been added to warm the HPT casing quickly during the initial warm up of the engine. This circuit ducts hot compressor discharge air into the HPT active clearance control manifold to expand the casing, thus opening cearances. It is used only during low power warm up. This circuit prevents blade tips from rubbing when a cold engine is accelerated to full power.

A start range turbine cooling circuit is used to avoid the possibility of back flowing the vane cooling circuits during starting. Substantial compressor seventh stage start bleed can depress the fifth and seventh stage cooling air supply pressures. Therefore, during start, compressor discharge air is substituted for fifth and seventh stage cooling air.

The HP turbine has gone through an extensive mechanical design refinement since Reference 1. The disks, blade retainers, impeller, shaft, static structure, shroud, and clearance control manifolding have changed. The changes are part shape, methods of attachment, flange configuration, method of windage shielding, and seal teeth configuration. The HPT, with all changes, is shown in Figure 5.

The cooling flow distribution system is unchanged from Reference 1. The cooling flow circuits are shown in Figure 5. Compressor discharge air cools the Stage 1 vane and the structure above the Stage 1 blade shroud. Air is drawn from the center of the split combustor diffuser for the rotor cooling circuit. The flow reversal into the center of the diffuser (Figure 5) separates foreign particles from air for the rotor cooling circuit. This flow is accelerated tangentially by a radial inflow inducer nozzle prior to boarding the rotor. This air purges the rotor cavities and cools the Stage 1 and Stage 2 blades. Seventh stage compressor bleed air cools the Stage 2 vanes, cools the structure above the Stage 2 blade shroud, purges the structure under the Stage 2 vane, and purges the wheel space cavities adjacent to that structure. Air that leaks through the compressor discharge seal is used to purge the cavity between the inner combustor case and the HPT Stage 1 disk. Fifth stage bleed purges the aft wheel space cavity after passing through the low pressure turbine Stage 1 vane.

Cooling air impingement and film are used to cool the Stage 1 vanes and bands. Two impingement inserts are used in the vane. The forward insert is now fed only from the inner diameter cavity whereas in the preliminary design it was fed from both inner and outer cavities.

The Stage 1 blade cooling method is unchanged. The Stage 1 blades use two cooling circuits. In the forward circuit, air traverses a three-pass (up-down-up) serpentine passage, flows through a row of holes in a radial web, impinges on the back side of the leading edge, and then flows through the airfoil wall to provide film cooling. In the aft circuit, air flows outward into a chamber. A portion of the air blows aft for convection cooling, and then exits at the pressure side of the trailing edge. The remainder of the flow traverses a down-up serpentine passage and discharges into the tip cavity.

The Stage 2 vane cooling method is also unchanged. Cooling air passes through holes in an insert to impinge on the vane wall, then cools by convection, and then is ejected at the pressure side of the trailing edge.

The Stage 2 blade cooling system has changed from that shown in Reference 1. Cooling air is now ejected from the airfoil perssure side wall at midchord near the tip rather than through the trailing edge. The blades use two serpentine circuits. The forward circuit flows upward adjacent to the leading edge, then down, and then up near midchord. The aft circuit flows upward adjacent to the trailing edge, then down, and then up near midchord. Ejecting the cooling air at midchord on the pressure surface reduces mixing

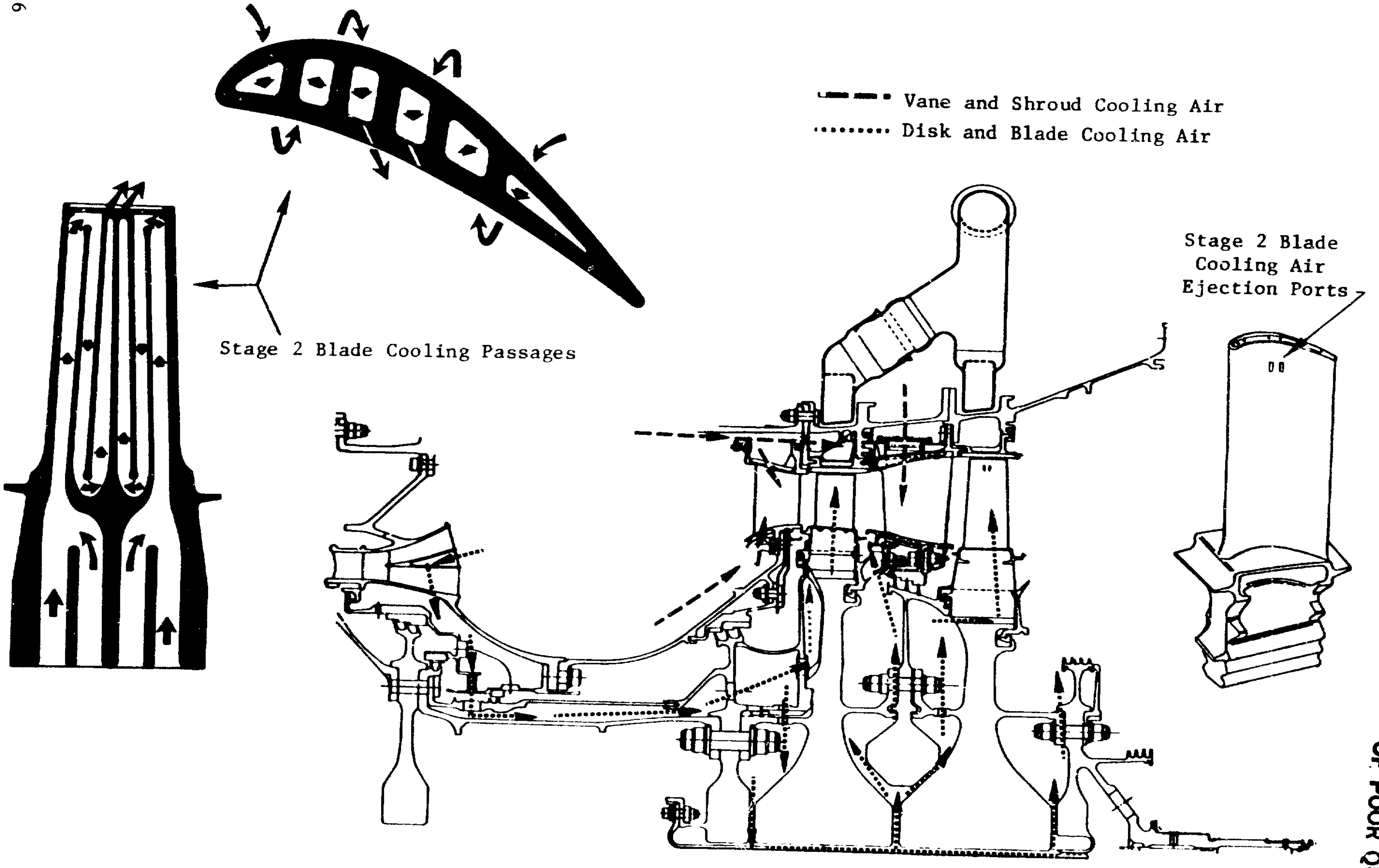


Figure 5. E^3 High Pressure Turbine.

losses. Replacing the trailing edge holes, as was the design in Reference 1, with ports near the tip avoids stress concentrations in the part of the blade which carries very high mechanical loads. The Stage 2 blade with the cooling air ejection ports is shown in Figure 5.

Total cooling flow has increased slightly. HPT cooling flow is shown in Table 6.

Table 6. HPT Cooling Flow Summary.

	% W_{25}	
	Previous Studies (Reference 1)	Current Status
Flow Entering Ahead of Stage 1 Vane Throat	9.24%	9.46%
Flow Entering Downstream of Stage 1 Vane Throat	9.00%	9.39%
Total Cooling, Purge and Leakage	18.24%	18.85%

HPT rig testing has been completed. Rig hardware was full size but was not of flight-type design. Cooling and leakage flow rates and ejection geometry matched the FPS design but internal cooling was not simulated. An inlet temperature of 436° C (1277° R) was used so that the ratio of cooling air temperature to main stream temperature matched the value for the FPS.

Performance of the HPT rig was mapped over the engine operating range, extending from subidle to high power conditions. The effects of variations in tip clearance, cooling flow rates and Reynolds number, were established. Maesured efficiency exceeded the goal for the fully developed FPS. The measured and goal efficiencies are shown in Table 7. Efficiency at engine starting conditions exceeded earlier projections. FPS start analyses, based on turbine and compressor rig results, indicate that the FPS can achieve reasonable start times while using only the pilot burner.

3.5 LOW PRESSURE TURBINE

The E^3 low pressure turbine (LPT) is a five-stage design using high aerodynamic loading. Because no bearing support is used between the HPT and LPT, the turbines are close coupled without struts or structural vanes. The LPT casing is a 360° (nonsplit) sturcture. Clearances are controlled by modulating casing cooling air, which is ducted from the fan stream to impingement tubes positioned around the casing. The LPT blading is not cooled except that purge air for the inner cavity is ducted through the Stage 1 vane. The low pressure turbine is shown in Figure 6.

Table 7. High Pressure Turbine Efficiency.

	FPS Requirements			Rig Goal	Rig Results		
	Maximum Climb	Maximum Cruise	Takeoff	Maximum Cruise	Maximum Climb	Maximum Cruise	Takeoff
HPT Efficiency	0.924	0.924	0.920	0.919	0.925	0.925	0.926

The LPT flowpath has changed from that reported in Reference 1. The outward slope of the first seven blade-rows is now continued through the remainder of the turbine at both the tip and the hub. The new flowpath is known as the flaired LPT. The original flowpath is indicated in Figure 6 for reference. The flowpath was changed in conjunction with a mixer improvement, discussed in Section 3.8. The intent of the LPT flowpath change was to reduce losses on the turbine, the rear frame, and the mixer. Increasing blade diameter resulted in lower turbine aerodynamic loading, and, therefore, improved performance. The change increases LPT efficiency 0.25%. The total effects of changing the turbine, mixer, and aft structure are shown in Table 8. The changes increased weight, but the efficiency improvements were enough to produce a net improvement in both aircraft fuel usage and direct operating cost.

The method for purging the aft rotor cavity has changed from that reported in Reference 1. LPT discharge bleed is now used to purge the rotor cavity under Stages 4 and 5, rather than fifth stage bleed. LPT discharge air is less costly to the cycle. This purge system is shown in Figure 7.

A more refined analysis of operating conditions and lives has been completed for the most critical LPT airfoils, the Stage 1 vane, and blade. The most significant change was a 40% reduction in Stage 1 vane gas load due primarily to an aerodynamic design change discussed later. The loads, stresses, and lives for the Stage 1 vane and blade are shown in Tables 9 and 10. The Stage 1 blade material was changed from René 80 + Hafnium to René 77, and the material for the Stage 2 vane was changed from René 80 to René 77. The higher strength materials were not necessary. The materials are shown in Figure 8. The structure supporting the seal under the LPT Stage 1 vane was changed to position the cooling air inducer at a lower diameter.

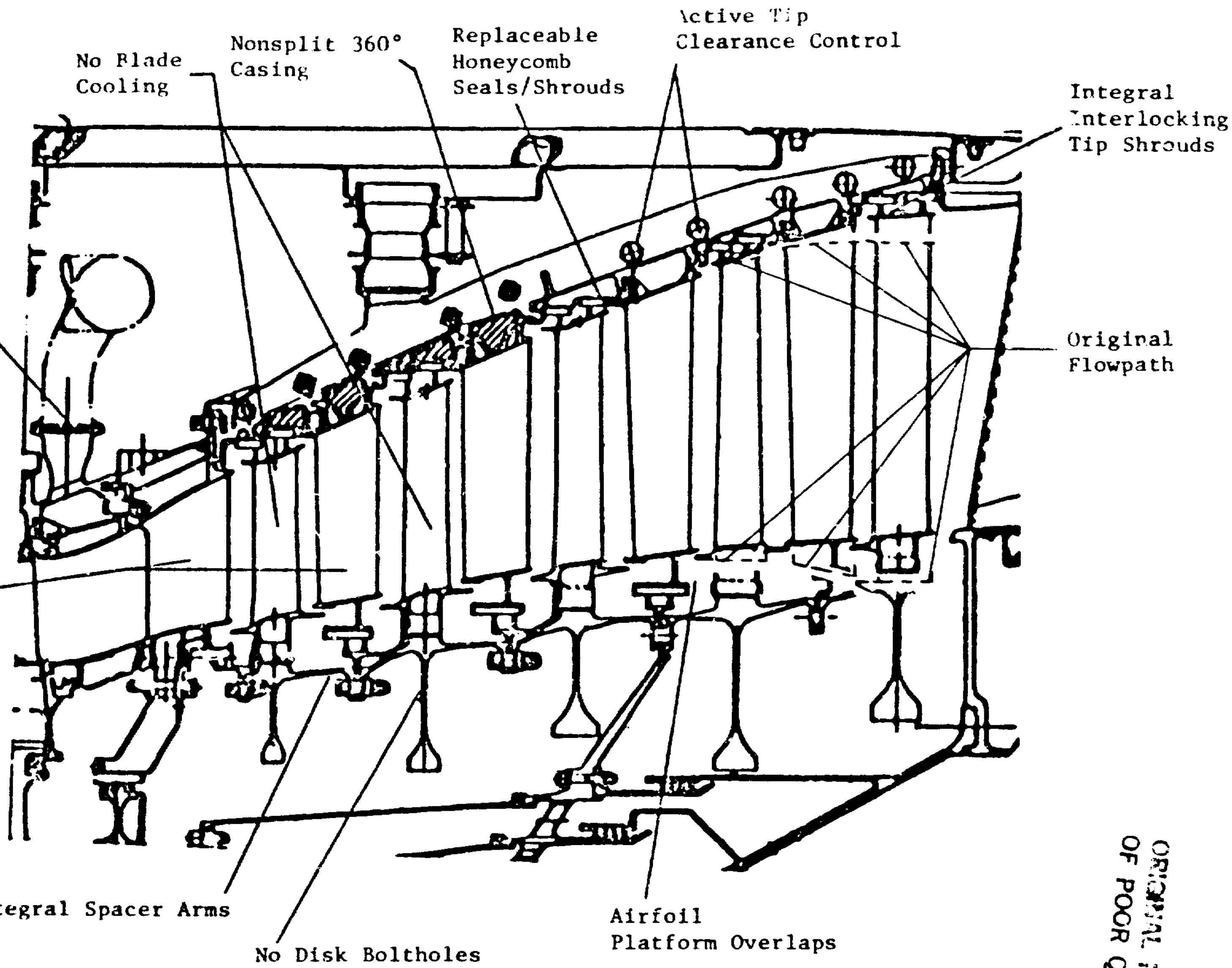


Figure 6. E^3 Low Pressure Turbine.

Table 8. Flaired Low Pressure Turbine/Mixer Effects.

Benefits		Δ SFC
LPT Efficiency Improvement		-0.16%
Mixer Performance		-0.20%
Total		-0.36%
Penalties	**Δ Weight**	**Δ Cost**
LP Turbine	+13.6 kg (+30 lb)	+ $600
Turbine Rear Frame	+10.4 kg (+23 lb)	+ $460
Mixer	+ 2.3 kg (+ 5 lb)	+ $100
Centerbody	+ 5.0 kg (+11 lb)	+ $220
Bearing Support Housing	+ 2.3 kg (+ 5 lb)	+ $100
Total	+ 33.6 kg (+74 lb)	+$1480
System Effect	**Δ DOC**	**Δ Fuel Burned**
Benefit [-0.36% ΔSFC]	-0.18%	-0.47%
Penalty [+33.6 kg (+74 lbs) +$1480]	+0.10%	+0.10%
Total	-0.08%	-0.37%

Since the LPT design was reported in Reference 1, testing and development have resulted in changes in the aerodynamic design.

A series of aerodynamic tests was conducted using 2/3 size, nonflight hardware air turbine rigs. All rigs used the original (nonflaired) flowpath.

In the initial series of tests, the LPT inlet duct and Stage 1 vane were tested alone, then each blade row was added and tested as a group, until the complete first two stages were tested. This testing revealed a flow deficiency originating along the outer wall in the Stage 1 vane.

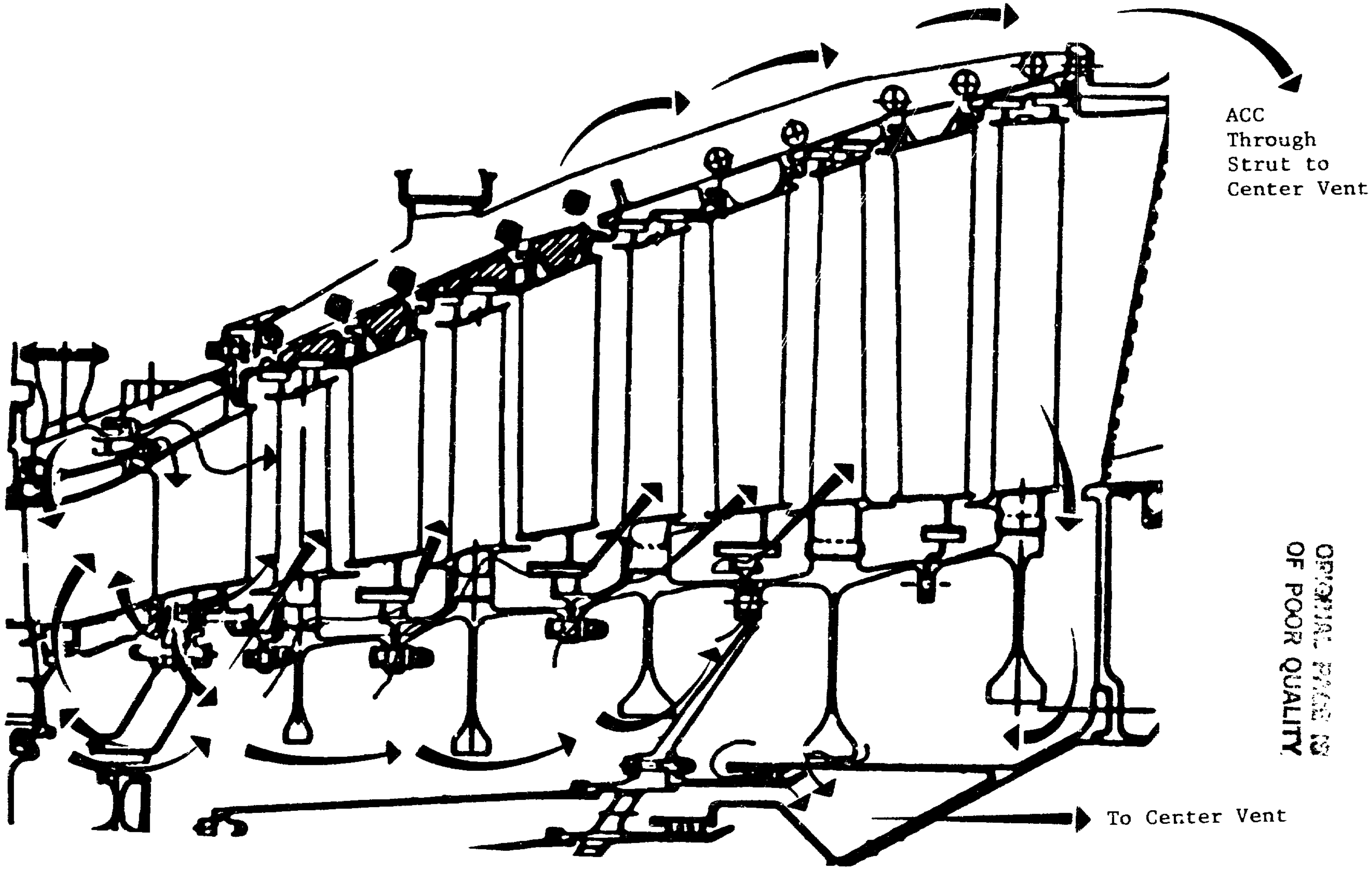


Figure 7. Low Pressure Turbine Purge System.

Table 9. Low Pressure Turbine Stage 1 Vane.

- Material: René 125
- Maximum Gas Total Temperature = 991° C (1816° F) Maximum Location
- Cooling Air Temperature (Purge) = 404° C (760° F)
  = 1.2% of W_{25} 5th Stage Purge Air
- Gas Load = 291 N/Vane (65.4 lb/Vane)
- ΔP Load = 263.5 N (59.25 lb) due to 71.0 KPa (10.3 psi)
- Bending Stress at 95% - 118.6 MPa (17.2 ksi)

  $\frac{\text{Rupture Life}}{\text{Required Life}} = 3.4$

  $\frac{\text{0.5\% Creep Life}}{\text{Required Life}} = 4.3$

  $\frac{\text{LCF Life}}{\text{Required Cycles}} > 1$

Table 10. Low Pressure Turbine Stage 1 Blade.

- Material: René 77
- Maximum Gas Total Temperature Relative to Blade = 909° C (1668° F) Maximum Location
- Shroud Bending Stress = 82.7 MPa (12.0 ksi)

  $\frac{\text{0.2\% Creep Life}}{\text{Required Life}} > 1$

- Airfoil: Compressive Stress = 61.3 MPa (8.9 ksi) at Root

  $\frac{\text{Rupture Life}}{\text{Required Life}} = 1.25$

  LCF: $\frac{\text{Calculated Cycle Life}}{\text{Required Life}} > 2$

- Dovetail: Effective Stress = 217 MPa (31.3 ksi)

  LCF: $\frac{\text{Calculated Cycle Life}}{\text{Required Life}} > 2$

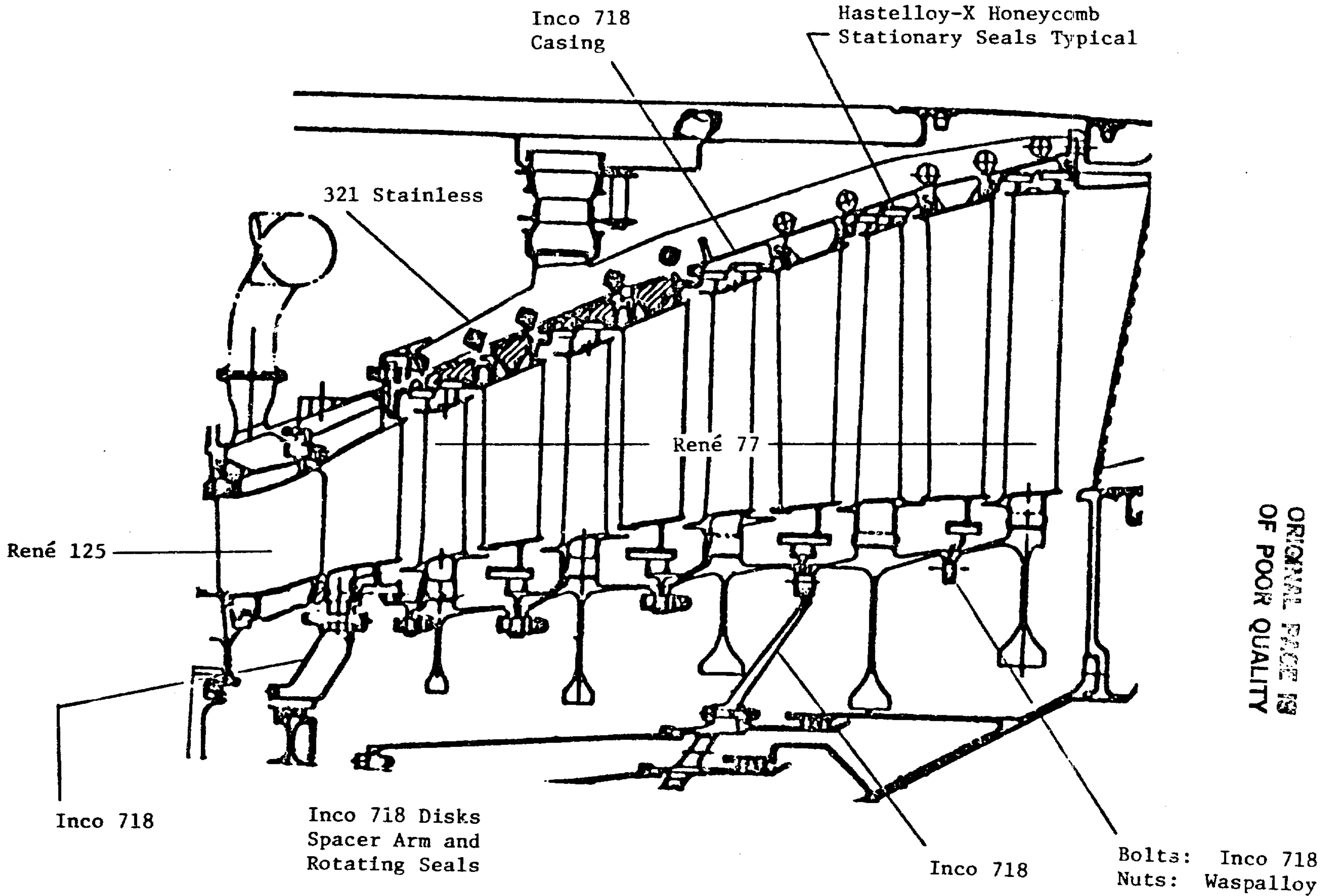


Figure 8. Low Pressure Turbine Materials.

The contour of the transition duct from the high pressure turbine discharge through the LPT Stage 1 vane was redesigned. The Stage 1 vector design was slightly changed to depress the static pressure of the vane trailing edge at the outer wall. The number of Stage 1 vanes was increased from 56 to 72, and the leading edge was made radial when viewed in a flowpath projection (constant axial width). The Stage 1 vane aspect ratio (vane height/channel throat) was increased by 31% and solidity (vane axial width/tangential spacing between vanes) was increased by 32%. Stage 1 blade hub solidity was increased by 9%. Platform overlaps were improved by reducing the axial gaps between rotating and stationary hardware, and by changing the contour of the platforms.

The designs changes were tested in a two-stage group. Efficiency of the two-stage group increased 0.75%. Then, the five stage group, including the redesigned transition duct and first stage, was tested. The five-stage group, when credited 0.25-point for the flaired FPS flowpath, slightly exceeded the FPS efficiency requirement for a fully developed turbine. Goal and measured efficiencies from the five-stage rig are shown in Table 11.

It should be noted that the ICLS test vehicle incorporates the improved transition duct and LPT Stage 1, but retains the original (nonflaired) aft stages.

Table 11. Low Pressure Turbine Efficiency.

	FPS Requirements			Rig Goal	Rig Results		
	Maximum Climb	Maximum Cruise	Takeoff	Maximum Cruise	Maximum Climb	Maximum Cruise	Takeoff
HPT Efficiency	0.917	0.917	0.921	0.911	0.915	0.915	0.917
					With 1/4 Pt Credited for Flaired Flowpath		
					0.918	0.917	0.920

3.6 TURBINE REAR FRAME

The FPS rear frame has extensively changed. The new FPS rear frame system establishes a technology advancement for large aircraft engines.

The basic function of the rear frame is to support the rotor. The E^3 rear frame must also distribute the large concentrated loads of the rear engine mounts. In addition, it must carry lubrication and purge air to the aft sump and provide enough aerodynamic solidity to straighten swirl leaving the turbine. In the GE FPS, the aft end of the core rotor is carried by the low pressure spool which, in turn, is positioned by the rear frame.

Blade tip clearances and frame thermal stresses place conflicting requirements on frame stiffness. In order to minimize rotor-to-stator deflections, and therefore maintain tight blade tip and seal clearances, the rear frame spring rates must be very high. High spring rates dictate more strength than do mechanical loads. The rear frame experiences severe thermal stresses due to the high temperature of the core stream and the cooler temperatures of the fan stream. Thermal stresses generally limit frame life. Thermal considerations, therefore, require a soft structure.

The frame described in Reference 1 used tangential struts. Because of the tangential orientation of the struts, thermal expansion of the struts and inner casing caused the inner casing to rotate. This movement accommodated thermal expansion without imposing excessive stresses. The spring rate of this frame was 0.875 x 10^8 N/m (500,000 lb/in.). Following the work reported in Reference 1, the spring rate requirement doubled to 1.75 x 10^8 N/m (1,000,000 lb/in.). The tangential strut design could not practically provide this stiffness.

The new frame uses radial struts in a polygonal outer casing. A traditional round casing experiences bending, concentrated at the junction with the struts, as the casing is forced toward a polygonal shape. The polygonal casing reacts differently. It experiences only tension. This scheme trades lower stress in the casing, where it is needed, for higher stress in the struts, where it can be tolerated. One of the features of the polygonal design is balanced stresses between the casing and struts, based on a three-dimensional finite element analysis. The frame is shown in Figure 9.

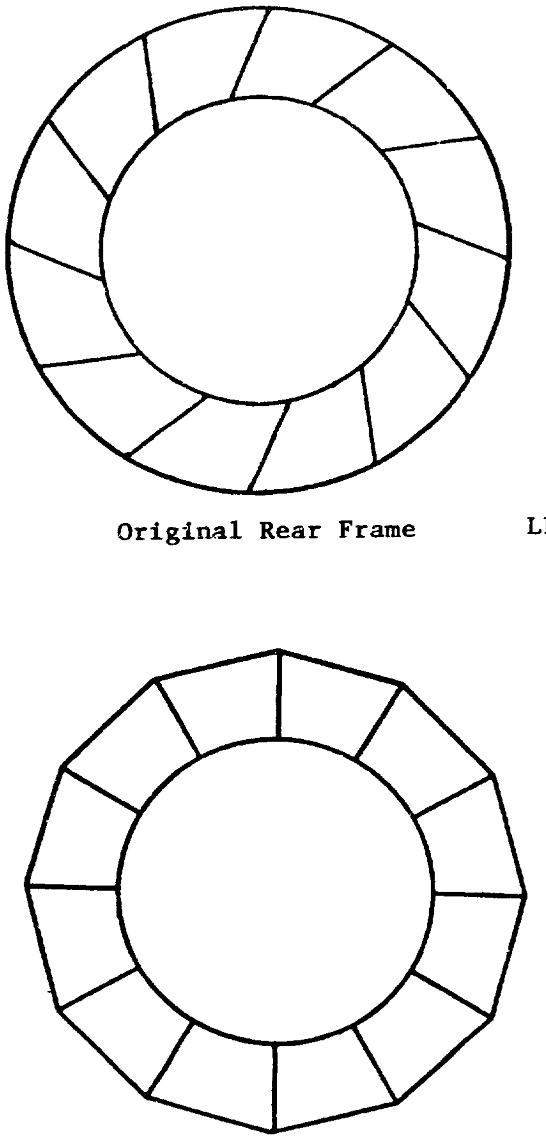
An additional problem is thermal stresses within the inner case of the frame during thermal transients. The inner case has two deep inner rings which are remote from the flowpath. The rings respond to changes in gas temperature more slowly than the flowpath part of the inner casing. To reduce thermal mismatch between the rings and the flowpath parts of the inner casing during transients, exhaust gas is bled inward and ducted around the inner rings. This heats the rings more quickly, more near the rate for the flowpath part, during an acceleration, and cools it more quickly during a deceleration.

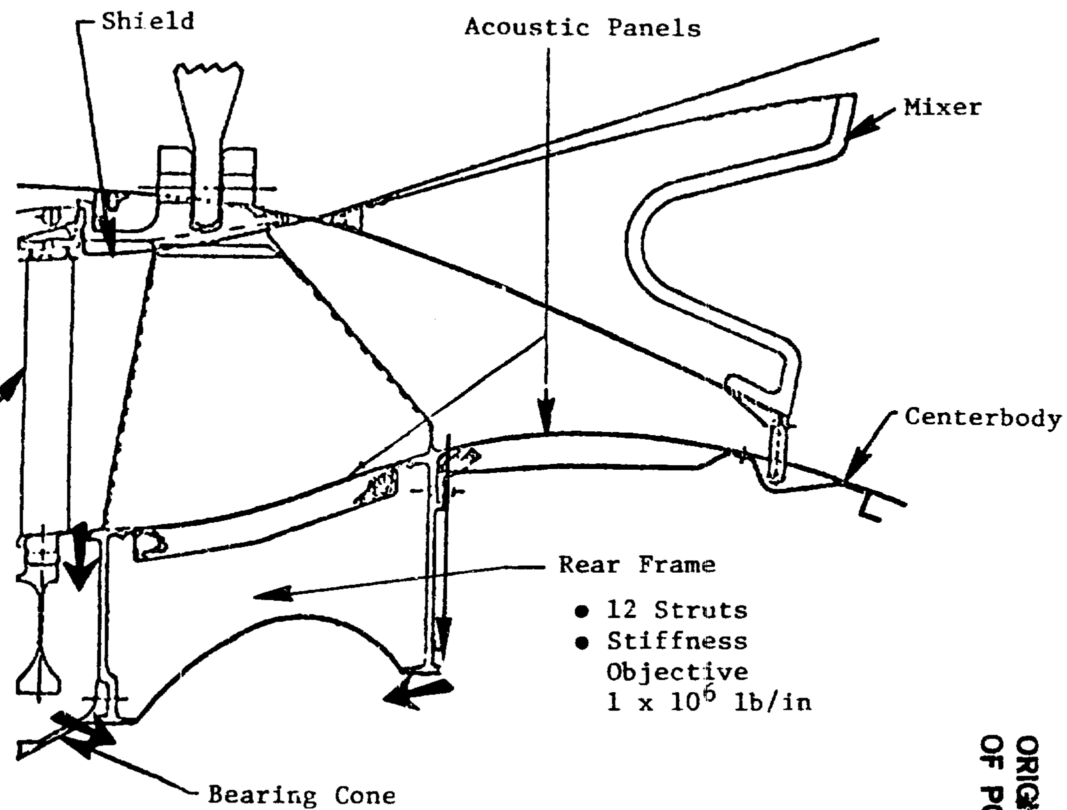
An additional change from Reference 1 is that the aft sump can no longer be removed from the frame while the rest of the engine is intact. This had been a convenient but not important feature and was dropped because it became impractical.

The design of the rear frame is described in more detail in Reference 2.

3.7 BEARING SYSTEMS, DRIVES, AND CONFIGURATION

There have been no significant changes in the FPS bearings, drives, and configuration areas. Details of the core thrust bearing with its spring support and viscous damper are shown in Figure 10. The forward sump is shown in Figure 2 and the aft sump is shown in Figure 11.





- Formed Sheet Material, Machined Rings Cast Fittings
- Chem-Milled for Low Weight with Local Reinforcement

Figure 9. Turbine Rear Frame.

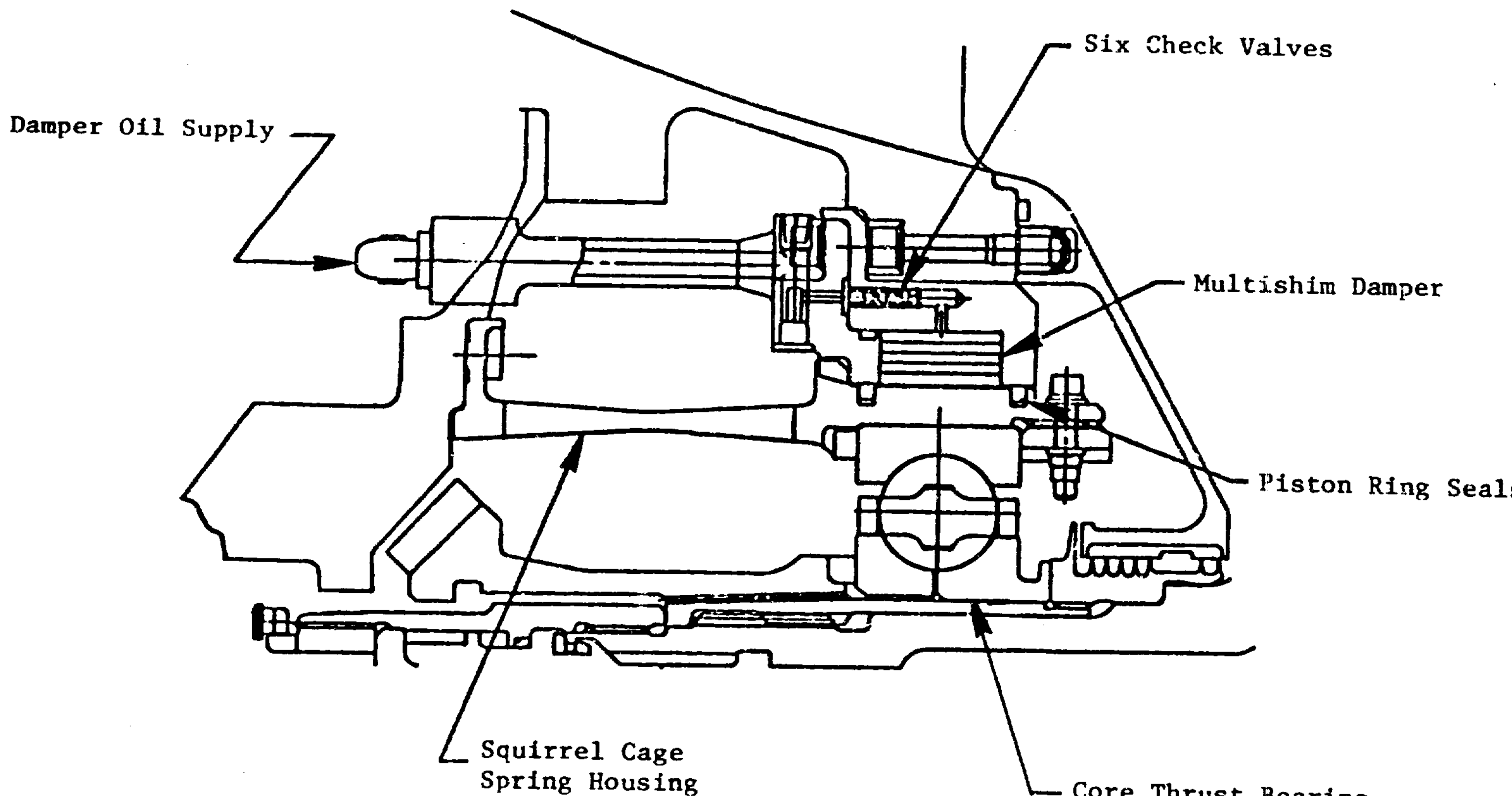


Figure 10. Forward Sump Thrust Bearing.

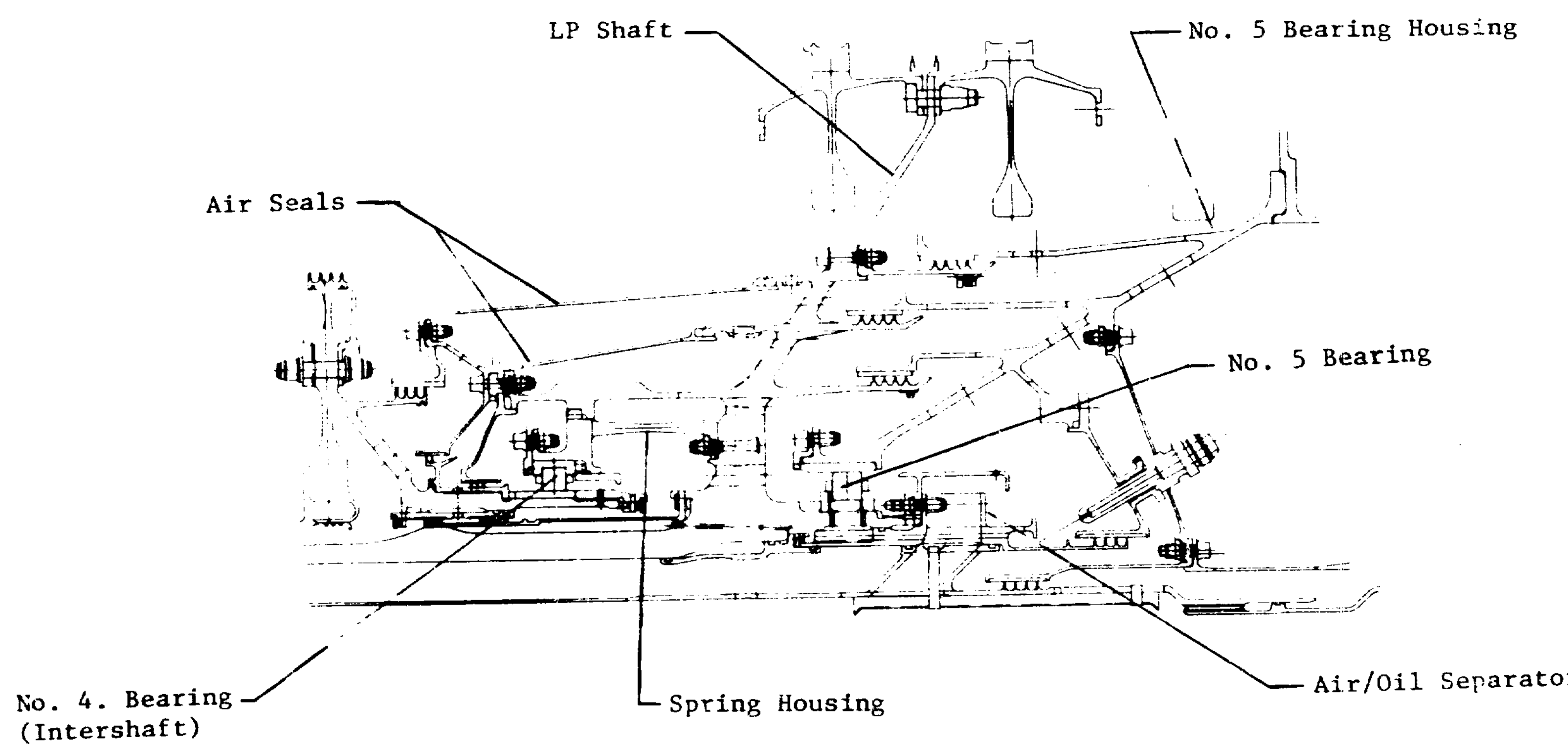


Figure 11. Aft Sump.

3.8 MIXER

The FPS uses a long fan duct and a convoluted mixer. The core and fan streams are mixed to provide a more uniform temperature at the exhaust plane. This produces a more uniform jet velocity which improves thrust and therefore fuel consumption.

Mixer technology was significantly advanced by E^3 program analyses and tests. A series of scale model mixers was evaluated at FluiDyne Engineering. From this testing, the lengthened mixer associated with the flaired LPT evolved. This is the scalloped 18-lobe mixer shown in Figure 12. The benefits for a lengthened mixer, compared to the mixer flowpath shown in Reference 1, are given in Table 8.

The FluiDyne tests provided data for a reassessment of the performance potential of a fully developed FPS mixer. It has been concluded that a fully developed FPS mixer would have a higher mixing effectiveness, but also a higher pressure drop, than the projection in Reference 1. This produces a still very significant, but reduced, sfc advantage for a mixed flow engine compared to a separate flow engine. The mixer tests, and old and new FPS projections are given in Table 12.

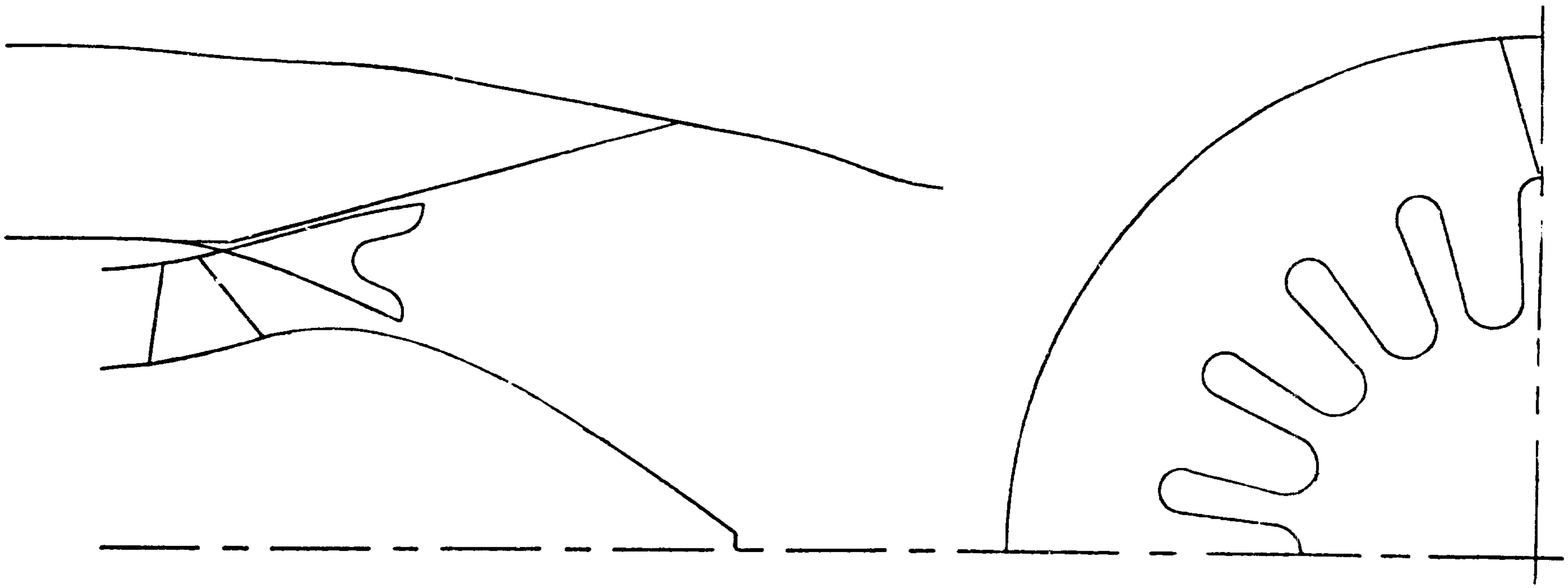
Table 12. Mixer Performance at Maximum Cruise.

	Original Goal (Reference 1)	Best Scale Model	FPS Projection
Mixing Effectiveness, %	75	79	85
Pressure Loss, $\Delta P/P$, %	0.20	0.57	0.57
SFC Improvement, %	3.1	2.6	2.9

3.9 NACELLE

The FPS uses a long duct, mixed flow nacelle. The nacelle has been lengthened and the boattail (outer cowling near the exhaust plane) angle has been reduced. This change resulted from the mixer change discussed in Section 3.8.

Powered scale models of both the original nacelle and the current nacelle were tested at NASA-Langley. The drags of isolated nacelles were



- 18 Lobes
- Scalloped Radial Sidewalls
- 45% Penetration
- 43-Inch Tailpipe Length, $L/D_{MP} = 0.52$

Figure 12. FPS Mixer Design.

measured and the wing/pylon/nacelle interference drag of nacelles installed under an advanced supercritical wing were also measured.

The current nacelle has 0.9% F_n lower isolated drag at cruise than the CF6-50C reference engine. This is based on analysis and test. The program goal is for a 0.7% reduction. The drag status in Reference 1 was a 0.6% reduction, made prior to wind tunnel tests. Program goals are stated in terms of isolated drag to avoid the need to specify an aircraft to establish interference drag. The interference drag tests showed that the FPS nacelle can be installed on a supercritical wing with equal or lower interference drag penalties than current technology separate flow nacelles such as the CF6-50C.

3.10 REVERSER

The FPS uses a cascade reverser with blocker doors in the fan duct. The core stream is not reversed but is partially spoiled by a sudden expansion into the quiescent fan duct at the mixing plane. The effectiveness of core thrust spoiling was measured during mixer testing at FluiDyne Engineering. These tests showed that core thrust spoiling was slightly more effective than was assumed in Reference 1. The reverser has not been changed from that shown in Reference 1.

3.11 MOUNT

The engine mount system has changed substantially from that reported in Reference 1. Mount link locations and orientations have been altered to further reduce bending and ovalization of the engine casing due to mount link loads. The links carrying thrust loads are located lower, nearer the horizontal thrust line to reduce thrust-induced moments. All aft links now attach to the rear frame.

The FPS uses seven mount links, shown in Figure 13. A pair of links in the vertical plane at the front frame carry forward, vertical, and side loads. Another pair of links at the front frame carry thrust loads. This pair is connected to the pylon mount frame through a pivoting "whiffle tree." A pair of links over the rear frame carry aft vertical loads. A short lateral link, acting with these, provides roll (or torque) and side load restraint. All links are mounted using uniballs.

The forward links are located within the core cowl. The aft lateral link is located within the pylon. The aft vertical links are streamlined and extend through the fan stream from the pylon to the rear frame. Link ends at the rear frame are covered by fairings on the core cowl.

3.12 CONTROL SYSTEM

While the E^3 control system has matured from that reported in Reference 1, the basic requirements and design have not changed.

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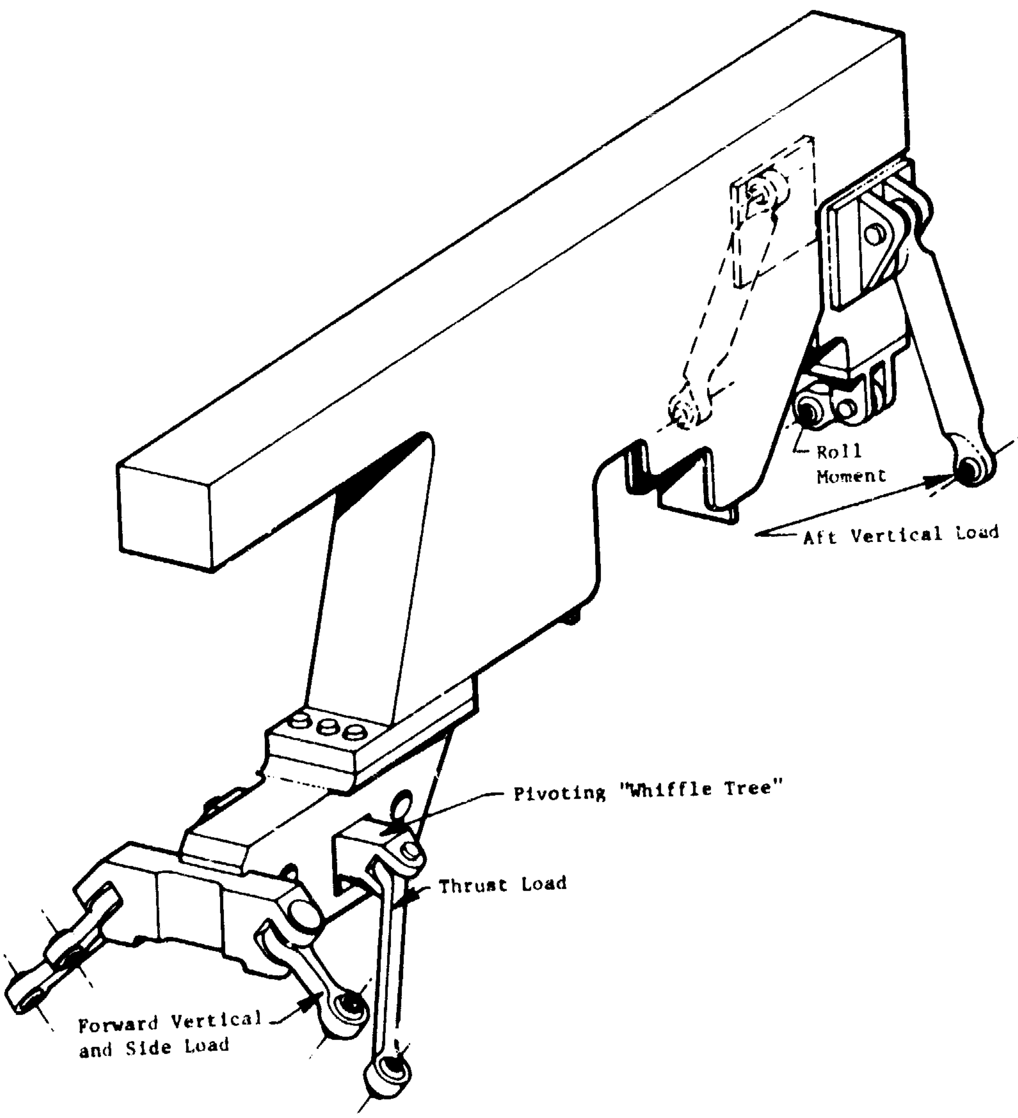

Figure 13. E^3 Mount Schematic.

The E^3 uses a full authority digital electronic control (FADEC) to manage fuel flow, fuel distribution, compressor variable stators, starting bleed air, active clearance control air, for the compressor, HPT and LPT, start range turbine cooling air, and reverse thrust. The control functions are shown in Figure 14.

As discussed in the HP turbine section, an active clearance control heating circuit has been added to warm the casings quickly following start up. The control keeps a heating air valve open until measured casing temperatures reach normal steady-state idle temperatures.

Air may be bled from the compressor seventh stage to compensate for flow capacity mismatch between the front stages and rear stages which occurs at low speeds during a start. This start bleed flow is controlled by a set of four butterfly valves. A ring which actuates the valves is driven by a single fuel-powered servoactuator. The servoactuator is controlled by the FADEC. An electrical position transducer is incorporated within the servoactuator to provide feedback to the control.

As discussed in Section 3.4, start range turbine cooling is used to assure adequate turbine cooling during starting. The two start range turbine cooling valves are actuated by the FADEC when the start bleed valves are open and when the engine is below idle speed.

The strategy for controlling clearances has been established. The FADEC senses casing temperatures, calculates target casing temperatures, and modulates cooling air valves to make the sensed casing temperatures match the calculated temperatures. Target casing temperatures are calculated using a schedule of fan inlet air temperature and core corrected rpm. There is an inherent time delay which gives extra clearance margin on takeoff and initial climb. Clearances for the compressor, HP turbine, and LP turbine are controlled independently.

The FPS uses a fuel heating system to improve fuel consumption. The environmental control system (ECS) air was selected as the heat source. Heat is transferred from the ECS air to the fuel. This recovers otherwise wasted energy. At idle, the lower fuel flow does not provide an adequate heat sink. Therefore, fan air cooling of the ECS air must be used at idle. At takeoff, climb and cruise, the fuel flow provides a more than adquate heat sink. Above idle, ECS air temperature is controlled by bypassing a portion of the air around the ECS air cooler. The fuel heating system avoids the loss of fan air during aircraft flight, which ordinarily is used to cool ECS air, and then is dumped overboard. The fuel heater/regenerator system is shown schematically in Figure 15.

Control of the fuel flow split between the pilot and main burners has been simplified. The earlier system used a throttling valve to the pilot burner and a metering valve to the main burner. The current system uses an open line containing an orifice in parallel with a "Pilot Zone Reset Valve" to the pilot burner. A "Main Zone Shutoff Valve" controls fuel to the main

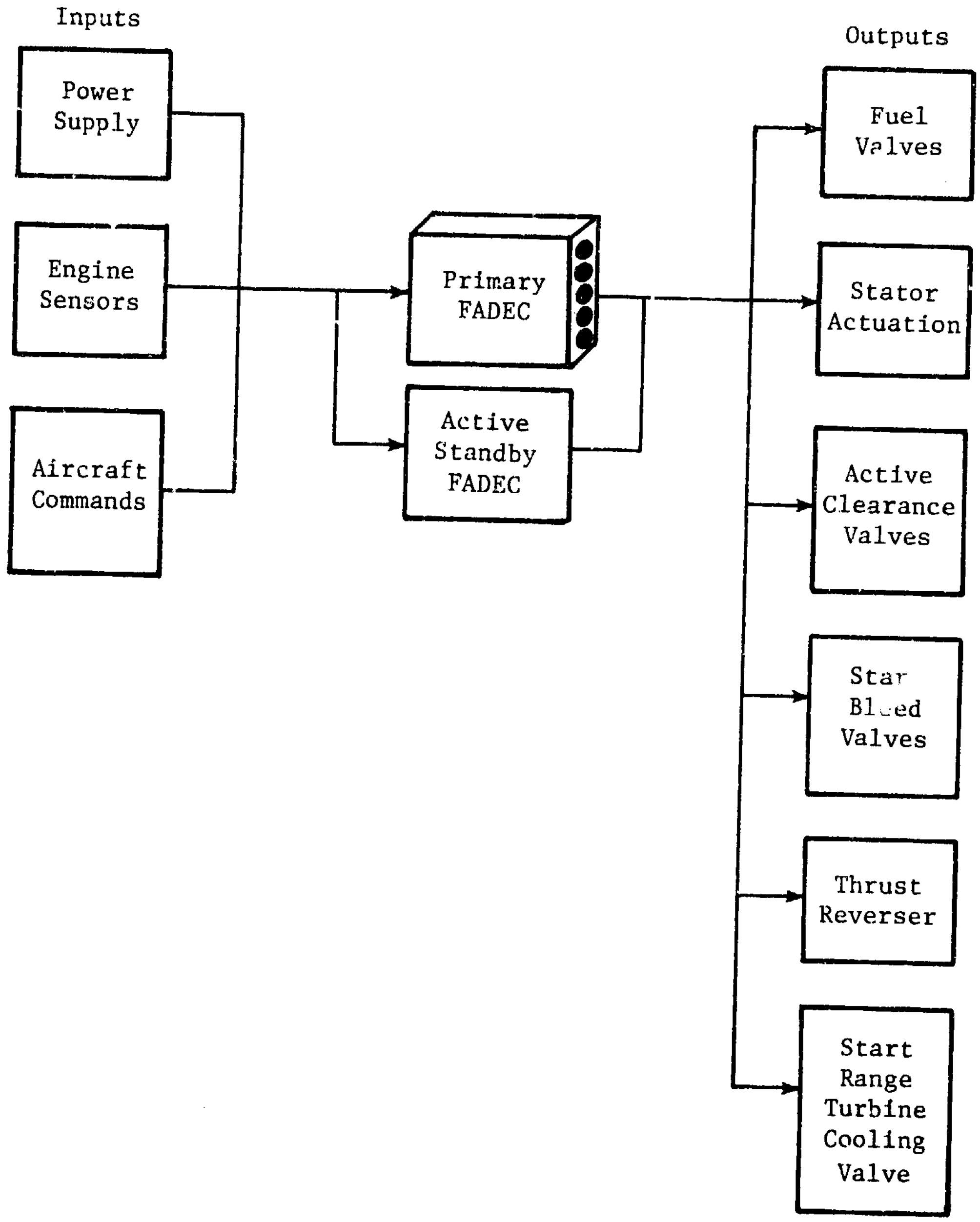

Figure 14. Digital Engine Control.

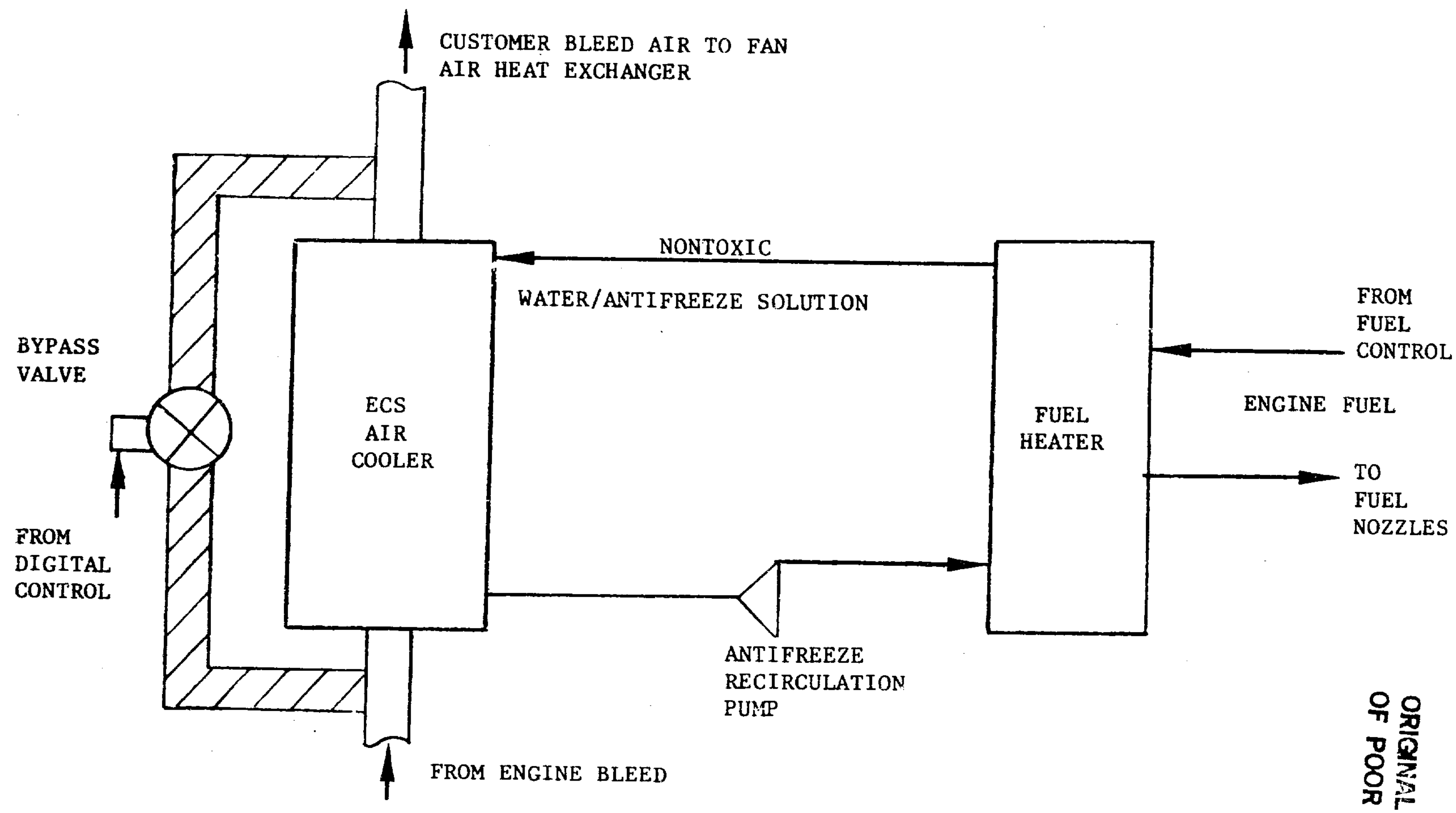

Figure 15. Fuel Heater/Regenerator Schematic.

burner. This system has the advantage of requiring only simple on/off valving rather than flow control valving. The flow split is fixed by the orifice and fuel nozzle flow characteristics. Only the pilot burner is used for starting and idle operation. In this mode, the pilot zone reset valve is open and the main zone shutoff valve is closed. During transition to double-annular burning, the main zone shutoff valve is opened and, in order to richen the main burner for ignition, the pilot zone reset valve is closed. For normal double-annular burning, both the pilot zone reset valve and main zone shutoff valve are open. The fuel system is shown in Figure 16.

3.13 ENGINE DYNAMICS

As in Reference 1, the Number 1 and 2 bearings support the forward fan shaft. The Number 3 bearing, which supports the front end of the core rotor, is spring mounted and uses a squeeze film damper. The Number 4 bearing supports the aft end of the core rotor from the LP shaft and is spring mounted. The core rotor soft support and squeeze film damper system are illustrated in Figure 17. The Number 5 bearing supports the aft end of the LP rotor.

Analysis subsequent to Reference 1 has verified that a damper at the Number 4 bearing is not necessary. A component mode analysis was developed to better understand the squeeze film damper characteristics and to obtain the most efficient rotor mount/damper configuration. Results from the component mode analysis were used to establish the overall damping characteristics of the engine system and the corresponding vibration response signature. It was determined through this analysis that the Number 3 bearing damper will provide the required damping for the whole system. Therefore, no changes have been made to the bearing and damper design. The analytical technique was verified by correlating compressor rig test data with analytical predictions.

The vibration model has been updated and the dynamic response characteristics were reevaluated. The current model is shown in Figure 18. The vibration characteristics and response levels have not changed significantly from Reference 1.

3.14 WEIGHT

The weight status is presented in Table 13. Both base engine weight and installation weight have increased from Reference 1.

3.15 COST

The FPS engine cost has been reevaluated. Current manufacturing costs for the 250th production FPS are shown in Table 14. Costs from Reference 1 are included for comparison. Costs are all expressed in 1980 dollars. Installed engine costs, in consistent year dollars, have increased 6%.

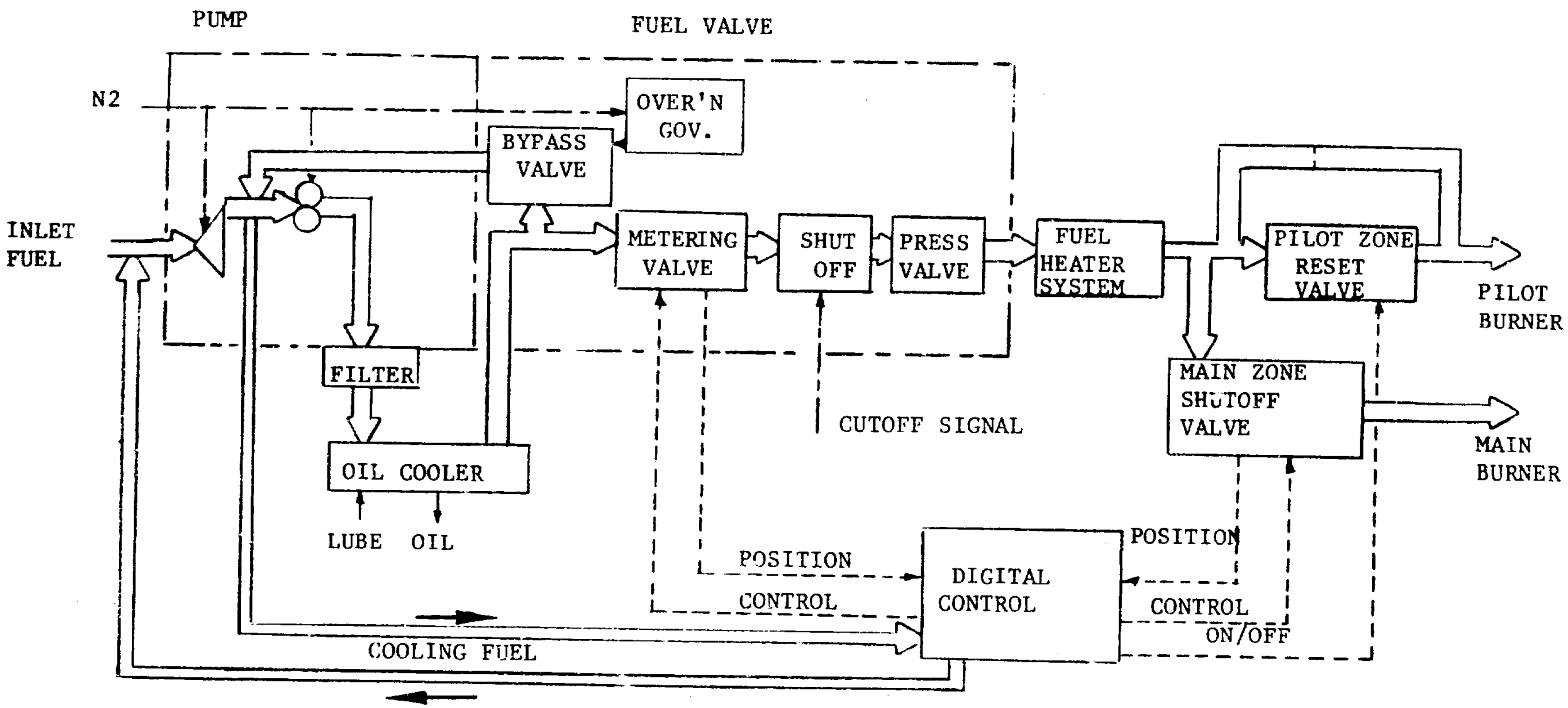

Figure 16. Fuel System.

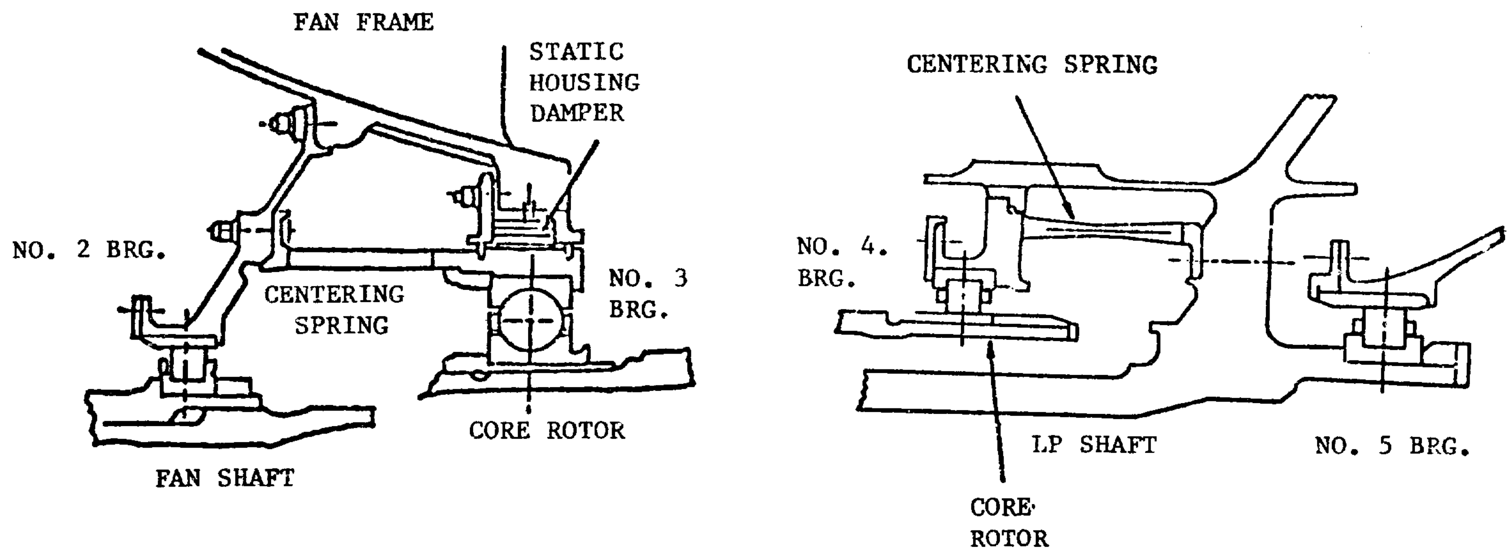

Figure 17. Combined Tuned Bearing Support and Damper Arrangement for the E^3 FPS Core Rotor.

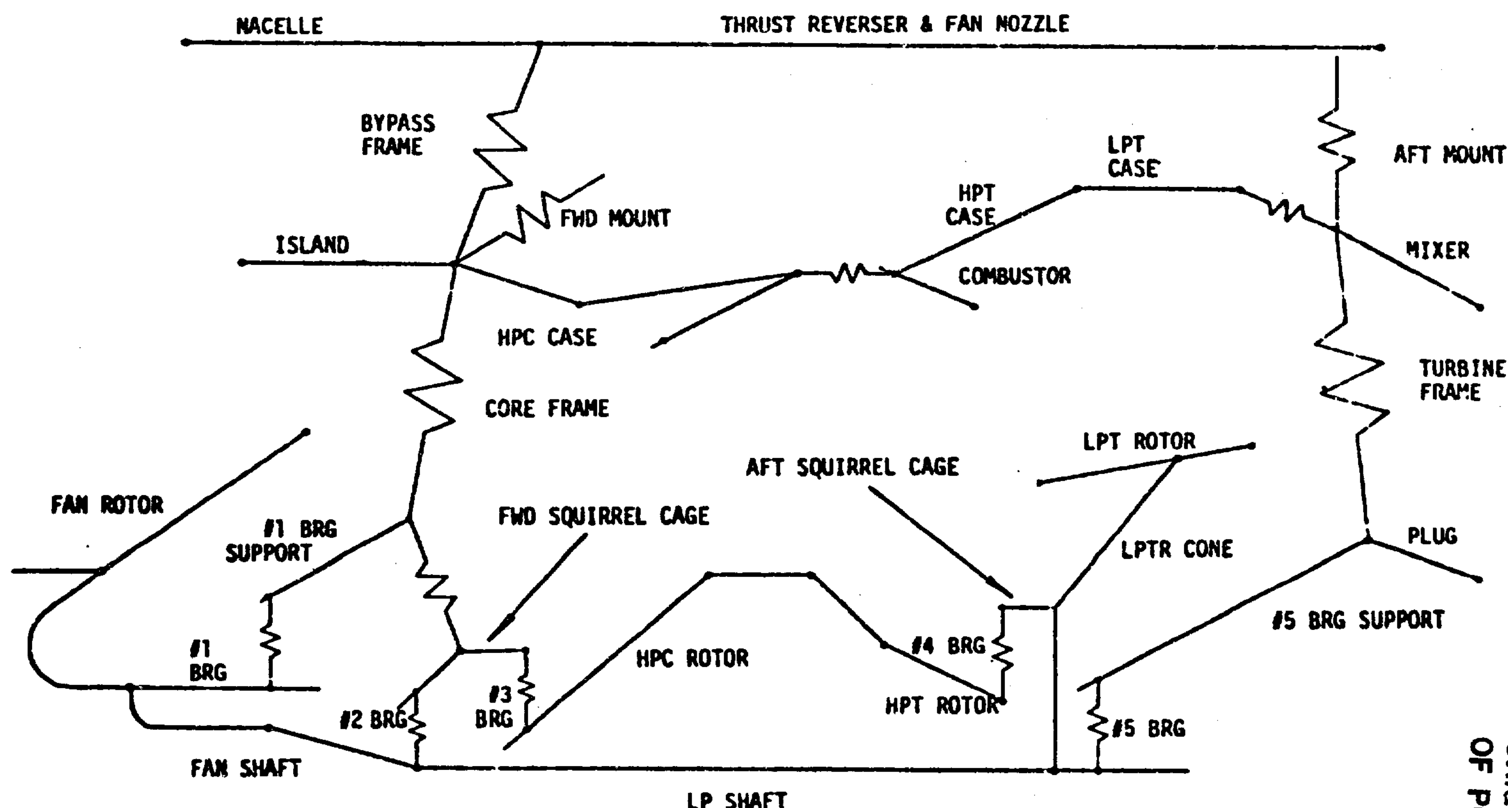

Figure 18. E^3/FPS System Vibration Model.

Table 13. E^3 FPS Weight Status.

	Previous Weight (Reference 1)		Current Weight		Change	
Bare Engine	kg	(lbm)	kg	(lb)	kg	(lb)
Fan Module	1066	(2350)	1103	(2431)	+37	(+81)
LP Turbine and Mixer Module	754	(1660)	837	(1846)	+83	(+186)
Compressor	481	(1060)	470	(1036)	-11	(-24)
Combustor	122	(270)	138	(303)	+16	(+33)
HP Turbine	404	(890)	414	(913)	+10	(+23)
Miscellaneous	463	(1020)	540	(1191)	+77	(+171)
Total	3290	(7250)	3502	(7720)	+212	(+470)
Installation						
Inlet	161	(355)	162	(358)	+1	(+3)
Reverser	304	(670)	379	(835)	+75	(+165)
Core Cowl, Pylon Sidewalls and Exhaust System	125	(275)	183	(404)	+58	(+129)
Engine Buildup	204	(450)	270	(595)	+66	(+145)
Total	794	(1750)	994	(2192)	+200	(+442)
Installed Engine	4084	(9000)	4496	(9912)	+412	(+912)

Table 14. E^3 FPS Engine Cost.

	Previous Cost Adjusted To 1980 $'s (Reference 1)	Current Cost In 1980 $'s	Change
Bare Engine			
Fan Module	$ 713,000	$ 559,000	-154,000
LPT Module	663,000	440,000	-223,000
Core Module	981,000	1,057,000	+76,000
Miscellaneous	325,000	598,000	+273,000
Total	$2,682,000	$2,654,000	-28,000
Installation			
Inlet	$ 130,000	217,000	+87,000
Fan Reverser and Duct	329,000	450,000	+129,000
Core Cowl and Tailpipe	98,000	122,000	+24,000
Engine Buildup	236,000	236,000	0
Total	$ 793,000	$1,033,000	+240,000

Maintenance costs have not been changed. Expressed in 1980 dollars, engine maintenance is projected to be $90.89 per engine flight hour.

3.16 NOISE

The FPS uses a high bypass ratio, wide spacing between the fan and fan OGV/frame, cut-off frequency tuning in the low pressure turbine, a mixer, and bulk acoustic treatment in the fan duct and in the core exhaust duct to contribute to lower noise.

The acoustic design has not changed. However, the technology for assessing noise has changed. Recent information from other programs shows that sideline shielding is lower than what had been previously expected. The FPS, reevaluated with this technology, still meets the noise goals with margin.

The E^3 has the goal of complying with FAR 36 (March 1978) noise standards. The current FPS is quieter than the goal noise level by the margins shown in Table 15. The aircraft used are advanced technology study aircraft from the aircraft/engine integration phase of the E^3 Program (Reference 3).

Table 15. E^3 Noise Margin from FAR 36.

	Noise Margin EPNdB		
	Takeoff	Sideline	Approach
Boeing Domestic Twin Jet	4.5	7.1	2.0
Lockheed Domestic Tri Jet	8.1	8.7	2.8
Lockheed International Quad Jet	7.3	8.7	3.7
Douglas Tri Jet	6.8	7.6	4.3

4.0 CYCLE

The basic thermodynamic cycle has not substantially changed from Reference 1. Takeoff thrust remains at 162.36 kN (36,500 lb), and the core size remains at 54.4 kg/sec (120 lb/sec) corrected airflow. The cycle parameters are shown in Table 16.

Cooling and leakage flows have been refined in the FPS cycle deck, and some component performance maps have been updated. The fan map has been updated to more accurately reflect low power fan efficiency. It was developed from recent CF6-50 fan data. The compressor flow, speed, and efficiency characteristics have been updated using E^3 rig results. Compressor efficiency at the design point has not been changed. The map from the E^3 HP turbine rig test has been incorporated into the cycle. In the future, as additional component test results become available, they will be incorporated into the FPS cycle deck. Component performance and secondary flow rates are summarized in Table 17.

The GE E^3 specific fuel consumption (SFC) goal is 12% improvement over the GE CF6-50C engine at maximum cruise thrust at 10,668 m (35,000 ft), Mach 0.8, on a standard day, with no bleed and power extraction and 100% inlet-ram recovery. The FPS SFC is currently 14.5% better than a CF6-50C at these conditions. Since the E^3 has a relatively smaller core than the CF6-50C, bleed air for the aircraft cabin has a higher penalty. However, the FPS uses a fuel heater/regenerator system described in Section 3.12. The CF6-50C uses fan air to cool aircraft bleed. The fuel heater regenerator system recovers waste heat from the bleed air and more than balances the bleed penalty for the smaller core. If customer bleed, power extraction, and the benefit due to recovering energy from bleed air with the fuel heater/regenerator system are considered, the installed SFC improvement becomes 14.9%.

The FPS can be grown to a 20% higher thrust without changing fan diameter. The growth cycle is presented in Table 18.

The E^3 deterioration goal is to experience no more than half of the CF6-50C in-service performance deterioration. The deterioration assessment has not changed. The FPS is projected to meet the deterioration goal.

Table 16. E^3 FPS Cycle Definition.

	Maximum Climb	Maximum Cruise	Takeoff
Uninstalled SFC (Standard Day) kg/N/hr (lbm/lbf/hr)	0.0556 (0.546)	0.0553 (0.542)	0.0299 (0.293)
Overall Pressure Ratio	37.7	35.8	29.8
Bypass Ratio	6.8	6.9	7.3
Fan Bypass Pressure Ratio	1.65	1.61	1.50
Fan Hub Pressure Ratio	1.67	1.63	1.52
Compressor Pressure Ratio	23.0	22.3	19.9
HPT Rotor Inlet Temperature, ° C (° F)	1285 (2345)	1246 (2274)	1338 (2441)

Table 17. FPS Cycle-Maximum Cruise Component Performance.

Component	Performance
Fan Bypass Efficiency	0.887
Fan Hub Efficiency	0.891
Compressor Efficiency	0.862
Combustor Efficiency	0.995
HPT Efficiency	0.925
LPT Efficiency	0.917
Mixing Effectiveness	0.75
Cooling Flow - % Compressor Inlet Flow	
Chargeable	11.32
Nonchargeable	9.46

Table 18. E^3 Growth for Fixed Fan Diameter.

	FPS Baseline Thrust	Throttle Push +5% Thrust	New Booster +5% Thrust	+10% Thrust	+20% Thrust
Maximum Climb 10,668 m (35,000 ft)/0.8M					
Uninstalled sfc kg/N/hr (lbm/lbf/hr)	0.0556 (0.546)	0.0564 (0.553)	0.0562 (0.551)	0.0570 (0.559)	0.0574 (0.563)
Overall Pressure Ratio	37.7	39.0	42.3	42.7	45.0
Bypass Ratio	6.8	6.7	6.1	6.1	5.
Fan Bypass Pressure Ratio	1.65	1.68	1.70	1.70	1.75
Fan Hub Pressure Ratio	1.67	1.70	1.90	1.87	2.05
Takeoff SLS 30° C (86° F)					
Net Thrust, kn (lb)	162.36 (36,500)	170.50 (38,330)	170.50 (38,330)	178.55 (40,140)	194.83 (43,800)
HPT Rotor Inlet Temperature, ° C (° F)	1341 (2445)	1365 (2489)	1351 (2464)	1393 (2539)	1443 (2629)

5.0 ECONOMIC UPDATE

As part of the E^3 program, three airframe manufacturers were funded to evaluate the FPS in their advanced transport aircraft. These companies were Boeing, Lockheed, and Douglas. Their results were published in 1980 in Reference 3. The E^3 design and performance used for their analysis was essentially the same as that reported in Reference 1.

The analyses provided an assessment of the direct operating cost (DOC) benefits due to E^3 for four different commercial transport aircraft. Each aircraft was evaluated using both the CF6-50C and the E^3 FPS. Aircraft fuel load, wing area, and weight were tailored to each engine. Fuel prices from 7.9¢ to 13.2¢ per liter (30¢ to 50¢ per gallon) were used.

Since then, fuel price has increased substantially and the E^3 has been modified as discussed in this report. Modifications to the E^3 FPS have produced the following net operational changes:

- Installed SFC improved 0.35%
- Weight increased 412 kg (912 lb)
- Engine cost increased $212,000
- Maintenance cost did not change.

The economic benefits attributable to the E^3 were reassessed using these changes. The evaluation was based on the methods used by the airframe manufacturers earlier in the program, adjusted to higher fuel prices. A fuel price of $0.396/liter ($1.50/gallon) in 1982 dollars was used to represent contemporary fuel prices, and $0.661/liter ($2.50/galllon) in 1982 dollars was used for possible future fuel prices. The resulting economic evaluations are shown in Table 19 and Figure 19. The results are presented as a percent reduction in direct operating cost from CF6-50C powered aircraft.

The increase in fuel price had the greatest overall impact on the DOC benefit due to the FPS compared to the CF6-50C. Changes in SFC, and cost were dominanted by the weight increase. Using the Lockheed domestic aircraft as an example, the changes in economic analysis stack up as shown on Table 20.

One of the E^3 program goals is to achieve a 5% reduction in DOC from a typical current production engine, taken as the CF6-50C. The DOC reduction due to the E^3 FPS exceeds the goal on all study aircraft, ranging from 7.1% to 14.5%, based on a fuel price of $0.396/liter ($1.50/gallon).

Table 19. E^3 DOC Improvements.

	E^3 Improvement in DOC Over CF6-50C		
	1979 Status E^3 at the 1979 Study Fuel Price	Current E^3 Evaluated Using $0.396/l ($1.50/g) Fuel Price in 1980 Dollars	Current E^3 Evaluated Using $0.661/l ($2.50/g) Fuel Price in 1980 Dollars
Boeing, 2 Engines, 196 Passengers 3704 km (2000 nmi) Design Flight 1232 km (665 nmi) Typical Flight	6.4% 4.0% At $0.106/l ($0.40/g) Fuel In 1977 Dollars	9.3% 7.1%	11.2% 9.2%
Lockheed, 3 Engines, 500 Passengers 5556 km (3000 nmi) Design Flight 2593 km (1400 nmi) Typical Flight	8.0% 6.8% At $0.0814/l ($0.308/g) Fuel In 1976 Dollars	10.4% 8.8%	12.1% 10.5%
Lockheed, 4 Engines, 500 Passengers 12,038 km (6500 nmi) Design Flight 5,556 km (3000 nmi) Typical Flight	12.0% 10.5% At $0.102/g ($0.387/g) Fuel In 1976 Dollars	14.5% 12.5%	16.4% 14.3%
Douglas, 3 Engines, 458 Passengers 5556 km (3000 nmi) Design Flight 1852 km (1000 nmi) Typical Flight	9.1% 8.1% At $0.132/l ($0.50/g) Fuel in 1978 Dollars	11.5% 10.0%	13.5% 12.0%

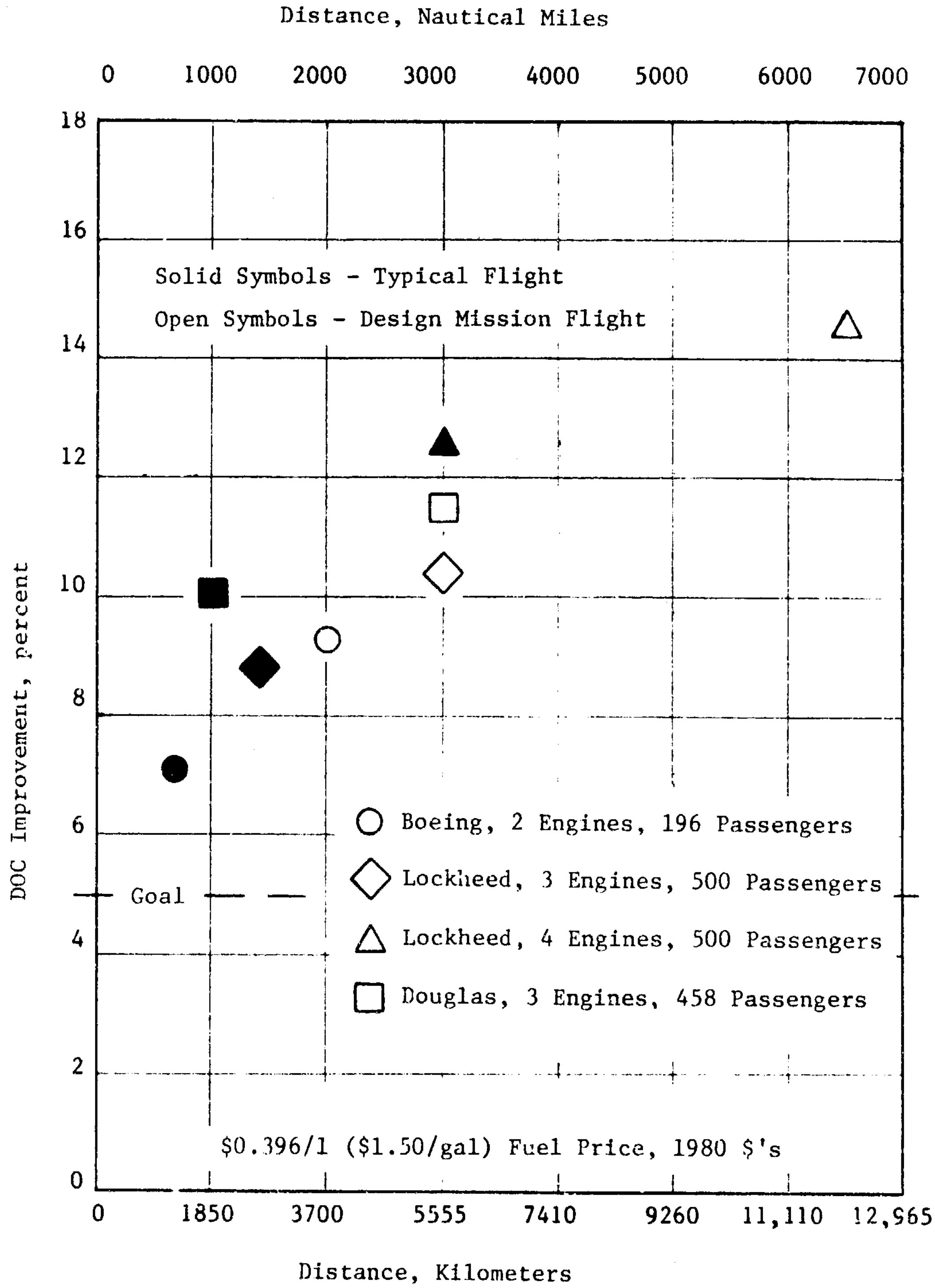

Figure 19. E^3 DOC Improvements.

Table 20. Breakdown of DOC Change for Lockheed Domestic Aircraft.

		DOC Improvement Over CF6-50C
1979 Engine at $0.0814/1 ($0.308/g), 1976 $'s		8%
1979 Engine at $0.396/1 ($1.50/g), 1980 $'s		11.7%
Engine Change Effect on % DOC Improvement		
SFC	+0.3%	
Weight	-1.3%	
Cost	-0.3%	
Maintenance	0	
Total	-1.3%	
Current Engine at $0.396/1 ($1.50/g), 1980 $'s		10.4%

6.0 CONCLUSIONS

The current Energy Efficient Engine Flight Propulsion System has the same basic thermodynamic cycle and engine configuration as reported in the preceding Preliminary Analysis and Design Report. However, refinements have been incorporated. These resulted from the execution of detailed designs, as contrasted to preliminary designs, and from component testing. The component design and test programs have successfully advanced the state-of-the-art as was required to meet E^3 goals.

Fuel price is currently three times the level used for earlier economic assessments. The higher fuel price has greatly increased the payoff for the higher efficiency technology in E^3.

The E^3 FPS is projected to meet or exceed NASA program goals. A comparison of the FPS status with E^3 program goals follows:

Fuel Consumption

Goal - To reduce SFC by at least 12% from the CF6-50C level, evaluated at maximum cruise without bleed or power extraction.

Status - SFC is 14.5% better at these conditions. If bleed and power extraction are considered, the SFC improvement is 14.9%.

Performance Retention

Goal - To experience no more than half of the service performance deterioration of a CF6-50C.

Status - 50% of the deterioration of a CF6-50C.

Direct Operating Cost

Goal - To reduce aircraft DOC by at least 5% from that for similar CF6-50C powered aircraft.

Status - A 7.1% to 14.5% lower DOC, depending on the aircraft used and the flight length.

Noise

Goal - To comply with FAR 36 (March 1978) noise standards.

Status - Meets these standards with margin.

Emissions

Goal - To meet EPA proposed standards for engines certified after January 1981.

Status - Meet these standards.

7.0 REFERENCES

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