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National Aeronautics and Space Administration

ENERGY EFFICIENT ENGINE

FLIGHT PROPULSION SYSTEM PRELIMINARY ANALYSIS AND DESIGN

FEDD-2 DATA SUPPLEMENT

June 1980

By

GENERAL ELECTRIC COMPANY

Prepared For

National Aeronautics and Space Administration

LEWIS RESEARCH CENTER
21000 BROOKPARK ROAD
CLEVELAND, OHIO 44135

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Project Manager: Mr. N.T. Saunders, NASA-Lewis Research Center, Cleveland, Ohio

16. Abstract

The characteristics of an advanced Flight Propulsion System (FPS), suitable for introduction in the late 1980's to early 1990's, has been more fully defined. It has been determined that all NASA goals for efficiency, environmental considerations, and economics could be met or exceeded with the possible exception of NO_x emission. In evaluating the FPS, all aspects were considered including component design, performance, weight, initial cost, maintenance cost, engine-system integration (including nacelle), and aircraft integration considerations.

In terms of the NASA goals, the current FPS installed specific fuel consumption has been reduced 14.2% from that of the CF6-50C reference engine. When integrated into an advanced, subsonic, study transport, the FPS produced a fuel-burn savings of 15 to 23% and a direct operating cost reduction of 5 to 12% depending on the mission and study-aircraft characteristics relative to the reference engine.

This Document presents FEDD-2 data supplementary to NASA CR-159583.

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FOREWORD

This is a supplemental report on 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. Neal T. Saunders is the NASA E^3 Project Manager; Mr. Lawrence E. Macioce is serving as NASA Assistant Project Manager. Mr. John Schaefer was the NASA Project Engineer responsible for the effort associated with the Flight Propulsion System - Preliminary Analysis and Design reported here. Mr. Martin C. Hemsworth served as manager of the E^3 Project for the General Electric Company. This report was prepared by Mr. Richard P. Johnston with the assistance of the responsible engine component design managers.

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LIST OF SYMBOLS AND ABBREVIATIONS

ACC	Active Clearance Control
BPR	Bypass Ratio
CDP	Compressor Discharge Pressure or Compressor Discharge Plane
DOC	Direct Operating Cost
E^3	Energy Efficient Engine
EPA	Environmental Protection Agency
EPNdB	Effective Perceived Noise in Decibels
FAR	Federal Airworthiness Regulation
FOD	Foreign Object Damage
FPR	Fan Pressure Ratio
FPS	Flight Propulsion System
HP	High Pressure
HPC	High Pressure Compressor
HPT	High Pressure Turbine
ICLS	Integrated Core/Low Spool
K	Spring Constant
K$	Kilodollars ($1000)
l/c	Length/Chord
LP	Low Pressure
LPT	Low Pressure Turbine
M	Mach Number
N	Rotational Speed
PAD	Preliminary Analysis and Design
P/P	Pressure Ratio
QCSEE	Quiet Clean Short-Haul Experimental Engine
R	Radius or Radial Dimension
sfc	Specific Fuel Consumption
SLS	Sea Level Static
SLTO	Sea Level Takeoff
SN	SAE Smoke Number
STEDLEC	Study of Turbofan Engines Designed for Low Energy Consumption

LIST OF SYMBOLS AND ABBREVIATIONS (Concluded)

T	Temperature
USTEDLEC	Unconventional STEDLEC
VSCF	Variable-Speed/Constant-Frequency (Generator)
W	Airflow or Gas Flow
α	Coefficient of Thermal Expansion
Δ	Prefix Indicating a Differential Increment

Subscripts

3	Combustor Discharge
4.1	HPT Inlet
12	Fan Inlet (at Tip)
25	Compressor Inlet
49	LPT Inlet
C	Coolant; or Centrifugal
f	Fuel
R	Radial
S	Static
T	Total

1.0 SUMMARY

The Energy Efficient Engine (E^3) Project is being conducted as part of the NASA Aircraft Energy Efficiency (ACEE) Program. An objective of this project is to develop the technology base for a new generation of fuel-efficient propulsion systems for future subsonic commercial-transport aircraft.

This report contains supplemental results of the preliminary analysis and design of an advanced Flight Propulsion System (FPS) done by the General Electric Company and reported in Reference 1. The advanced FPS would be more fuel efficient than current commercial turbofans while, at the same time, being more attractive economically and environmentally. This preliminary analysis and design was performed to more fully define and verify the system characteristics of an FPS that could be introduced into commercial service in the late 1980's to early 1990's. Preliminary analysis and design also established the technology needs and provided the basis for the design of component development hardware and the integration effort to follow in the E^3 project.

In this report and Reference 1, all aspects of the FPS are addressed including component design, engine system integration (including nacelle) and aircraft integration results. Results of the FPS preliminary design indicate that all of the NASA E^3 Project goals, with the possible exception of the emission goal for nitrous oxides (NO_x), should be met or exceeded.

The following is a comparison of the original NASA E^3 goals with the current FPS status.

FPS Characteristic	NASA Goal	FPS Status
• Installed Specific Fuel Consumption (sfc)	Minimum 12% Reduction from CF6-50C*	14.2% Reduction
• Direct Operating Cost (DOC)	Minimum 5% Reduction from CF6-50C on Equivalent Aircraft	5 to 11.6% Reduction Depending on Mission and Aircraft
• Noise	Meet FAR36 (1978) Provision for Growth	Meets with Margin
• Emissions	Meet EPA Proposed 1981 Standards	Meets with Margin Except for NO_x
• Performance Retention	Minimum 50% Reduction from CF6-50C Levels	Projected to Meet

An illustration of the installed FPS is given in Figure 1.

*Measured at maximum cruise thrust at M = 0.8, 10,668 m (35,000 ft).

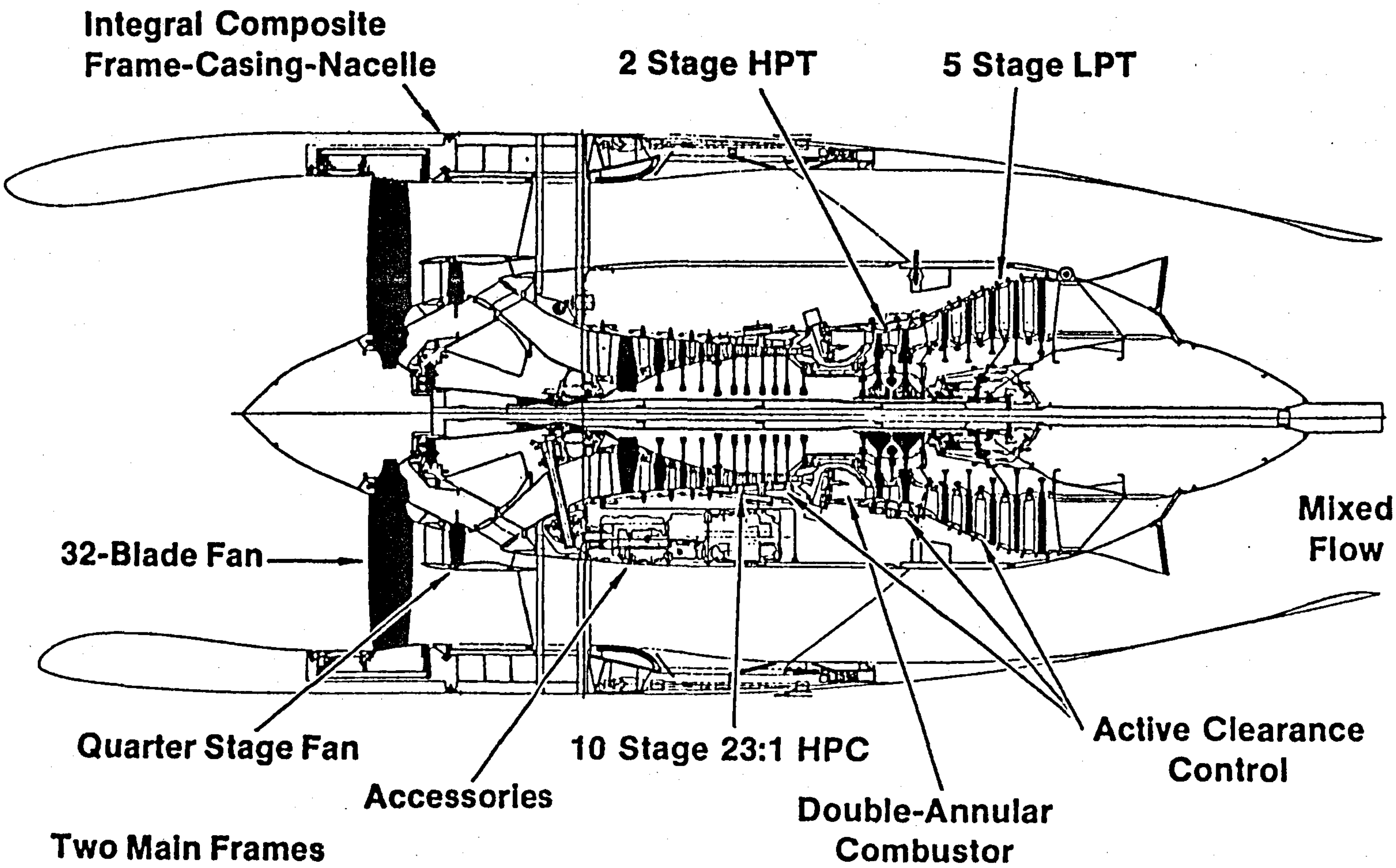


Figure 1. FPS Features.

The FPS incorporates a long-duct nacelle composed primarily of advanced composite construction with extensive use of acoustic absorbers on the inner surface. The wide-chord, titanium, 32-blade fan features a lowered midspan shroud and low tip speed to enhance efficiency and reduce noise. A quarter-stage booster provides additional core supercharging and centrifuges foreign objects from the core air to help prevent foreign object damage (FOD). A moderately loaded, five-stage, low pressure turbine (LPT) drives the fan and booster. Selective aerodynamic loading and stage blade number are used to reduce LPT noise. A mixer is used to mix the hot core-exhaust gas with the cooler fan air to improve the sfc of the engine and reduce exhaust noise. The mixer also spoils core thrust in the reverse mode - allowing the weight and cost of a core reverser to be eliminated from the installed FPS.

An active clearance-control system is employed on the aft portion of the High Pressure Compressor (HPC), the High Pressure Turbine (HPT), and the LPT. Active clearance control enables minimum clearances to be maintained and permits larger clearances during transients when current engines would ordinarily experience performance-deteriorating tip wear.

A 10-stage, highly loaded HPC is driven by a 2-stage turbine. The compressor produces a 23:1 pressure ratio at the maximum-climb-power design point. The combustor is a double-annular configuration, with two combustion zones, designed to reduce pollutant emissions at all power settings. A shingled liner design is utilized in the combustor for longer life and reduced maintenance cost. Accessories are driven by a core-mounted accessory gearbox. Core mounting reduces nacelle frontal area and consequent aerodynamic drag. Two main frames with special mounting designs are utilized to minimize engine casing distortion and consequent blade-tip and seal wear.

Some of the cycle/performance characteristics of the E^3 are given below:

Overall Pressure Ratio, Max. Climb	38
Bypass Ratio, Max. Climb	6.8
Fan Pressure Ratio, Max. Climb	1.65
Turbine Inlet Temperature, ° C (° F)	
Takeoff, 30° C (86° F) Day	1343 (2450)
Altitude, Max. Cruise, Std. Day	1188 (2170)
Max. Cruise sfc, Std. Day, kg/N-hr (lbm/lbf-hr)	
Uninstalled	0.0553 (0.542)
Installed	0.0583 (0.571)
Max. Cruise Δsfc (Relative to CF6-50C), % (Isolated Installed Nacelle Drag)	-14.2

In the design size, the following system characteristics have been estimated for the E^3:

Takeoff Thrust, kN (lbf)	162.36 (36,500)
Weight, kg (lbm)	
Uninstalled Engine	3,288 (7,250)
Installed Engine	4,082 (9,000)
Cost, K$ (1977 Dollars)	
Uninstalled Engine	1,955
Installed Engine	2,533
Maintenance Cost, $/Flight-Hour (1977 Dollars) Bare Engine and Thrust Reverser	66.25

These results were supplied to three aircraft company subcontractors (The Boeing Company, McDonnell Douglas Corporation, and the Lockheed-California Company) for use in the aircraft-integration portion of the study. Each subcontractor evaluated the projected FPS installed on appropriate advanced-transport designs and compared the results against a properly scaled CF6-50C installed on a transport of the same advanced technology. The results project block fuel savings of from 15 to 23% and reductions in Direct Operating Costs (DOC) of from 5 to 12% depending upon the aircraft and mission studied. These results clearly indicate that the major goals set by NASA for the Energy Efficient Engine should be met with this configuration.

2.0 INTRODUCTION

The NASA Energy Efficient Engine (E^3) Component Development and Integration Project under Contract NAS3-20643 with the General Electric Company was initiated January 2, 1978. The initial-study concepts for the current engine program were largely derived from a previous NASA-sponsored study (NAS3-20627) "E^3 Preliminary Design and Integration Studies" (Reference 2). In addition, several of the advanced material, cycle, and configuration concepts came from other earlier NASA-sponsored studies (References 3, 4, 5, and 6).

The objective of the E^3 program is the development of technology to improve the energy efficiency of propulsion systems for subsonic, commercial aircraft of the late 1980's and early 1990's. The need for the development of more fuel-efficient engines has become apparent in view of the expected continuing shortage of petroleum-based fuels. The E^3 Project is a major element of the NASA Aircraft Energy Efficiency (ACEE) Program.

The following technical goals were established for the fully developed FPS by NASA:

- Fuel Consumption - Minimum 12% reduction is installed sfc compared to a CF6-50C at maximum cruise thrust, M = 0.8 at 10,668 m (35,000 ft) altitude on a standard day.
- Noise - Comply with FAR36 (1978) with provisions for growth.
- Emissions - Comply with EPA (1981) Standards for new engines.
- Performance Retention - A 50% reduction in the rate of performance deterioration in service as compared to the CF6-50C.

To meet and demonstrate the NASA Aircraft Project goals, the E^3 Project has four major technical tasks structured as follows: Task 1 addresses the design and evaluation of the E^3 Flight Propulsion System (FPS); this is the propulsion system designed to meet the requirements for commercial service and includes a flight nacelle. The Task 1 results establish the requirements for the experimental test hardware including the components, core, and integrated core/low-spool. Task 2 consists of the design, fabrication, and testing of the components and includes supporting technology efforts. These supporting technology efforts are performed where required to provide verification of advanced concepts included in the propulsion system design. In addition, more advanced technologies, not specifically included in the propulsion system design (but which provide the potential for further performance improvements), are also explored. Task 3 involves the design, fabrication, and test evaluation of a core engine consisting of the compressor, combustor, and high pressure turbine. Integration of the core with the low-spool components and test evaluation of the integrated core/low spool (ICLS) comprise Task 4. At the conclusion of the program, the latest performance of the experimental hardware (integrated core/low-spool and parallel core and component efforts) will be factored into a final propulsion system/aircraft evaluation (as part of continual ongoing evaluations in Task 1) to determine achievable performance as compared to the program goals.

This report is a supplement to the Preliminary Analysis and Design (PAD) Report (Reference 1). It contains system and component design details of the FPS that were not included in the PAD report because they have been judged to have significant early commercial potential and as such are reported in accordance with "For Early Domestic Dissemination (FEDD) Category 2 Data" provisions.

This report is comprised of excerpts, from the PAD report, to which FEDD Category 2 information has been added. As such, it should be used in conjunction with the PAD report.

Data in this report are arranged for convenient use in conjunction with the PAD report. Sequencing and section numbering of the material are identical, and cross references are provided to facilitate easy location of the corresponding material in the main report.

3.0 FLIGHT PROPULSION SYSTEM PRELIMINARY DESIGN AND PERFORMANCE

3.1 FLIGHT PROPULSION SYSTEM (FPS) DESIGN (Reference Page 7, PAD Report)

For the purpose of comparison, the FPS design and an installed CF6-50C were used for this preliminary design study. Figure 2 is an over/under cross section of an FPS and CF6-50C scaled to the same altitude-maximum-climb installed thrust.

During the FPS preliminary design, some changes in the initial study FPS cooling flows were made. Table 1 illustrates how the cooling flows, sinks, and sources changed. The overall total of cooling flows increased by only 0.4% of W_{25}, however.

Another aspect of the preliminary design was the assessment of compression compatibility. Stall margins for four important operating points of the fan and core compressor are shown in Table 2. In all cases, available stall margin is more than adequate.

3.2 CYCLE AND PERFORMANCE (Refernece Page 42, PAD Report)

The E^3 cycle parameters are shown in Table 3 for the three key rating points of maximum climb, maximum cruise, and sea level static takeoff. The climb and cruise points are defined at 10,668 m (35,000 ft), Mach 0.8 flight conditions. The cycle design point (for component matching) is at the maximum-climb flight condition at an uninstalled thrust level of 40.211 kN (9040 lbf) as established for the initial-study cycle.

As part of the FPS cycle studies, thrust growth paths were explored. Thrust growth levels of +5%, +10%, and +20% were evaluated and are summarized in Table 4.

3.3 PERFORMANCE RETENTION (Reference Page 52, PAD Report)

No FEDD-2 data were generated for this section.

3.4 MATERIALS AND PROCESSES (Reference Page 56, PAD Report)

No FEDD-2 data were generated for this section.

3.5 ACOUSTICS (Reference Page 69, PAD Report)

No FEDD-2 data were generated for this section.

3.6 PROPULSION-SYSTEM/AIRCRAFT INTEGRATION (Reference Page 79, PAD Report)

No FEDD-2 data were generated for this section.

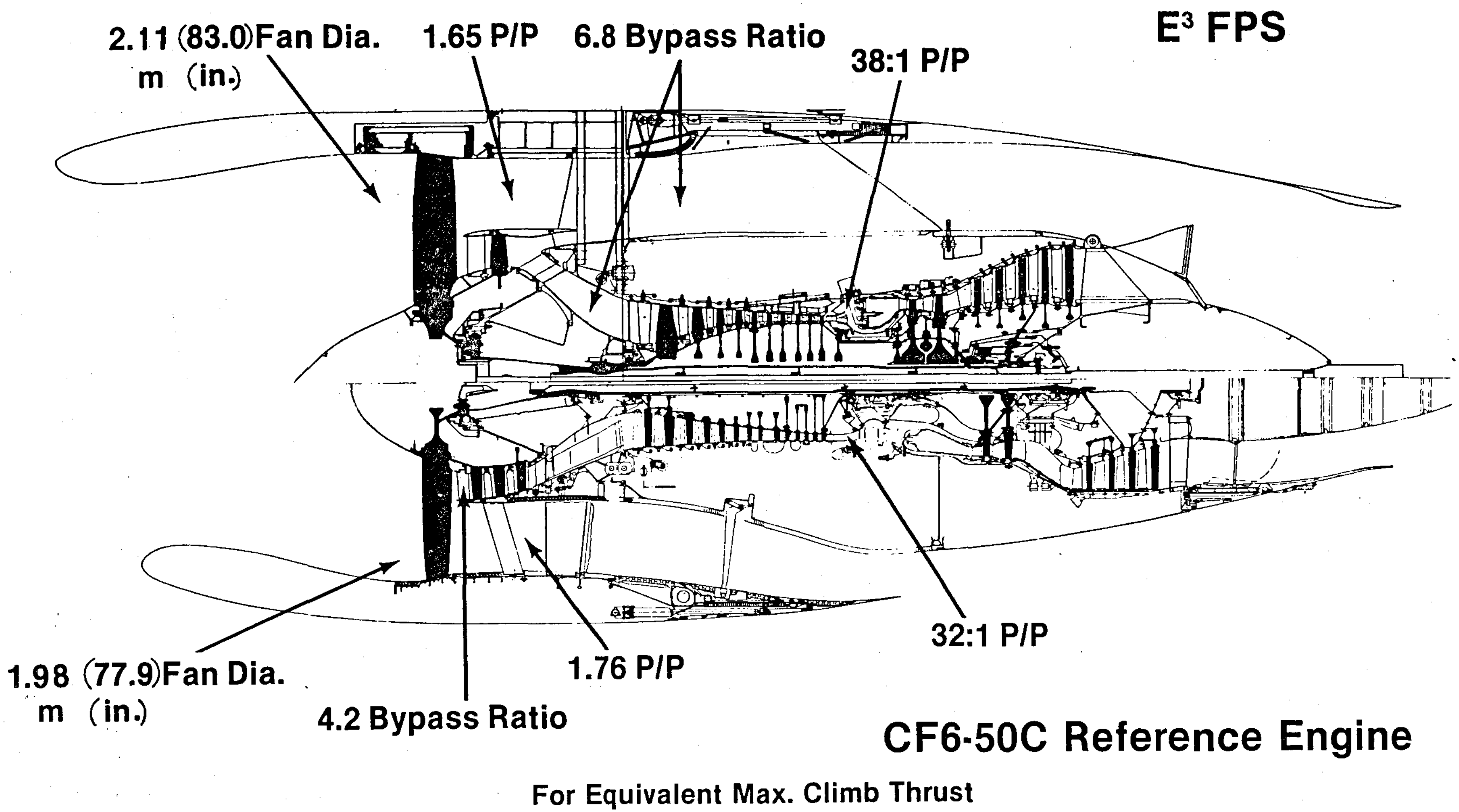


Figure 2. Engine Cycle Comparison - Maximum Climb.

(Reference Figure 4, page 13, PAD Report)

Table 1. Revised Cooling Flows.

Initial-Study FPS			Current FPS		
Source	%W25	Sink	Source	%W25	Sink
Stage 2	0.50	Sump Purge	Compressor Inlet	0.75	Sump and HP Rotor Purge
Leakage	0.20	Fan Duct	Compressor Inlet	0.30	LPT Case
Stage 6	0.75	LPT Rotor Cavity	Stage 5	0.40	Stage 2 HPT Rotor
Stage 6	1.25	Stage 2 HPT Rotor	Stage 5	0.90	LPT Rotor Cavity
Stage 7	2.30	Stage 2 HPT Vane	Stage 7	2.0	Stage 2 HPT Vane
CDP	15.1	Stage 1 HPT	CDP	16.15	Stage 1 HPT
Total	20.1		Total	20.5	

Table 2. Preliminary Stability Assessment.
(Reference Table 5, Page 25, PAD Report)

Component	SLS Ground Idle	SLS Takeoff	0.8/0.7 km (35,000 ft) Max. Climb	0.8/10.7 km (35,000 ft) Max. Cruise
Fan				
Margin Available, %	3.5	15.8	15.5	16.6
Required	1.3 ± 0.3	11.3 ± 1.3	2.7 ± 1.3	2.7 ± 1.3
Margin Remaining	2.2 ± 0.3	4.5 ± 1.3	12.8 ± 1.3	13.9 ± 1.3
HPC				
Margin Available, %	34.4	29.2	25.2	27.2
Required	23.5 ± 0.5	19.5 ± 3.1	19.0 ± 3.0	19.3 ± 3.0
Margin Remaining	10.9 ± 0.5	9.7 ± 3.1	6.2 ± 3.0	7.9 ± 3.0

Table 3. E^3 FPS Cycle Definition.
(Reference Table 12, Page 49, PAD Report)

Parameter	Max. Climb*	Max. Cruise	Takeoff
Uninstalled Net Thrust, kN (lbf)	40.211 (9040)	37.476 (8425)	162.36 (36500)
Uninstalled sfc (Std. Day), kg/N-hr (lbm/lbf-hr)	0.0557 (0.546)	0.0553 (0.542)	0.0300 (0.294)
Overall Pressure Ratio	37.7	36.1	29.7
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	1.51
Fan rpm (Physical)	3538	3436	3404
Compressor Pressure Ratio	23.0	22.6	20.0
Core rpm (Physical)	12645	12520	13152
Corrected Compressor Flow, kg/sec (lbm/sec)	54.43 (120.0)	53.6 (118.3)	49.32 (108.5)
HPT Rotor Inlet Temperature,** ° C (° F)	1282 (2340)	1244 (2272)	1343 (2450)

*Cycle Match Point
**Temperature at the ambient flat-rating temperature

4.0 COMPONENT PRELIMINARY ANALYSIS AND DESIGN
(Reference Page 99, PAD Report)

4.1 FAN (Reference Page 99, PAD Report)

Alternate configurations were evaluated as part of the preliminary study of the FPS fan. The initial fan characteristics are shown in Figure 3. Alternate configurations that were evaluated are shown in Figures 4 through 8. System design effects were determined; as a result, the 32-blade fan shown in Figure 6 was chosen for the current FPS. Estimated system benefits resulting from this fan configuration were a decrease in DOC of 0.06% and a fuel-burned advantage of 0.33% as compared to the initial 38-blade fan. The new fan was also estimated to cost $4,000 less but to weigh 45.4 kg (100 lbm) more.

The FPS fan has an inlet diameter of 2.11 m (83 in.) and an inlet radius ratio of 0.342. At the aerodynamic design point for the maximum-climb condition, 10,668 m (35,000 ft), Mach 0.8, a corrected fan tip speed of 411 m/sec (1350 ft/sec) and a specific flow of 209 kg/sec-m^2 (42.8 lbm/sec-ft^2) has been employed.

The following tabulation presents fan design parameters for the altitude maximum climb, maximum cruise, and sea level takeoff conditions.

Parameter	Max. Climb	Max. Cruise	Takeoff
Corrected Speed,%	100	97.1	88.7
Corrected Flow kg/sec (lbm/sec)	643.7 (1419)	643.1 (1398)	577.9 (1274)
Bypass Stream			
Adiabatic Efficiency	0.879	0.887	0.900
Polytropic Efficiency	0.887	0.894	0.905
Pressure Ratio	1.65	1.61	1.50
Core Stream			
Adiabatic Efficiency	0.885	0.892	0.897
Polytropic Efficiency	0.893	0.899	0.903
Pressure Ratio	1.67	1.63	1.51
Bypass Ratio	6.8	6.9	7.3

A preliminary fan operating map is shown in Figure 9 as a function of percent corrected flow. Campbell diagrams of the fan and quarter-stage blading are shown in Figures 10 and 11. No likely resonances are indicated by the preliminary vibration analysis shown here.

4.2 COMPRESSOR (Reference Page 112, PAD Report)

FPS core compressor design features favoring high efficiency include:

Table 4. E^3 Growth Capability.
(Reference Table 15, Page 53, PAD Report)

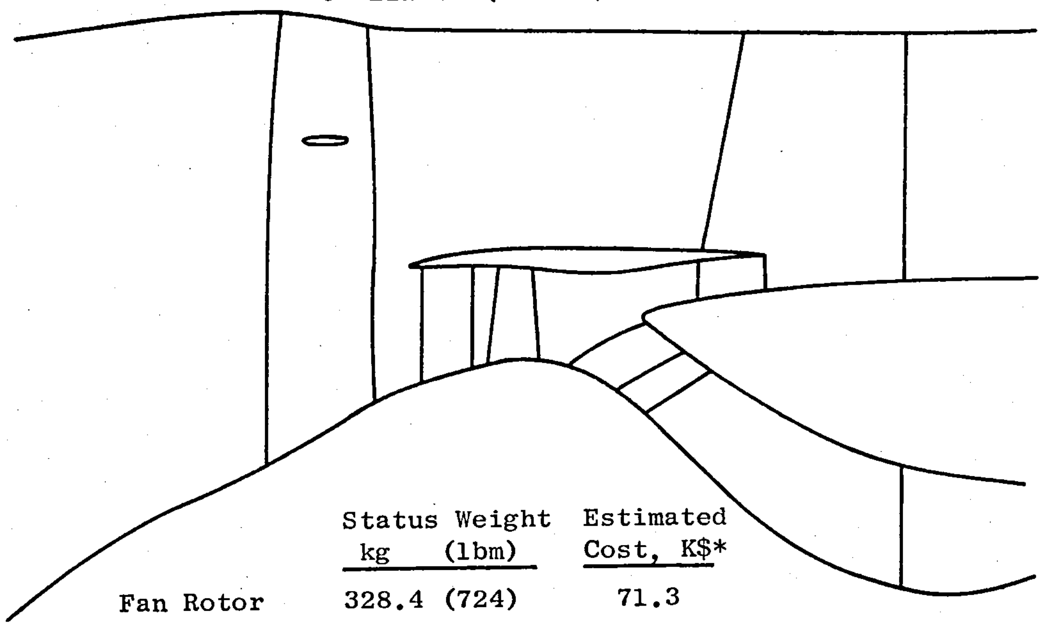
Max. Climb - 10,668 m (35,000 ft)/0.80 M

Parameter	FPS	Throttle Push +5%	+5%	+10%	+20%
Net Thrust, kN (lbf)	40.211 (9040)	42.213 (9490)	42.213 (9490)	44.215 (9940)	48.263 (10850)
Uninstalled sfc (Std Day) kg/N/hr (lbm/lbf/hr)	0.0556 (0.546)	0.0564 (0.553)	0.0562 (0.551)	0.0570 (0.559)	0.0577 (0.566)
Overall Pressure Ratio	37.7	39.0	42.3	42.7	45.0
Bypass Ratio	6.8	6.7	6.1	6.1	5.4
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)

Parameter	FPS	Throttle Push +5%	+5%	+10%	+20%
Net Thrust, kN (lbf)	162.36 (36500)	170.50 (38330)	170.50 (38330)	178.60 (40150)	194.83 (43800)
HPT Rotor Inlet Temp., ° C (° F)	1343 (2450)	1367 (2493)	1353 (2467)	1394 (2541)	1443 (2630)

- 38 Blades
- 70% Span Shroud
- Booster
- 0.35 Radius Ratio
- 88.2% Bypass Efficiency
- 89.2% Core Efficiency
- 411.5 m/sec (1350 ft/sec) Fan Tip Speed
- 211 cm (83 in.) Fan Diameter



	Status Weight kg (lbm)	Estimated Cost, K$*
Fan Rotor	328.4 (724)	71.3
Booster	72.1 (159)	18.0
Containment	109.8 (242)	5.7

*Based on 250th initial-study engine cost, 1977 $.

Figure 3. E^3 Initial Fan - Baseline.
(Reference Figure 54, page 105, PAD Report)

- 70% Span Shroud
- 0.3996 Radius Ratio
- 426.7 m/sec (1400 ft/sec) Tip Speed
- 214 cm (84.2 in.) Fan Diameter

Change From Baseline

-0.4% Bypass Efficiency

-4.5% Core Efficiency

+0.1% LPT Efficiency

+3 cm (1.2 in.) Fan Diameter

-$18K 250th Engine Cost

-34 kg (75 lb) Weight

+0.69 Sfc

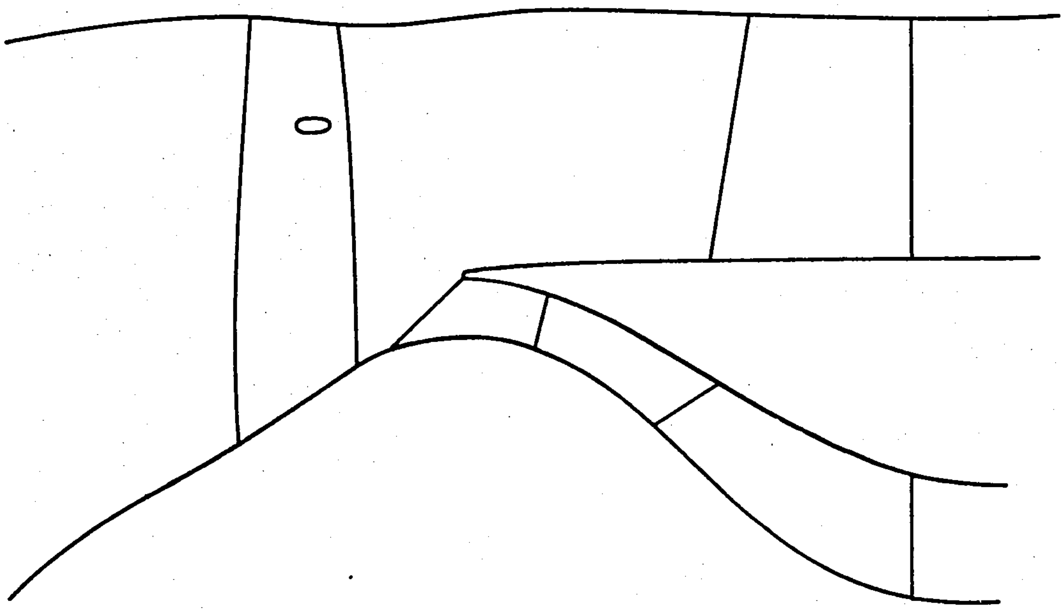


Figure 4. Thirty-Eight-Blade Design - No Booster.

(Reference Figure 55, page 106, PAD Report)

- No Shroud
- No Booster
- 0.42 Radius Ratio
- 408.4 m/sec (1340 ft/sec) Tip Speed
- 2.8 cm (85.7 in.) Fan Diameter

Single Blade Cost

Solid ≈ \$1500

Hollow ≈ \$3000

(1978 \$'s/250th Engine)

Change From Baseline

+1.3% Bypass Efficiency

-3.6% Core Efficiency

-0.4% LPT Efficiency

+7 cm (2.7 in.) Fan Diameter

Cost (250th Engine): -\$28K (Solid Blades)
+\$14K (Hollow Blades)

Weight: +67.1 kg (148 lb) (Solid Blades)
≈0 (Hollow Blades)

-0.17 Sfc

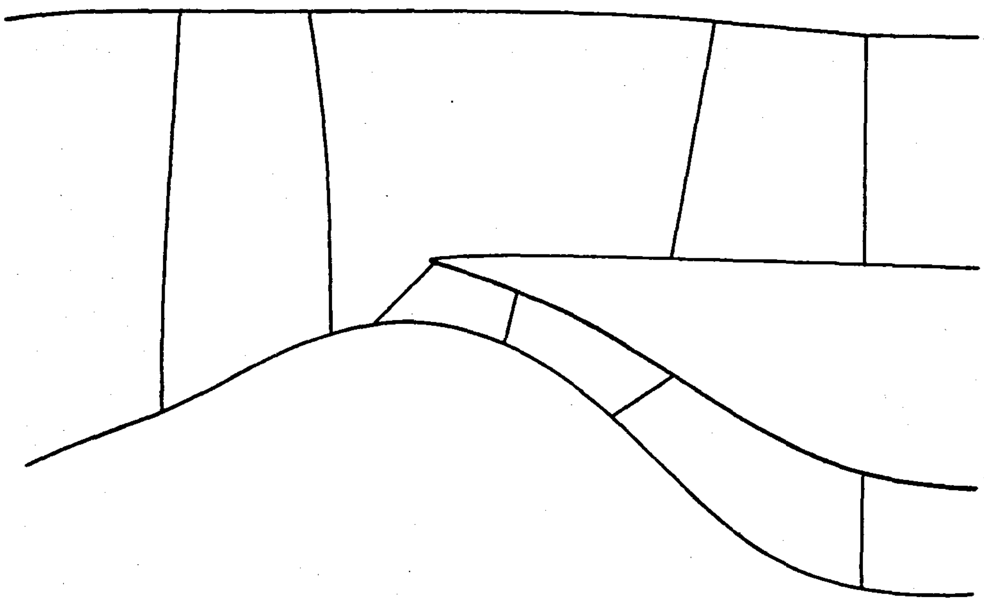


Figure 5. Twenty-Eight-Blade Design - Pin Root.
(Reference Figure 56, page 107, PAD Report)

- 50% Span Shroud
- 0.40 Radius Ratio
- 420.6 m/sec (138 ft/sec) Tip Speed
- 216 cm (84.9 in.) Fan Diameter

Change from Baseline

+0.2% Bypass Efficiency

-4.0% Core Efficiency

0% LPT Efficiency

+5 cm (1.9 in.) Fan Diameter

-$22K 250th Engine Cost

+51.3 kg (113 lb) Weight

+0.31 Sfc

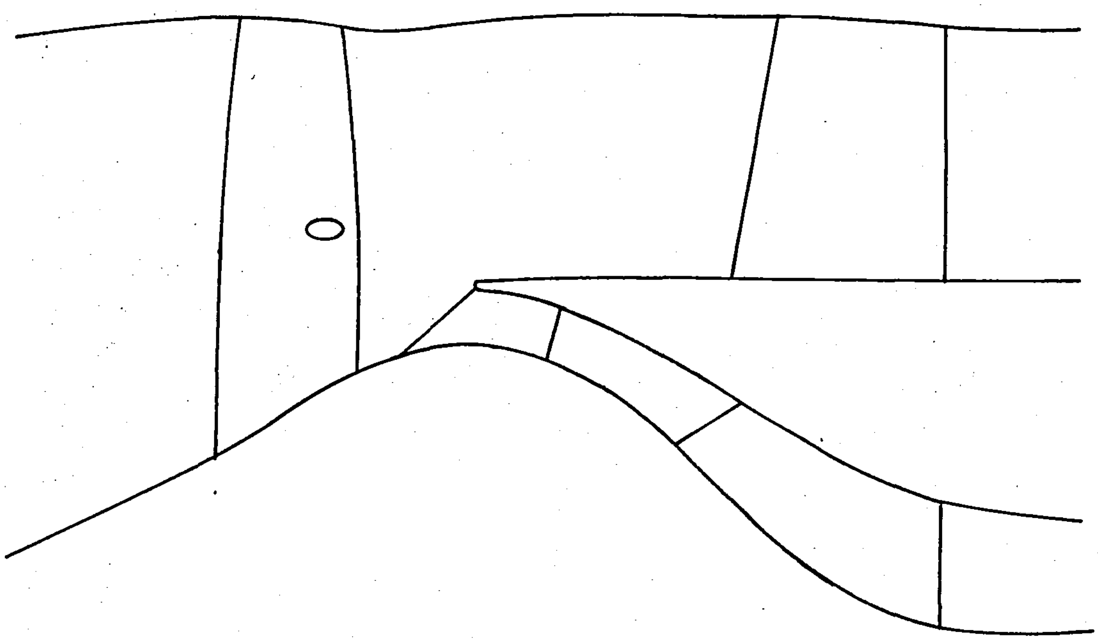


Figure 6. Thirty-Two-Blade Design - No Booster.
(Reference Figure 57, Page 108, PAD Report)

- 0.31 Radius Ratio
- Hollow Airfoils
- 411.5 m/sec (1350 ft/sec) Tip Speed
- 208 cm (81.9 in.) Fan Diameter

Change From Baseline

+0.8% Bypass Efficiency

+0.3% Core Efficiency

+0.1% LPT Efficiency

-3 cm (1.1 in.) Fan Diameter

+$23K 250th Engine Cost

+133.4 kg (294 lb) Weight

-0.62 Sfc

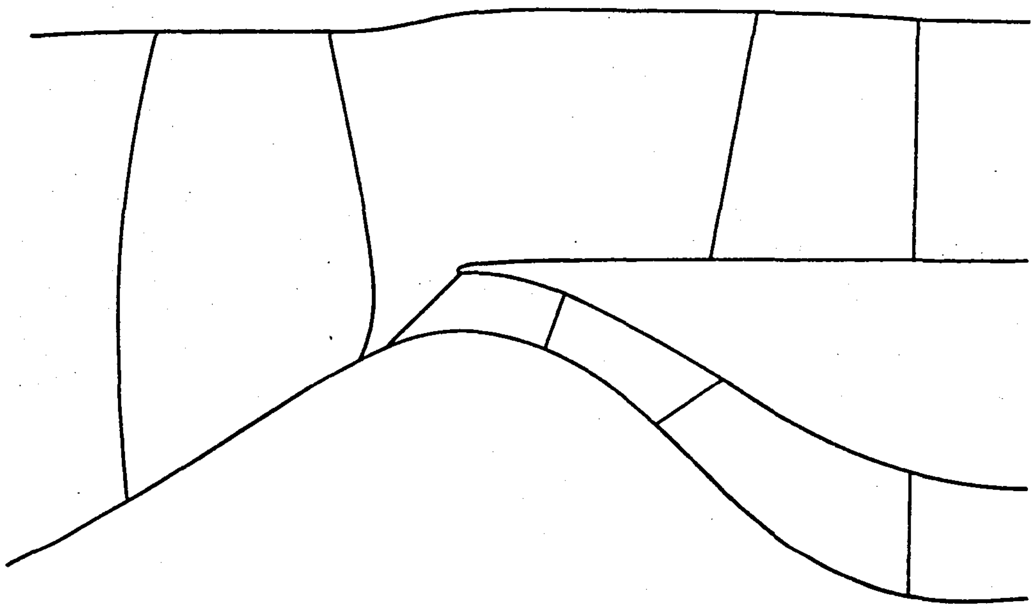


Figure 7. Twenty-Blade Design - No Shroud or Booster.
(Reference Figure 58, page 109, PAD Report)

- 50% Span Shroud
- 0.35 Radius Ratio
- 411.5 m/sec (1350 ft/sec) Tip Speed
- 211 cm (83 in.) Fan Diameter

Change From Baseline

+0.5% Bypass Efficiency

0% Core Efficiency

0% LPT Efficiency

0 cm Fan Diameter

Cost (250th Engine): -$4K (+$43K, Hollow Outer Panel)

Weight: +45.4 kg (100 lb) [-1.4 kg (3 lb), Hollow Outer Panel]

-0.33 Sfc

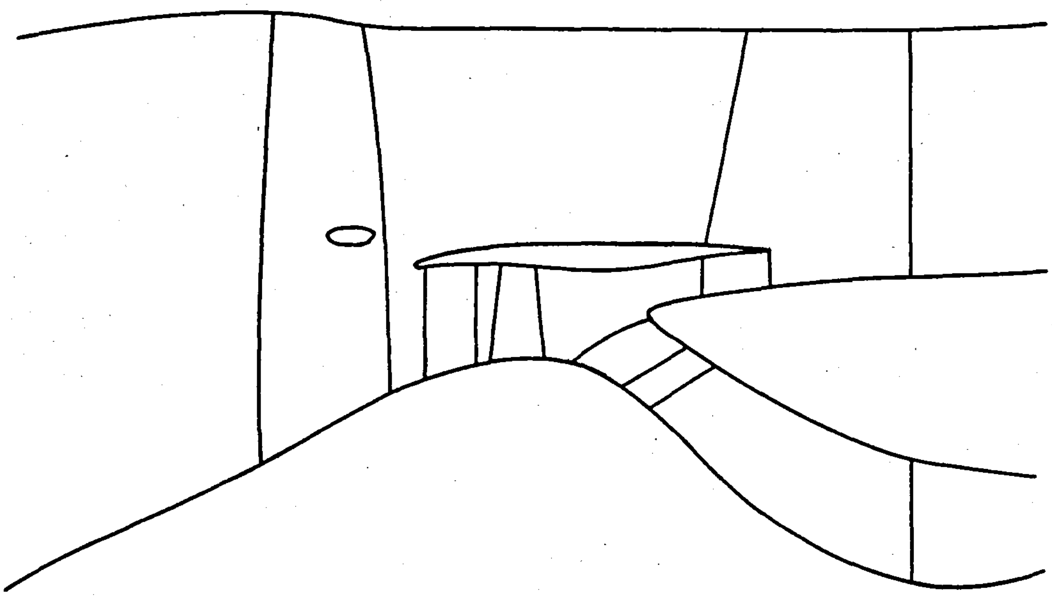


Figure 8. Thirty-Two-Blade Design - With Booster.
(Reference Figure 59, page 110, PAD Report)

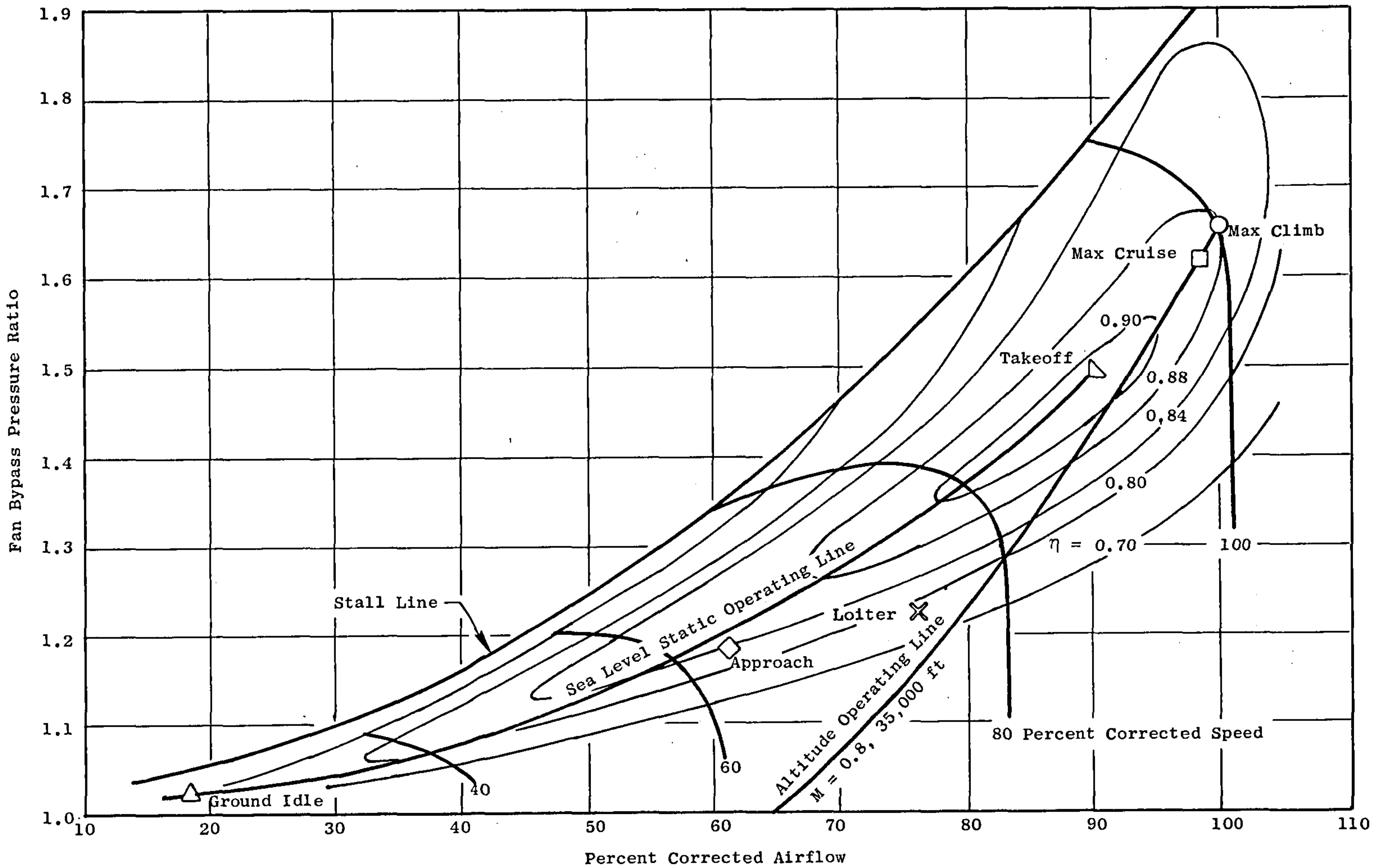


Figure 9. Preliminary Fan Operating Map.
(Reference Figure 51, Page 100, PAD Report)

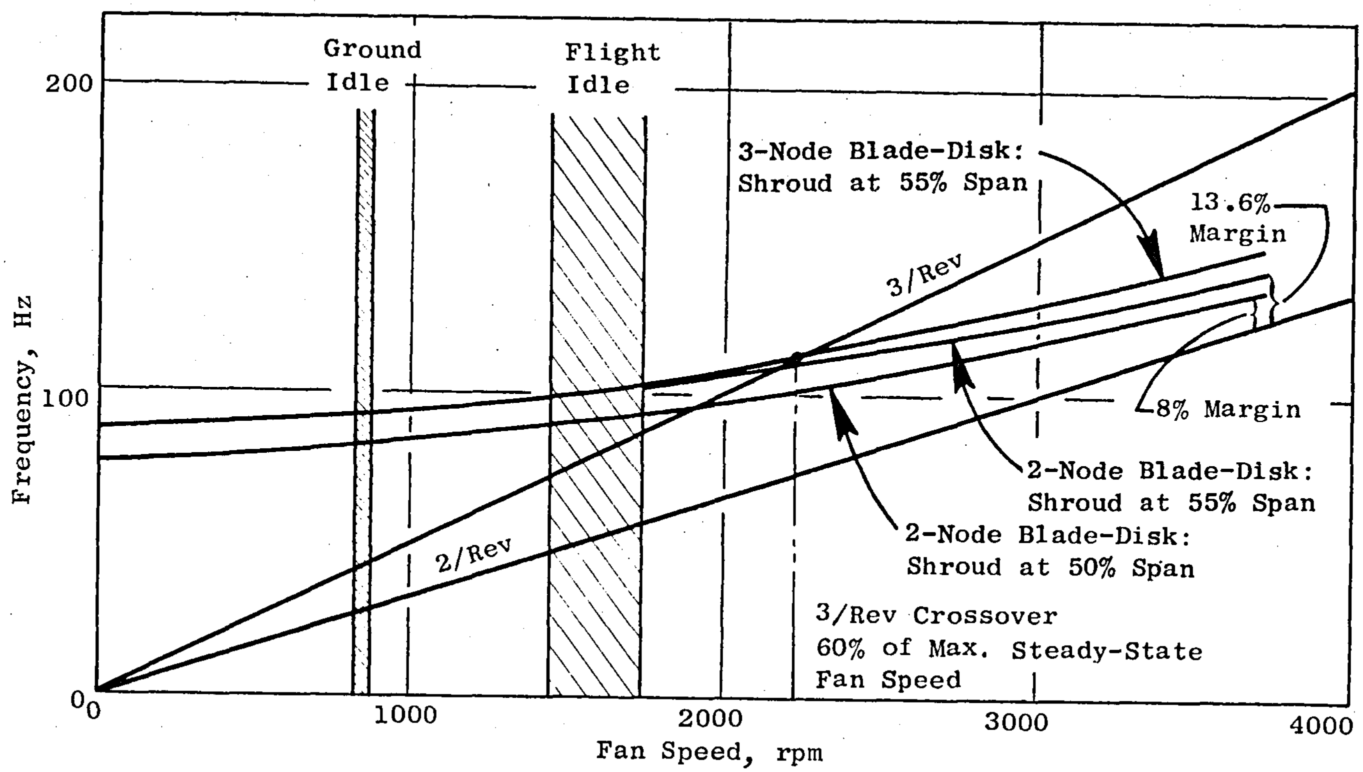


Figure 10. E^3 32-Blade Fan, Preliminary Coupled-Blade-Disk Campbell Diagram. (Reference Figure 60, page 113, PAD Report)

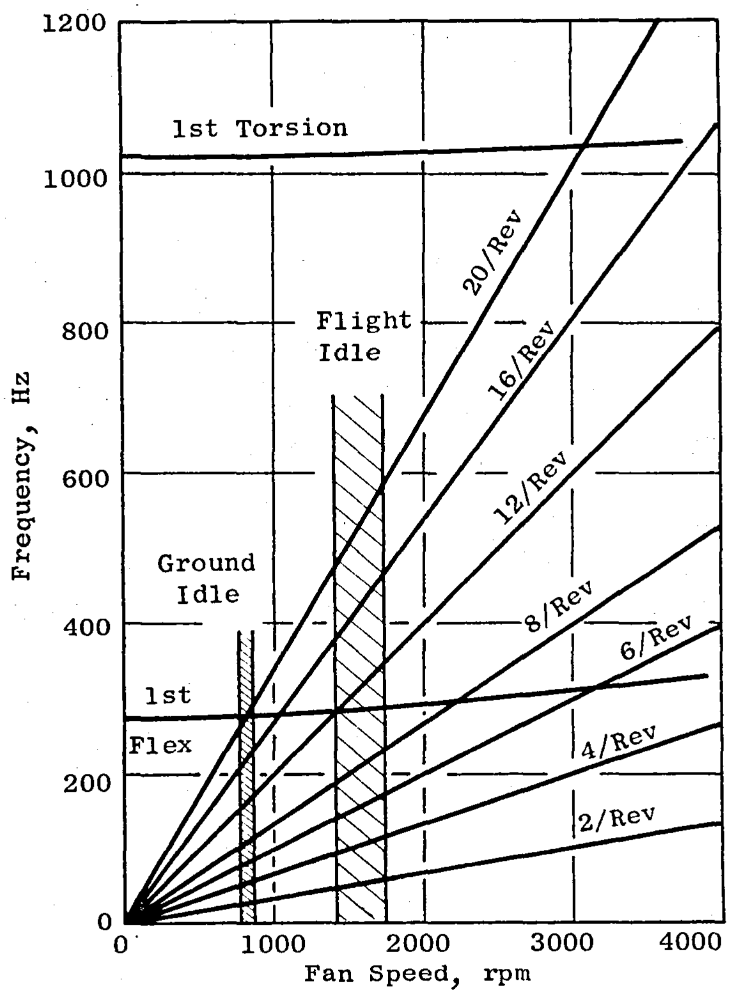


Figure 11. E^3 Quarter-Stage Preliminary Blade Campbell Diagram.

(Reference Figure 61, page 114, PAD Report)

- Low Inlet Radius Ratio: 0.50
- Moderate through-flow Mach number: specific flow is 185.5 kg/sec-m^2 (38 lbm/sec-ft^2), and exit Mach number is 0.30.
- Rotor Cooling for better clearance control accomplished by the use of 0.59% W_{25} flow through the bore regions.

The high inlet corrected tip speed of 453 m/sec (1495 ft/sec) and high exit radius ratio of 0.93 were design features favoring compactness. Compressor rim and tip speeds by stage are shown in Figure 12. Figure 13 presents the blade aspect ratio and radius ratio by stage. A typical blade Campbell diagram is shown in Figure 14 along with the expected mode shapes. No significant resonant conditions are indicated by these results.

The core compressor design (100%) point is at the altitude-maximum-climb condition. Operating parameters at four conditions are given in Table 5. A preliminary compressor operating map is shown in Figure 15 as a function of percent design flow.

4.3 COMBUSTOR (Reference Page 131, PAD Report)

A key advanced feature of the FPS combustion section is the split-duct diffuser shown in Figure 16. By splitting the prediffuser, it is significantly shortened, and more precise direction of air is possible for the double-annular combustor.

As shown in Figure 16, cooler pitch-line air is bled off the aft center portion of the prediffuser. This bleed location not only reduces the amount of air required for core turbine cooling but also essentially eliminates the possibility of entrained dirt entering the blade-cooling system.

4.4 HIGH PRESSURE TURBINE (Reference Page 157, PAD Report)

Cooling of the turbine has been allocated in the most fuel-efficient manner for long design lives. Figure 17 is a schematic of the core turbine cooling circuit and a brief summary of the sources and flow quantities.

Figure 18 shows the cooling flows and cross section of the Stage 2 turbine vane. For the Stage 2 blade, Figure 19 indicates how the trailing-edge cooling-flow discharge was arranged to increase turbine useful work. The effective turbine efficiency was increased by 0.26% resulting in a decrease in FPS sfc of 0.182%.

Table 6 summarizes the materials, cooling, stresses, and numbers of blades and vanes in the core turbine. With the stress and temperature levels shown, the blade and vane will meet life requirements.

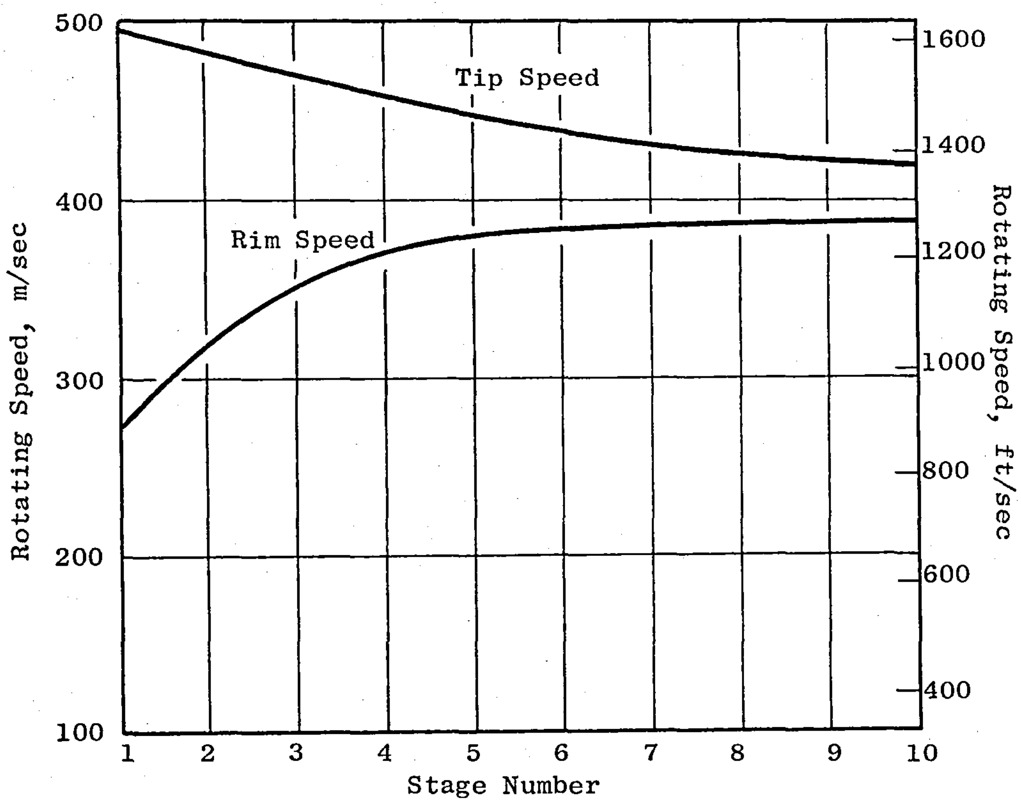


Figure 12. Compressor Tip Speed and Rim Speed.

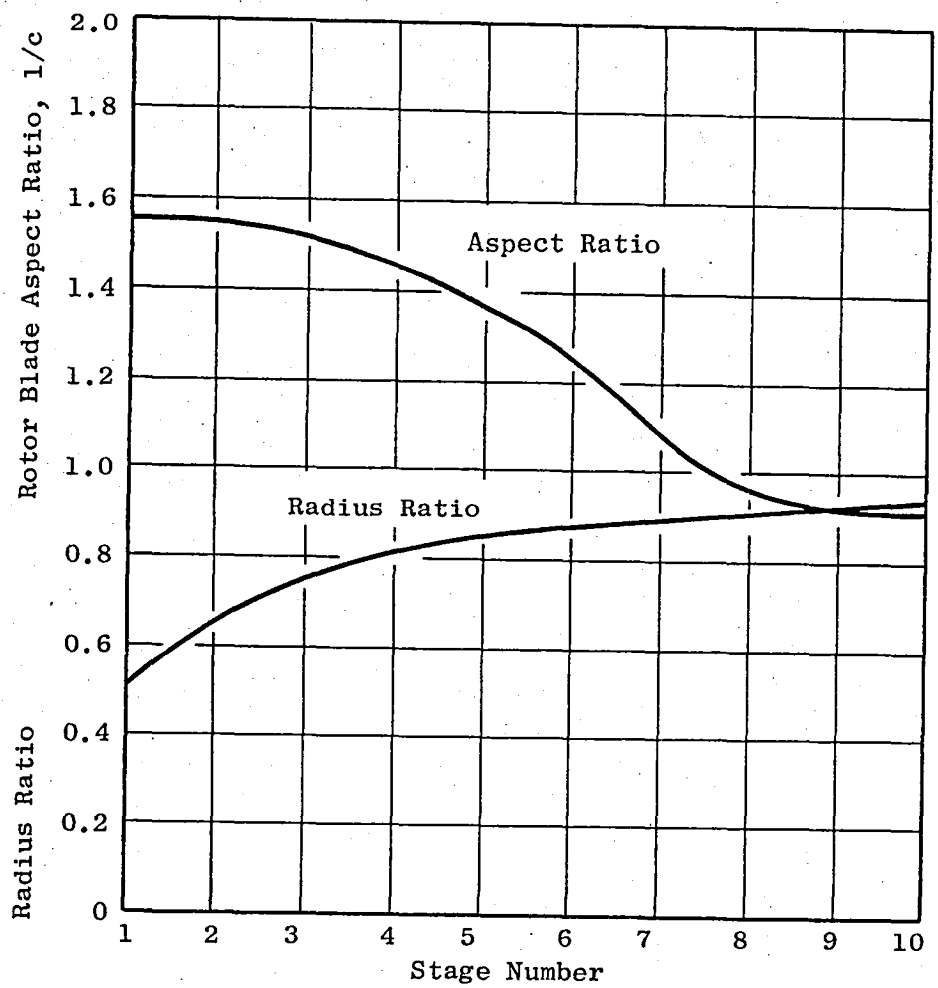


Figure 13. Compressor Rotor Blade Aspect Ratio and Radius Ratio.

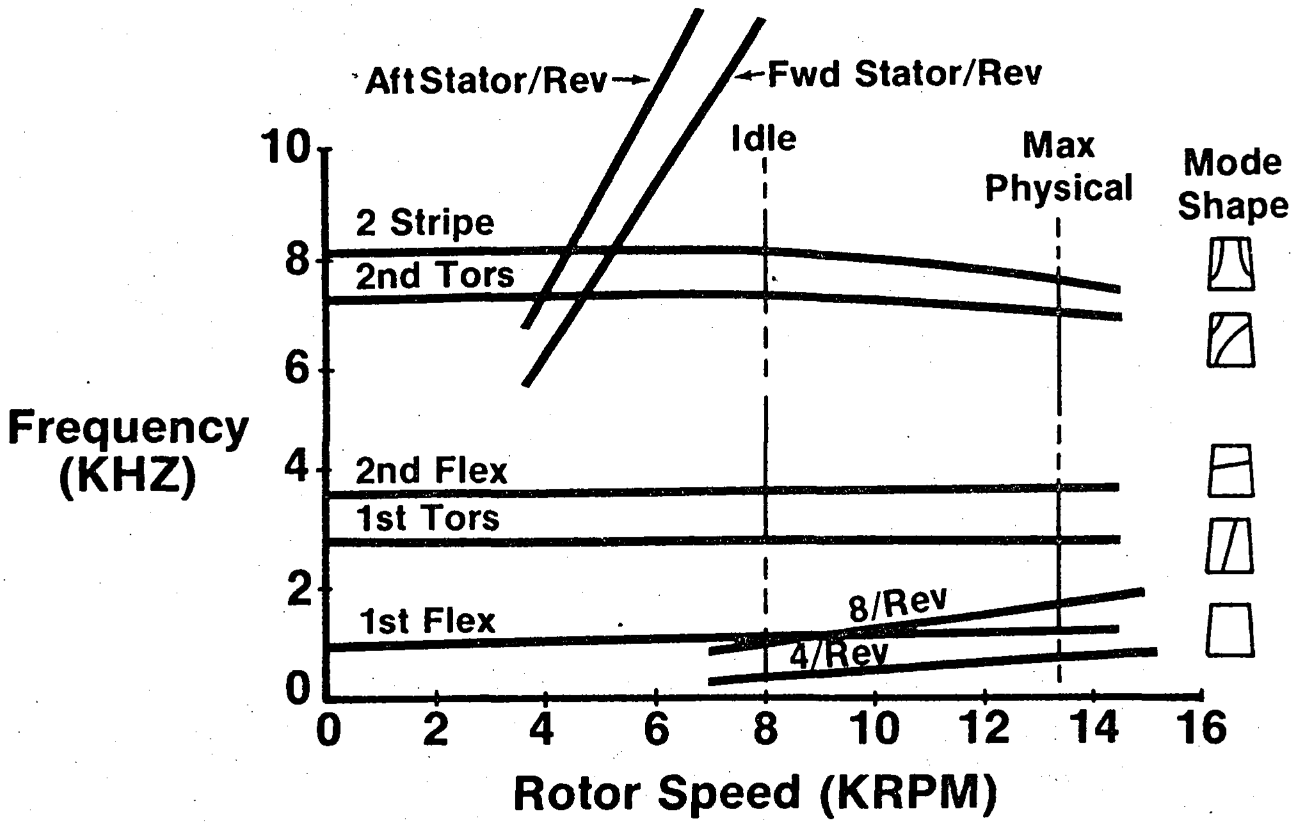


Figure 14. Compressor Rotor Blades; Typical Campbell Diagram. (Reference Figure 68, page 128, PAD Report)

Table 5. Core Compressor Operating Parameters.
(Reference Page 117, PAD Report)

Parameter	Max. Climb	Max. Cruise	Takeoff	Idle
Corrected Speed, % Design	100.0	99.5	97.7	76.8
Total Pressure Ratio	23.0	22.4	20.1	4.2
Inlet Temperature, K (° R)	304 (548)	310 (543)	328 (590)	292 (526)
Inlet Pressure, kPa (psi)	59.6 (8.65)	58.1 (8.42)	105.6 (21.8)	104.8 (15.2)
Corrected Airflow kg/sec (lbm/sec)	54.4 (120.0)	53.5 (118.0)	49.3 (108.7)	12.4 (27.4)
Adiabatic Efficiency	0.857	0.861	0.865	0.712
Polytropic Efficiency	0.903	0.905	0.908	0.763

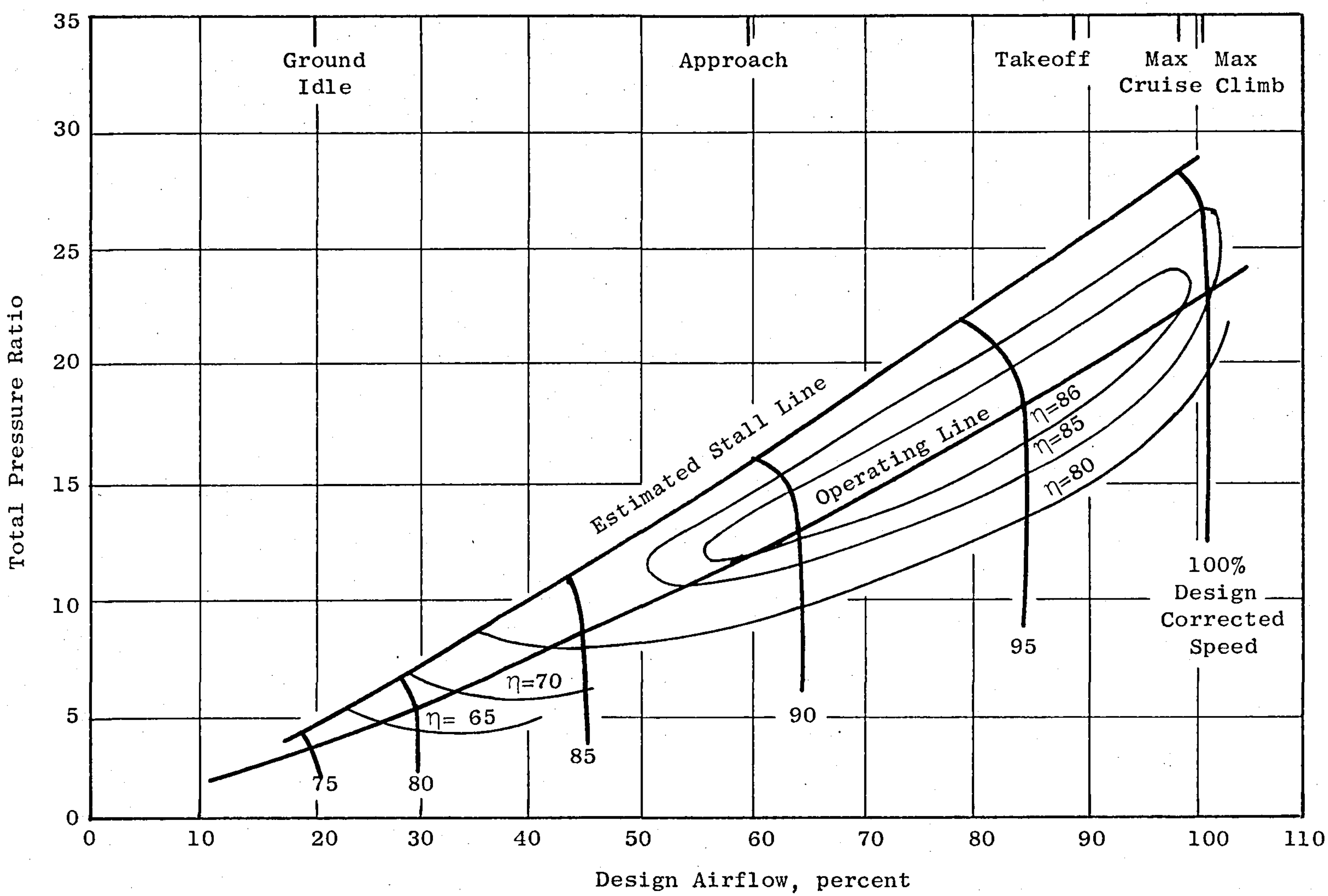


Figure 15. Core Compressor Performance Map Estimated from Stage Characteristics, without Starting Bleed.

(Reference Figure 63, Page 118, PAD Report)

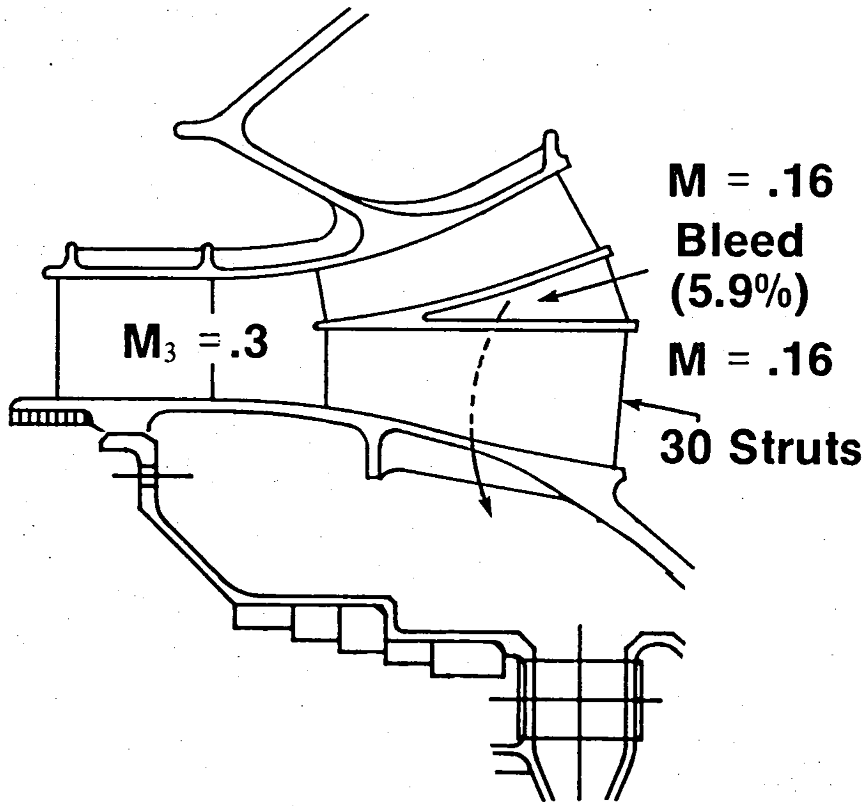


Figure 16. Split Duct Diffuser Design.
(Reference Figure 71, page 132, PAD Report)

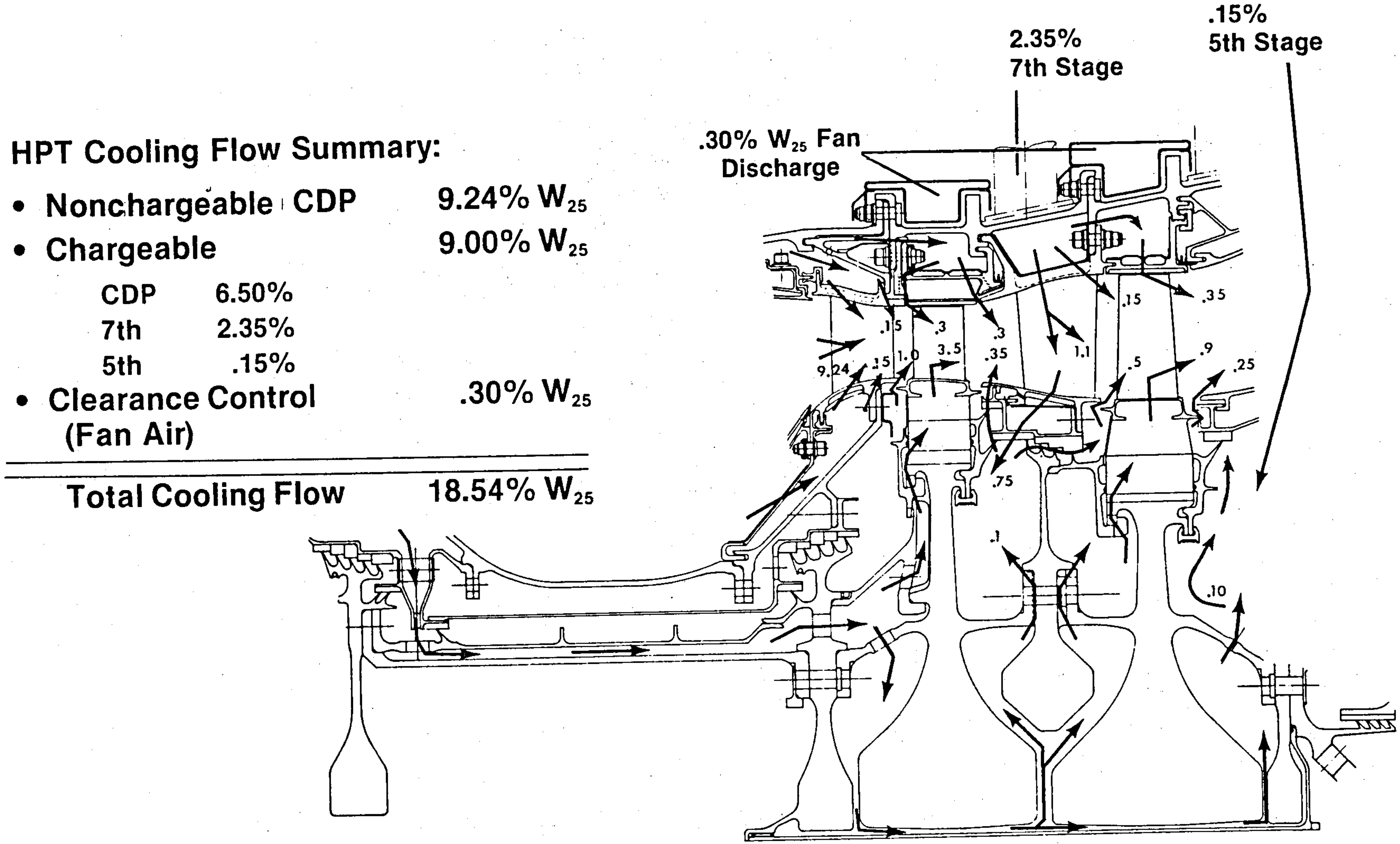


Figure 17. E^3 High Pressure Turbine Cooling Flow Distribution.

(Reference Figure 87, page 164, PAD Report)

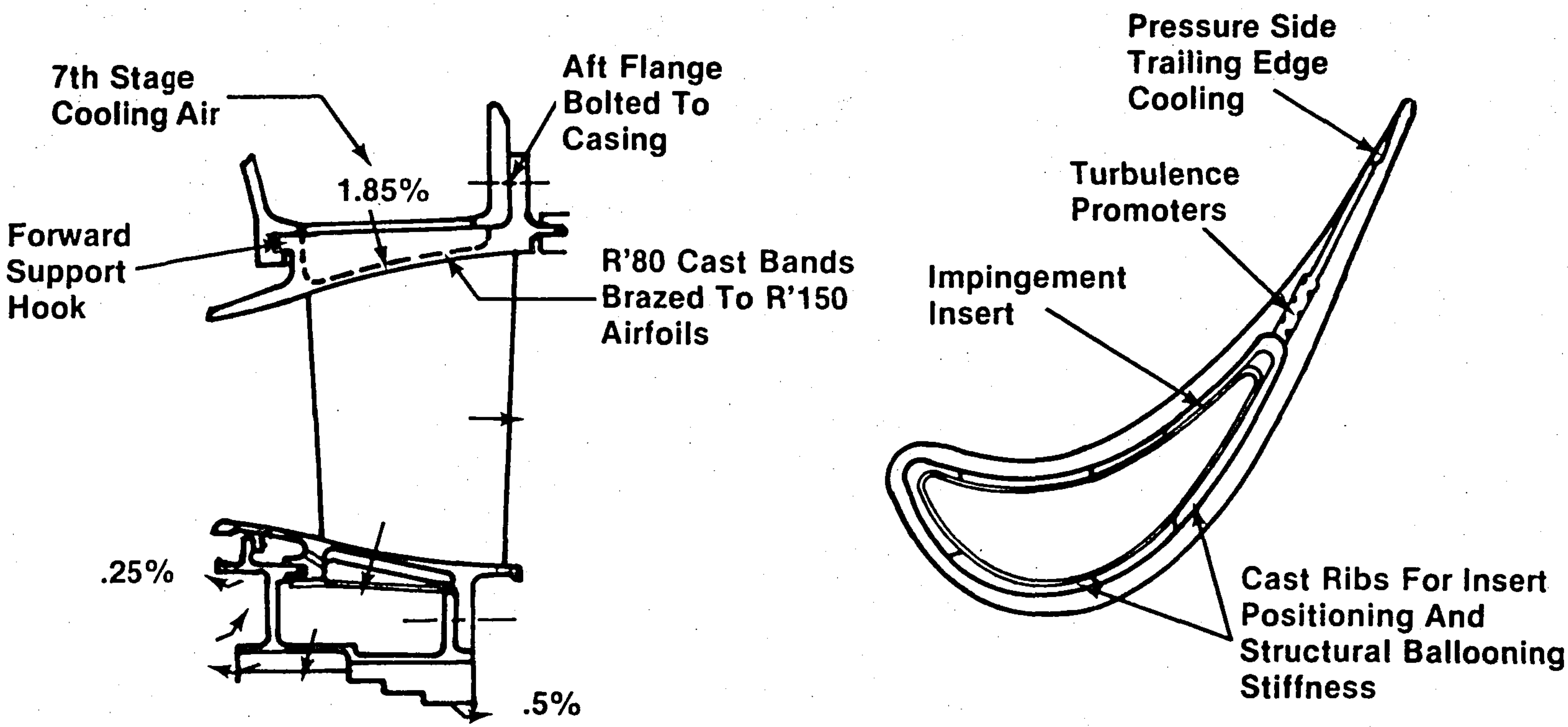


Figure 18. E^3 High Pressure Turbine Stage 2 Nozzle Vane.

(Reference Figure 92, page 169, PAD Report)

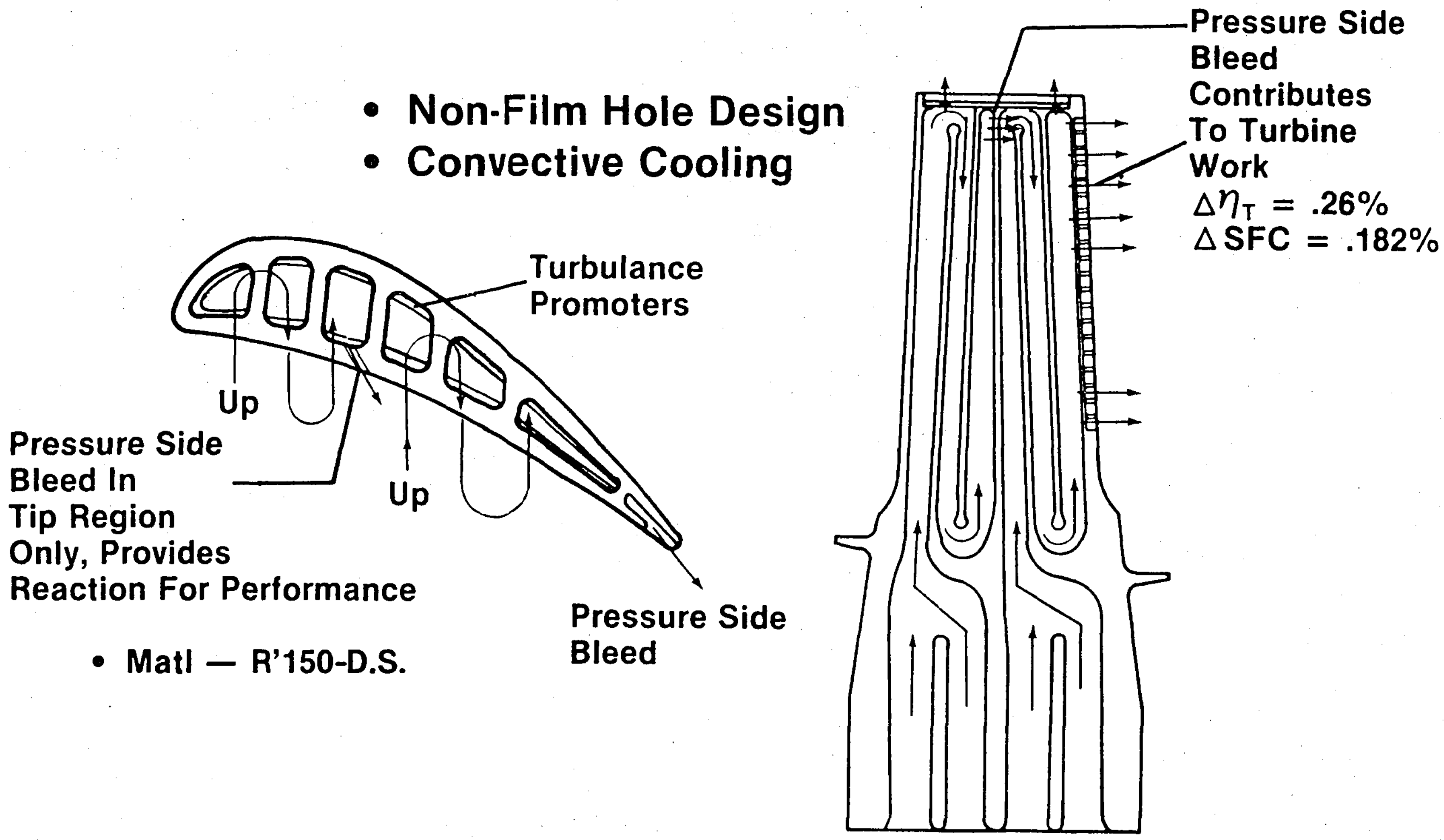


Figure 19. E^3 High Pressure Turbine Stage 2 Blade.

(Reference Figure 93, page 171, PAD Report)

Table 6. HPT Stages 1 and 2 Blades and Vanes.
(Reference Table 56, Page 172, PAD Report)

Parameter	Stage 1	Stage 2
Number of Blades	76	70
Number of Vanes	46	48
Blade Material	René 150	René 150
Vane Material	MA 754	René 150
Base Design Speed, rpm	13,414	13,414
Tip Speed, m/sec (ft/sec)	514 (1686)	533 (1750)
Design $T_{4.1}$, ° C (° F)	1421 (2590)	1421 (2590)
Coolant Temperature, ° C, (° F)	596 (1105)	591 (1096)
Pitch-Line Bulk Temperature, ° C (° F)	949 (1740)	927 (1700)
Airfoil Cooling Flow, % W_{25}	3.3	0.75
Pitch Centrifugal Stress, MPa (ksi)	122.0 (17.7)	186.2 (27.0)
Root Centrifugal Stress, MPa (ksi)	208.2 (30.2)	317.2 (46.0)
Area Ratio	1.6	1.9
Life Mission Mix, Hours	18,000	18,000

The operating efficiency of the core turbine is improved by the use of an ACC system over the turbine case. The goal for the turbine at maximum cruise is to maintain an average 0.041 cm (0.016 in.) tip clearance for both stages. The ACC system will also delay deterioration by permitting more open clearances during periods of high engine-case deflection such as at takeoff rotation.

4.5 LOW PRESSURE TURBINE (Reference Page 175, PAD Report)

The low pressure turbine is designed for high efficiency under the aerodynamic loads imposed by the cycle. Figure 20 illustrates the inner and outer flowpath configuration employed in the FPS to achieve the performance goal. Since there is a large drop in gas stream temperature going through the core turbine, the only cooling air required is to purge the outer and inner turbine cavities. A cooling summary of the LPT purge air is given on Figure 20.

The efficiency goal for the LPT requires that an average tip clearance of 0.039 cm (0.015 in.) be maintained over all stages. As was shown (Reference Figure 12, page 24, PAD report), this clearance goal appears to be achievable over the front stages but will be exceeded over Stage 5. This is due to the large effect of the various flight maneuver loads on clearance over Stage 5. It is estimated, however, that an average effective clearance of 0.039 cm (0.015 in.) can be achieved when all stage clearances are considered.

4.6 TURBINE FRAME AND MIXER (Reference Page 191, PAD Report)

No FEDD-2 data were generated for this section.

4.7 BEARINGS SYSTEMS, DRIVES, AND CONFIGURATION (Reference Page 201, PAD Report)

The sump system, Figure 21, is a center-vent design. Sump air (0.24% W_{25}), is delivered from the leading edge of the inlet core struts to the No. 1 bearing sump and from there to the aft sump through the fan shaft. Deoiled sump air is ejected from the engine through a center-vent exhaust stinger.

The drive system was designed to operate off the core shaft and to provide the pads with proper rotation and speed for the various accessories. Figure 22 illustrates the drive scheme, numbers of teeth per mesh, and the initial and final drive speeds.

4.8 CONTROL SYSTEM (Reference Page 219, PAD Report)

NO FEDD-2 data were generated for this section.

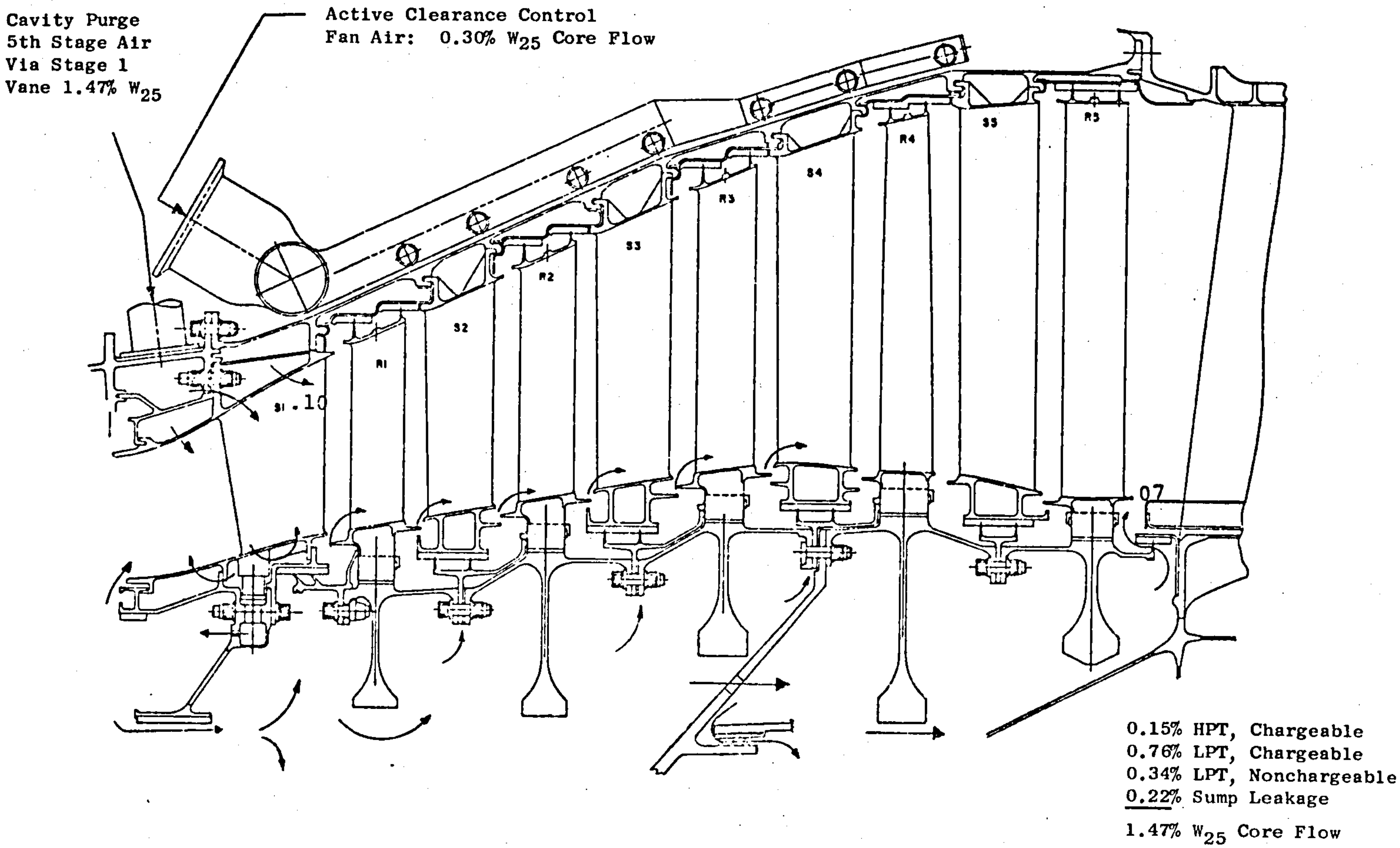


Figure 20. Cooling System - E^3 Low Pressure Turbine.

(Reference Figure 100, page 184, PAD Report)

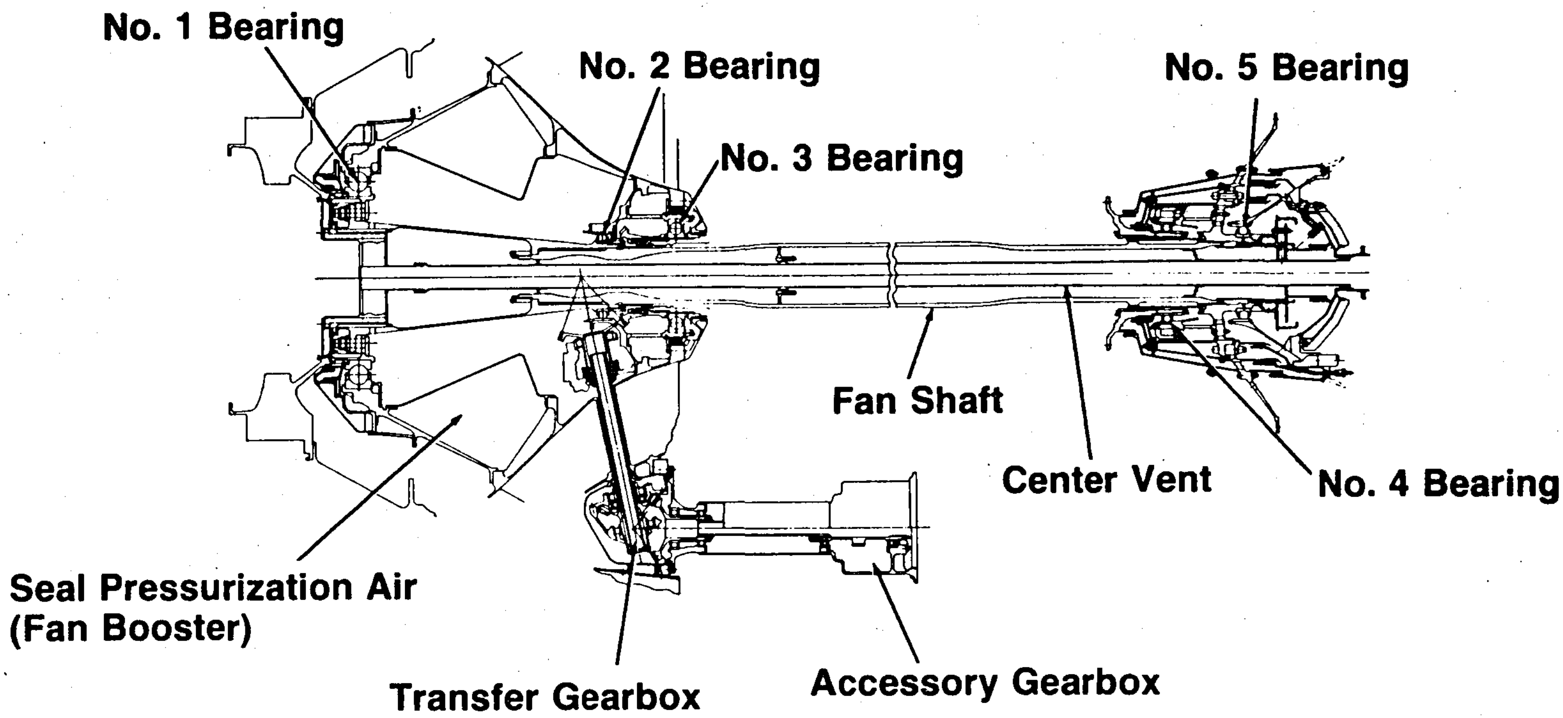


Figure 21. FPS Sumps and Drive System.
(Reference Figure 110, page 205, PAD Report)

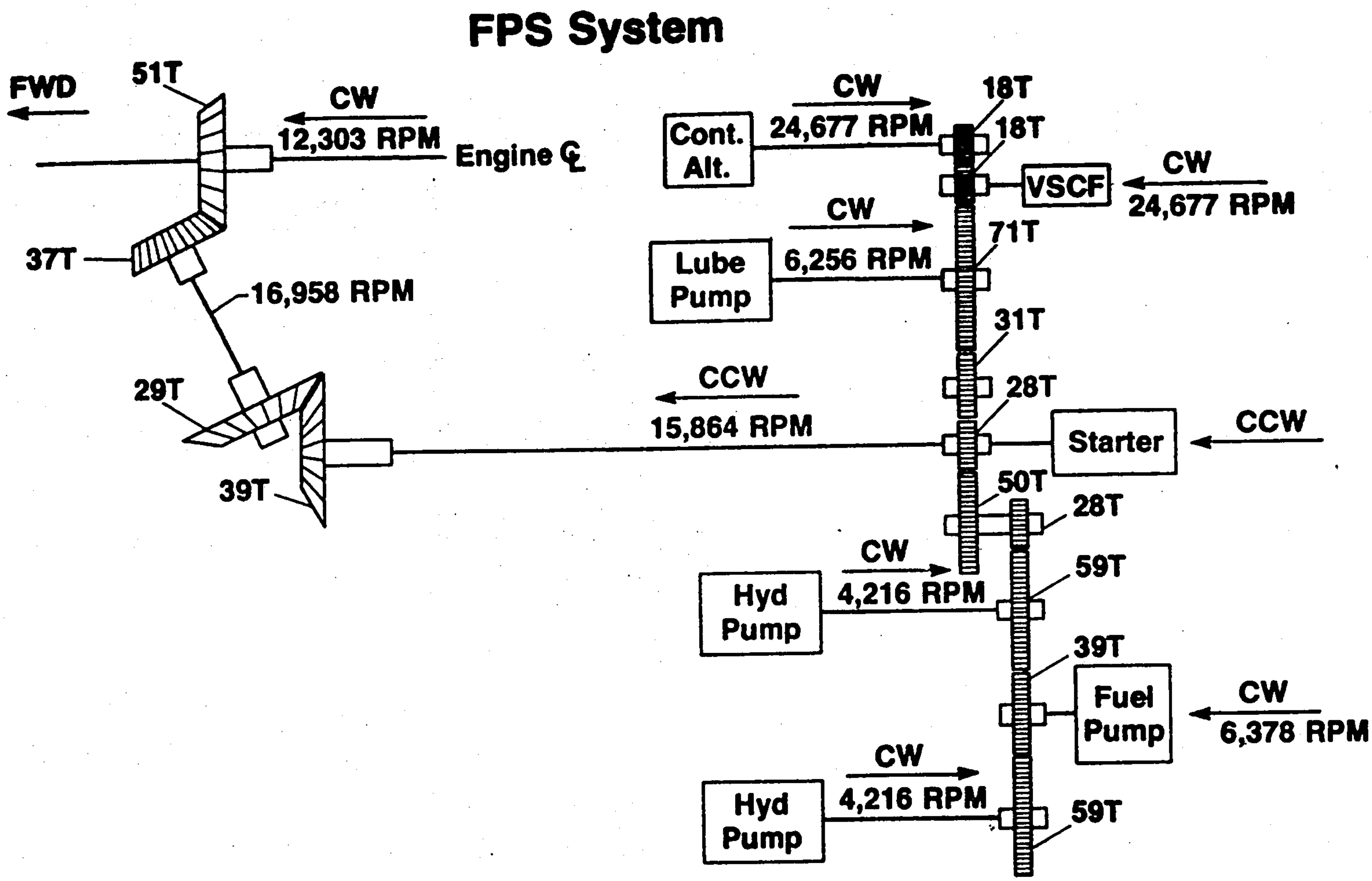


Figure 22. E^3 Accessory Drive Gear Schematic.
(Reference Figure 119, page 217, PAD Report)

4.9 NACELLE DESIGN (Reference Page 236, PAD Report)

The aerodynamics of the reverser, shown in Figure 23, were based on previous General Electric experience. Cascade areas were sized to provide a 6% effective area margin, fully deployed, relative to the discharge-flow requirements of the fan bypass. The desired fan operating line for reverse thrust is 4% lower in pressure ratio at corrected airflow than the normal, forward-thrust-mode, fan operating line at static condition. This was chosen in order to provide additional stall margin, if required, and to provide a reduction in core engine speed and turbine temperature at fan speed relative to forward-thrust-mode operation.

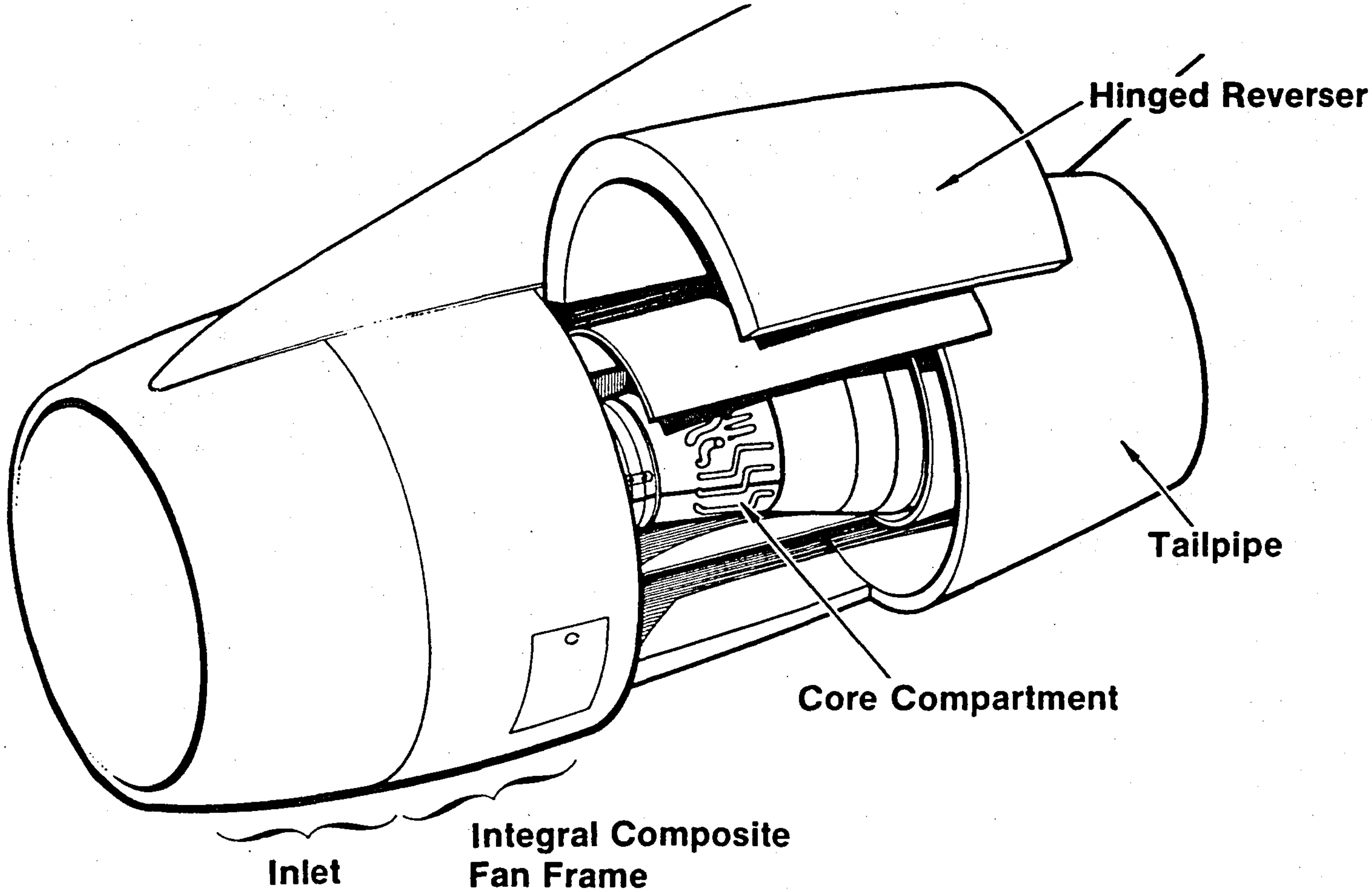


Figure 23. Nacelle General Arrangement.
(Reference Figure 130, page 238, PAD Report)

5.0 CONCLUSIONS

The preliminary design of the Flight Propulsion System (FPS) has indicated that all NASA goals for the General Electric Energy Efficient Engine (E^3) Project can be met. The current status of the FPS design, as compared to the NASA program goals, is as follows:

NASA Goal	FPS Status
• 12% Reduction in sfc (Installed, Altitude Max. Cruise)	14.2% Reduction Projected
• 5% Reduction in DOC	5 to 11.6% Reduction depending on mission/aircraft
• Meet FAR 36 (March 1978) noise requirements for new engines	Meets with a minimum 3 EPNdB margin at all points
• Meet Proposed EPA (1981) Emissions Standards for new engines	CO/HC with margin, no margin on NO_x
• Half of the in-service performance deterioration of current engines	Projected to meet

The installed FPS sfc reduction of 14.2% at maximum cruise compared to the CF6-50C has been estimated based on performance goals for the components and anticipated reductions in isolated-nacelle drag. If a fully installed engine is considered (one with customer bleed and power extraction), the relative sfc reduction increases to 14.6%. Aircraft integration studies indicate that with the FPS projection of installed engine weight and performance achieved, reductions in block fuel consumption ranging from 14.5 to 21.7%, depending on the aircraft/mission, can be attained.

The studies have estimated that a 5 to 11.6% reduction in DOC is achievable with the above FPS characteristics and the projected, initial engine cost, and maintenance costs.

Achievement of the performance-retention goal would increase the projected fuel and DOC savings. The fuel savings would then become 15.4 to 22.9% , and DOC savings would range from 5.3 to 12.3%. Since many of the advanced design features of the engine such as mounting, active clearance control, improved shroud materials, and the quarter-stage debris separation (for example) enhance performance retention, General Electric is projecting that the retention goal will be met.

Evaluation of the acoustic performance of the FPS when integrated with advanced aircraft indicates that the FAR 36 (March 1978) acoustic requirements for newly certified engines will be satisfied. Calculation of noise levels for various study aircraft showed that a 3 EPNdB margin could be maintained for the most critical aircraft condition (approach) on the aircraft that required the highest approach power setting. Calculation of the noise levels that could be expected with the growth version of the FPS (+20% thrust) indicated that this engine could also be certified under FAR 36 (March 1978) rules but without a 3 EPNdB margin at all points.

Meeting the emissions goals under the proposed EPA (1981) standards for nitrous oxide (NO_x) will be very difficult. Projected NO_x levels meet the goal, but do not permit any margin for engine-to-engine variation. The hydrocarbon (HC), smoke, and carbon monoxide (CO) goals should be met with adequate margin to ensure that all production engines meet the standard. The double-annular combustor, although potentially controlling emissions better than any other General Electric configuration, does add a weight and cost penalty to the overall FPS system. Future emission requirements will determine if it is retained or replaced by a simpler combustor.

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