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Follow-On Technology Requirement Study for Advanced Subsonic Transport

Bruce E. Wendus, Donald F. Stark, Richard P. Holler, and Merle E. Funkhouser
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LIST OF ACRONYNMS and ABBREVIATIONS

ADP	Advanced Ducted Propulsor
A/F	Airfoil
Alt	Altitude
AST	Advanced Subsonic Transport
ATCC	Advanced Technology Common Core
BPR	Bypass Ratio
CDT	Compressor Discharge Temperature
CET	Combustor Exit Temperature
COD	Constant Outside Diameter
CORR	Corrected
DOC+I	Direct Operating Cost Plus Interest
EGV	Exit Guide Vane
EIS	Entry Into Service
FPR	Fan Pressure Ratio
HPC	High-Pressure Compressor
HPT	High-Pressure Turbine
IC	Intermediate Case
ID	Inner Diameter
IGV	Inlet Guide Vane
LPC	Low-Pressure Compressor
LPT	Low-Pressure Turbine
MTOGW	Maximum Takeoff Gross Weight
OD	Outer Diameter
OEW	Operating Empty Weight
OPR	Overall Pressure Ratio
Poly	Polytropic
PR	Pressure Ratio
SL	Sea Level
SLS	Sea Level Static
SM	Surge Margin
Std	Standard
TCA	Turbine Cooling Air
TCLA	Turbine Cooling and Leakage Air
TOGW	Takeoff Gross Weight
TSFC	Thrust Specific Fuel Consumption
VAMP	Vehicle Analysis Modular Program
VJR	Jet Velocity Ratio (Fan Duct/Engine Core)

LIST OF SYMBOLS

AN^2	Turbine Exit Annulus Area × Rotor Speed Squared
Btu	British Thermal Unit
F	Fahrenheit
ft/min	Feet Per Minute
ft/sec	Feet Per Second
ft	Feet
hp	Horsepower
in.	Inch
K	Kelvin
k	Thousands
ksi	Thousands of Pounds Per Square Inch
lbm	Pounds, Mass
lb	Pounds, Force or Weight
lb/sec	Pounds Per Second
Mn	Mach Number
N_1	Low Spool Speed
N_2	High Spool Speed
nm	Nautical Mile
$\frac{N}{\sqrt{\theta}}$	Corrected Speed
P	Pressure
psia	Pounds Per Square Inch, Absolute
P_T	Total Pressure
R	Rankin
rpm	Revolutions Per Minute
T_2	Fan Inlet Total Temperature
T_3	Compressor Discharge Total Temperature
T_4	Combustor Exit Total Temperature
T_T	Total Temperature
U	Wheel Speed
V_j	Jet Velocity
W	Flow
W_{ae}	Core Air Flow
W/A	Flow/Area
W_C	Corrected Flow

1. SUMMARY

A study was conducted to define and assess the critical or enabling technologies required for a year 2005 entry into service (EIS) engine for subsonic commercial aircraft, with NASA Advanced Subsonic Transport goals used as benchmarks. Two engines were selected for this study — a baseline current technology engine and an advanced technology engine. The baseline engine is a turbofan based on 1995/96 EIS technology, e.g., PW4084. The year 2005 EIS advanced technology engine is an Advanced Ducted Propulsor (ADP) engine.

Performance analysis showed that the ADP design offered many advantages compared to the turbofan. The ADP's lower fan pressure ratio (FPR) gives it a propulsive efficiency advantage resulting in lower thrust specific fuel consumption at cruise (14.6 percent), a thrust growth advantage, and the option to have a smaller size core engine. The ADP's fan drive gear combined with the variable geometry fan and low-pressure compressor (LPC) allows the fan, LPC, and low-pressure turbine to run at optimum speeds and efficiencies. The ADP's reduced combustor exit temperature (T_4) at takeoff, relative to a turbofan rated to similar thrusts, allows the ADP to have improved turbine airfoil life for the same climb T_4 or allows the ADP to run a hotter climb T_4 for the same turbine airfoil life.

An airplane/engine simulation study using a long range quad aircraft quantified the effects of the ADP engine on the economics of typical airline operation. The economic figure of merit for this study was direct operating cost plus interest (DOC+I), which included both engine and aircraft related operating costs and ownership costs. Results of the economic analysis show the ADP propulsion system provides a 6.6 percent reduction in DOC+I with half the reduction resulting from fuel burn. Engine and airframe maintenance effects were small.

Critical and enabling technologies for the year 2005 EIS ADP were identified and prioritized. Critical technology paths were defined.

2. INTRODUCTION

This study defined and assessed the critical or enabling technologies required for a year 2005 entry into service (EIS) engine for subsonic commercial aircraft, with NASA Advanced Subsonic Technology goals used as benchmarks. Two engines were defined and used to identify and evaluate technology features: a 1995/96 EIS baseline turbofan engine and a high technology Advanced Ducted Propulsor (ADP) engine. A performance analysis was performed to determine the advantages of a 2005 EIS ADP design over the conventional turbofan. A mission analysis was performed to quantify the effects of the ADP engine on the economics of typical airline operation. The economic figure of merit for this study was direct operating cost plus interest (DOC+I), which includes both engine and aircraft related operating costs and ownership costs. The class of aircraft chosen for this study was a long range quad (four engines) 470 passenger aircraft with today's three class seating standards. Propulsion system influence factors effecting thrust specific fuel consumption, drag, weight, maintenance cost, and engine price on DOC+I were determined including the effects of airframe price assumptions on DOC+I. The technologies that are critical or enabling in reaching the 2005 EIS ADP engine were prioritized and critical technology paths were defined.

3. ENGINE DESCRIPTION

Two engines were selected for use in Task XXXVIII, a state-of-the-art turbofan engine and an Advanced Ducted Propulsor (ADP) engine. Section 3.0 provides descriptions of the selected engines and comparisons of the two cycles in terms of thrust specific fuel consumption (TSFC) and rating temperatures, i.e., compressor discharge and combustor exit temperatures.

3.1. 1995 EIS TURBOFAN ENGINE

The turbofan engine used as a basis for comparison in Task XXXVIII is designated the STF1043. The STF1043 represents a year 1995/96 entry into service (EIS) turbofan with PW4084 technology and bypass ratio (BPR). The fan diameter is 94 in., the takeoff thrust is 60,000 lb at sea-level static, and the cruise TSFC is 1 percent improved relative to a 1993 production engine. Component efficiencies are given in Table 1.

3.2. 2005 EIS ADP ENGINE

The ADP engine chosen for Task XXXVIII is designated the STS1046. Two studies were conducted prior to the final definition of the STS1046, a low shaft study and a high-pressure compressor (HPC) stage pressure ratio loading study. The results of the low shaft study are given in Section 3.2.1 and the HPC results are discussed in Section 3.2.3.3.

Table 1. 1995 EIS Turbofan/2005 EIS ADP Component Comparison — Component Aero Point

	1995 EIS Turbofan STF1043		*2005 EIS ADP STS1046*	
Flight Condition, Alt/Mn	35k/0.80		35k/0.85	
Power Setting	Bucket		42.5 W/A Fan	
Thrust, lb	9000		7930	
Core Size, lb/sec	16.5		5.4	
Efficiencies, %				
Fan OD Stage	90.5	Base	93.4	+2.9
Fan ID + LPC Poly	90.8	Base	90.4	-0.4
HPC Poly (Including IC and EGV)	89.0	Base	92.0	+3.0
HPT	90.6	Base	87.5*	-3.1*
LPT	92.9	Base	93.5	+0.6
Fan Drive Gear System	N/A		99.3	
TCA, % WAE	15.5	Base	24.0	+8.5
Burner Pressure Loss, % Δ P/P	3.8	Base	5.7	+1.9

** Single stage based*

The STS1046 represents a 50,000 lb sea-level static thrust category engine. The projected 10-year market for such an engine in the 2005 to 2014 time period is 3,600 engines. The STS1046 represents the combination of an advanced turbofan propulsion system and core, which would improve TSFC about 5 percent over the 10-year (1995 to 2005) time period, and the ADP concept, which would improve propulsive efficiency and reduce TSFC by approximately another 9 percent. Since the basic configuration and concept are not by themselves size limited, consideration of a particular market segment is academic and should not be considered as total market potential for an advanced core/ADP configuration.

3.2.1. Low Shaft Study

A preliminary structural analysis conducted on a version of the ADP engine early in the low shaft technology study indicated that a properly designed low shaft could not fit within the bore dimensions of the high-pressure turbine disk. The earlier engine design incorporated a 120.9 in. variable pitch fan that resulted in an engine bypass ratio of 22.6 at cruise design conditions. Coupled with the fan was a five-stage low-pressure compressor with an inlet flow of 114.6 lb/sec and a pressure ratio of 4.04. The core was an 85 percent scale version of the Advanced Technology Common Core (ATCC) and incorporated a six-stage high-pressure compressor powered by a high work single stage high-pressure turbine. Powering the low spool was a five-stage low-pressure turbine with an expansion ratio of 14.36. Installed engine design tables of this configuration predicted a maximum low shaft torque of over 30,000 ft-lb at sea-level takeoff during hot day conditions. To transmit this torque and fit within the bore dimensional requirements of the scaled ATCC, a new shaft material with extremely high strength and high stiffness-to-weight capabilities was required. Specifically, material strength increases of 67 percent over current steel or 39 percent over Waspaloy were needed for a full-life design. Similar studies on the high-pressure turbine (HPT) disk also showed an overstressed condition if the bore diameter was increased to accommodate a larger low shaft. Material improvements necessary to reach full disk life were similar to what was needed for the low shaft. These material improvements were not considered reasonable for a 2005 EIS engine. Consequently, a low shaft study was conducted to guide the selection of a revised ADP cycle and component definition that would satisfy a 2005 EIS.

The low shaft study started with a V2500 growth engine that had an overall pressure ratio (OPR) and BPR of 30 and 4.8, respectively, at 0.8 Mn/35,000 ft maximum cruise condition. To determine the effects of low shaft torque capability on engine cycle and rating schedules, the V2500 was modified step-by-step into a 55 OPR ADP with BPR ranging from 10 to over 22. For the low shaft study, the specific modifications to the V2500 engine were as follows:

1. Replace the V2500 fan with a 1.4 pressure ratio, variable pitch fan (increases torque requirements as a result of slower fan tip speed and larger fan diameter).
2. Introduce a gearbox into engine (reduces torque requirements through a low turbine speed increase).
3. Increase fan inner diameter (ID) plus low-pressure compressor (LPC) pressure ratio from base to 3.93 (increases torque requirements as a result of an increase in low spool power requirements).
4. Introduce ADP engine thrust lapse characteristics (reduces maximum torque requirements relative to a required cruise thrust level).
5. Modify low shaft wall thickness from 0.3 in. to 0.4 in. (impacts torque capability).
6. Scale down core to reflect 55 OPR cycle (results in a smaller low shaft with less torque capabilities).
7. Use advanced Waspaloy (PWA1112) low shaft materials and design procedures (increases torque capability).

The above analysis resulted in a quantitative assessment of the various factors that make up the torque requirements of an 2005 EIS very high bypass ratio ADP and indicated that the gearbox was the greatest contributor to solving low shaft torque problems. Also of significance was the impact that ultra-high engine pressure ratios had on limiting the low shaft dimensions and hence torque capability. Increasing engine pressure ratios resulted in a smaller hot section with a corresponding smaller HPT disk and shaft diameters.

Figure 1 summarizes the results of the study for an engine BPR of 16.3 and an OPR of 55. Along the horizontal axis are the seven changes that were studied while the vertical axis is a parameter called *Low Shaft Degree of Difficulty*. A degree of difficulty of 2.0 indicates a torque level 100 percent above what is allowed for a full-life part and represents an unacceptable design. Likewise a degree of difficulty of 1.0 results in a full-life design while less than 1.0 represents excess life. Note in Figure 1 that for a full-life shaft with a 0.3 in. wall thickness and the indicated engine cycle (55 OPR, 16.3 BPR), the material torque capability must be increased to 56 percent better than what was used in the base V2500. This particular low shaft used AMS6304, which is a conventional steel alloy, in addition to a design stress margin that was very conservative. The major part of the improvement needed by the ADP at 16.3 BPR and 55 OPR can be easily accommodated by incorporating the low shaft design philosophies and material (PWA1112) of the recently qualified PW4084. The remaining improvement comes from a 10 percent increase in the yield strength of the PWA1112 Waspaloy material and is considered a moderate risk development program for the 2005 EIS time frame. The new material, called advanced Waspaloy, was used to define the ADP low shaft used in this study. Figure 2 compares the material characteristics of both AMS6304 and PWA1112 along with the stress margins used in the two referenced operational engines.

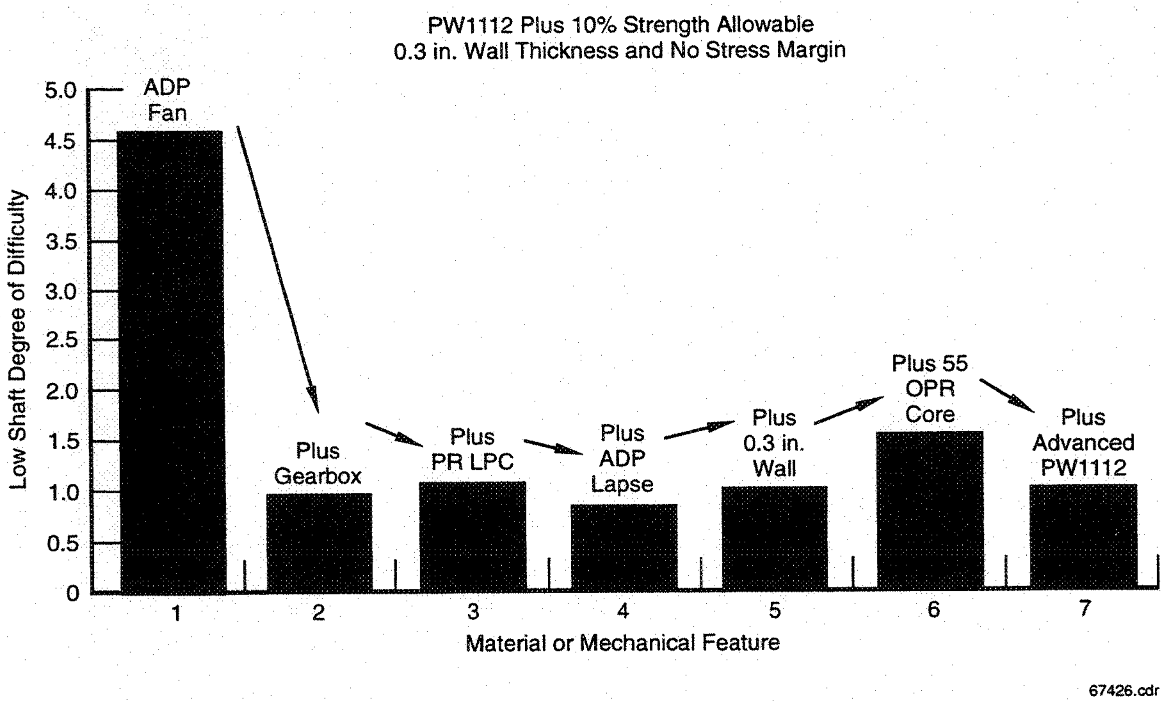


Figure 1. 2005 EIS ADP Low Shaft Torque Summary

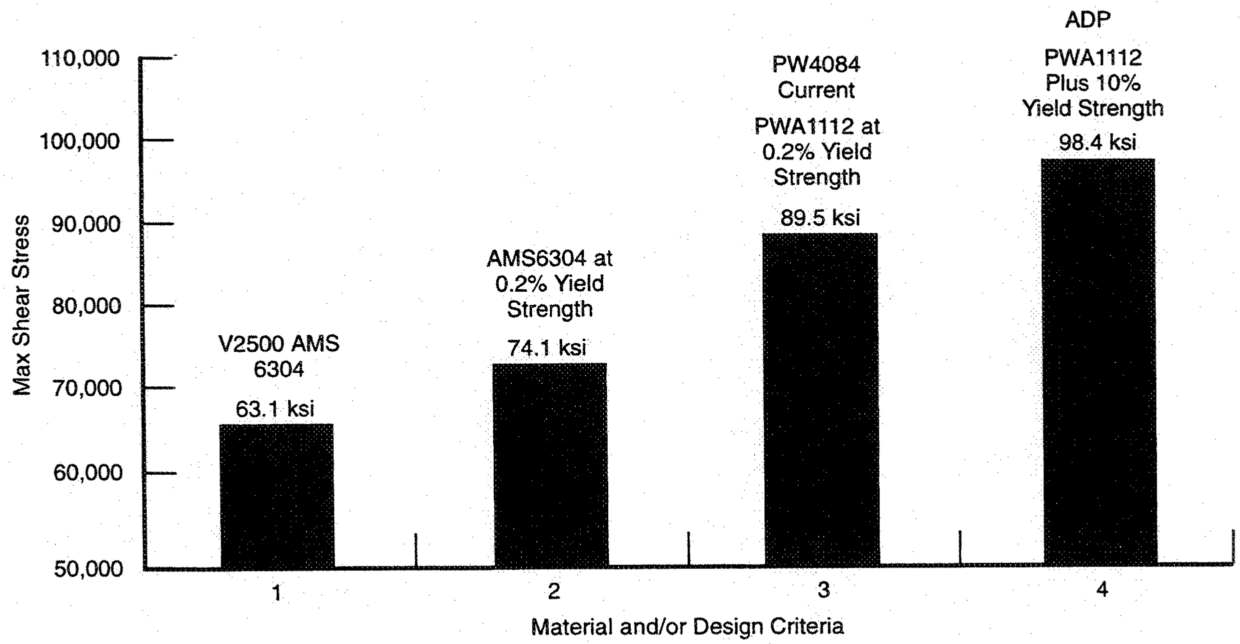


Figure 2. Low Shaft Material Capabilities Established for 2005 EIS ADP

The results of the analysis were then applied specifically to a derivative of the full sized ATCC that had a corrected flow of 6.35 lb/sec exiting the high-pressure compressor. Design studies indicated that the largest diameter low shaft that could fit this core and also satisfy critical speed margin had a radius of 1.75 in. and a wall thickness of 0.3 to 0.4 in. The material selected was an improved PWA1112 (advanced Waspaloy) that had a projected 0.2 percent yield strength of 98.4 ksi. Based on the above assumptions, the maximum torque allowable in the 2005 EIS ADP engine at sea-level takeoff hot day conditions was approximately 490,000 in-lb. These results helped define the final ADP engine.

3.2.2. Engine Description

The STS1046 is an Advanced Ducted Propulsor engine configuration that combines an ultra-high bypass ratio, variable pitch fan with a derivative of the Advanced Technology Common Core. Engine OPR and bypass ratio are 55 and 16.7, respectively, at 0.85 Mn/35,000 ft (T_2=471°R) maximum climb rating conditions where installed thrust is 10,538 lb. Sea-level (0.2 Mn) takeoff thrust is 43,200 lb during hot day conditions that establishes many of the temperature and speed limits of the engine shown in Figure 3. The variable pitch fan is followed by a six-stage variable geometry low-pressure compressor, both of which are powered by a six-stage low-pressure turbine through a 4.2:1 gearbox. The core is a derivative of the ATCC and is composed of a six-stage high-pressure compressor powered by a single stage turbine. Figure 4 illustrates overall engine arrangement as well as selected component inlet pressures, temperatures, and corrected airflows at maximum climb flight conditions. Technologies and materials selected are consistent with an EIS date of 2005.

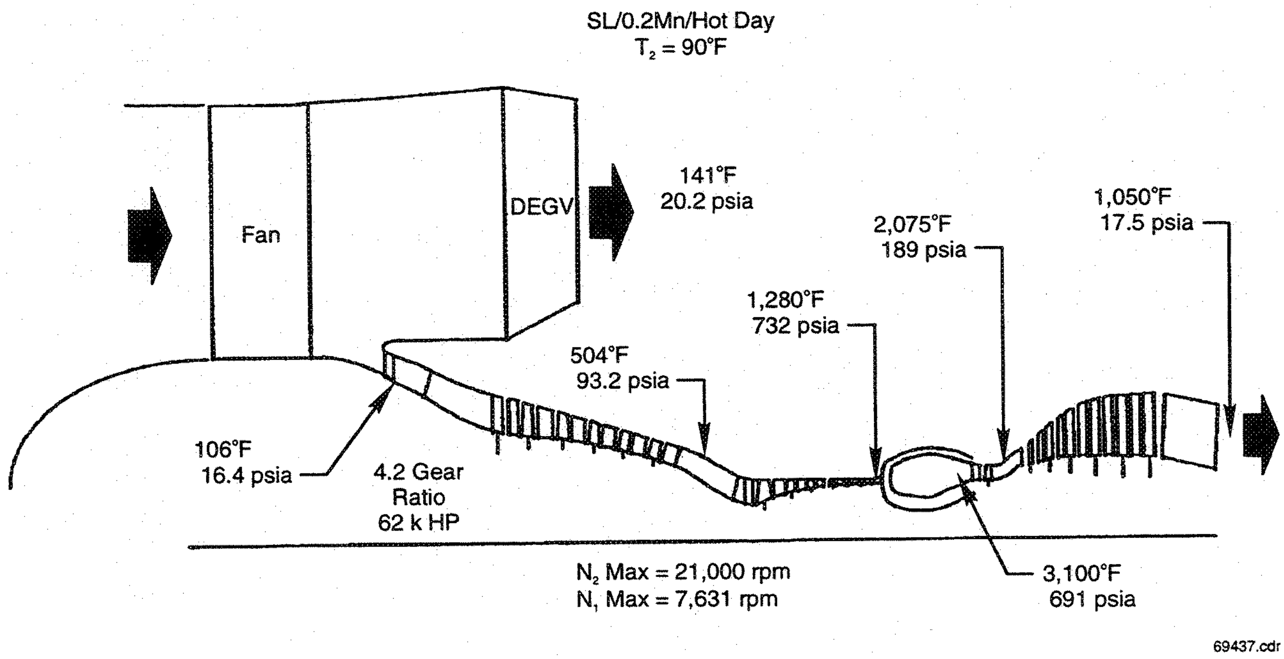


Figure 3. 2005 EIS ADP Maximum Temperatures and Pressures

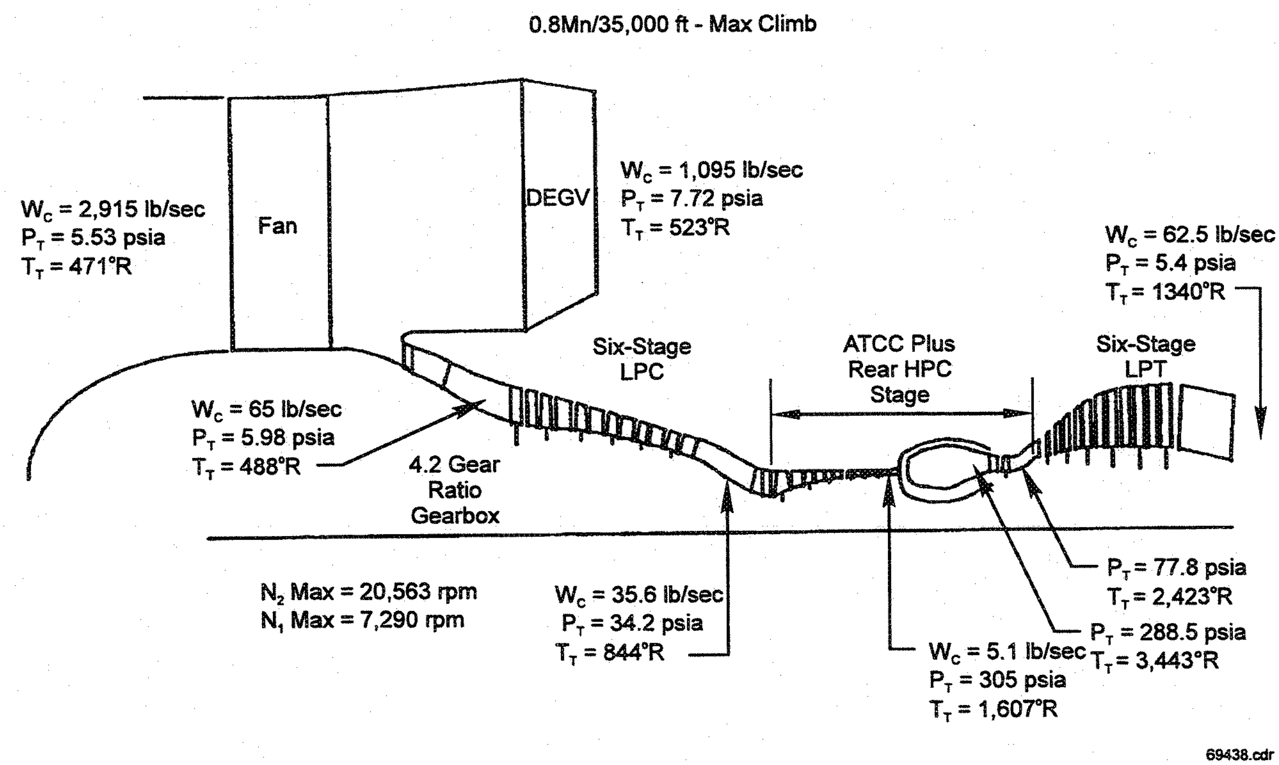


Figure 4. 2005 EIS ADP General Engine Arrangement

3.2.3. Component Description

Component efficiencies for the STS1046 ADP are listed in Table 1. The ADP component efficiency levels reflect Pratt & Whitney estimates for 2005 EIS.

3.2.3.1. Variable Pitch Fan

The high efficiency, variable pitch fan has a diameter of 118.8 in. and an inlet hub-to-tip radius ratio of 0.4. Low noise and high efficiency are as a result of several features incorporated into the design including advanced aerodynamic blading, low corrected rotor tip speed, and noise acoustic treatments. The fan tip and root pressure ratios are 1.32 and 1.08, respectively, at the fan aerodynamic design point (0.85 Mn/35,000 ft cruise). At the same flight point, fan rotor tip efficiency is 95.1 percent with an inlet specific flow of 42.5 lb/sq ft and a corrected tip speed of 850 ft/sec. The fully reversible variable pitch fan consists of 18 blades and 40 duct exit guide vanes that are located 1.6 chord lengths behind the fan rotor for acoustic reasons. The component efficiency of 93.4 percent in Table 1 includes 0.5 percent for exit guide vane pressure loss.

The level of fan tip speed is made possible by the ADP fan drive gear system. The reduction ratio of 4.2 was selected to optimize both the low shaft and the fan speeds to maximize efficiencies of the fan, LPC, and low-pressure turbine (LPT). The level falls within design range for a planetary type gear system consisting of a ring gear and five planets. The system was sized for a maximum input shaft horsepower (hp) of 42,000 at takeoff and has an efficiency level at cruise of 99.3 percent.

3.2.3.2. Low-Pressure Compressor

Coupled to the high speed side of the gearbox is a six-stage LPC that has an inlet flow and pressure ratio of 130.8 lb/sec and 4.83:1 respectively, at the aerodynamic cruise design point. The average pressure ratio per stage is 1.3:1. All stages have variable stators to maximize efficiency and provide stall free operation. The inlet tip speed is 1,306 ft/sec with physical rotor speed set by the low turbine AN^2 limit. The flowpath was determined at the front by the fan root and exit guide vane dimensions as well as the high speed gearbox and, at the rear, by the inlet size of the high-pressure compressor. The LPC employs rugged, low aspect ratio (1.5 average) blading and an average gapchord ratio of 0.8. Advanced computational code technology was used to design the LPC and resulted in predictions of high polytropic efficiency (92 percent) and good stall margin (25 percent). The efficiency in Table 1 (90.4 percent) includes fan ID rotor, stator pressure loss, strut pressure loss, and LPC inlet guide vane (IGV) pressure loss. There are 830 airfoils (375 blades and 455 vanes).

A stator, strut, and inlet guide vane are required between the fan ID and the LPC in an ADP, unlike a conventional turbofan that requires only a stator. An ADP uses a strut behind the stator for structural support and an IGV is needed after the strut. There are 80 stators, 13 struts and 96 IGVs.

The LPC is followed by an intermediate case that provides a transition between the LPC and the HPC. An aerodynamic loading parameter was used as a sizing criteria to establish overall shape and length.

3.2.3.3. High-Pressure Compressor

A six-stage and an eight-stage configuration were evaluated for use as the HPC. The eight-stage version was evaluated to determine what benefit, if any, could be derived from using a lower pressure ratio per stage design compared to the six-stage version. The six-stage configuration was selected for the STS1046 and it is described in this section. The eight-stage version is also described below along with its impact on the engine design and reasons why the eight-stage version was not selected for the STS1046.

3.2.3.3.1. Six-Stage High-Pressure Compressor

The high-pressure compressor is a derivative of Pratt & Whitney's ATCC. The original ATCC five-stage compressor was designed under the auspices of the U.S. Navy's Swept Aero Compressor and U.S. Air Force's Enhanced Flow Compressor programs and was rig tested in the U.S. Air Force Compressor Research Facility in 1992 . For use in the STS1046, the high-pressure compressor was modified with the addition of a rear stage that provided added pressure capability at a slightly reduced rotor speed. Exit corrected airflow was reduced from 6.3 to approximately 5.4 lb/sec as a result of the modification. The six-stage configuration results in a pressure ratio of 9:1 (average pressure ratio per stage of 1.44:1) with a corrected tip speed of 1,261 ft/sec and an inlet specific flow of 35.6 lb/sq ft at maximum climb. Compressor inlet hub-to-tip radius ratio is 0.6. The goal efficiency of 92 percent polytropic at cruise is the result of advanced computational codes, airfoil sweep and bow, and low leakage mechanical features such as brush seals and integrally bladed rotors. The efficiency includes intermediate case and exit guide vane (EGV) losses. There are 772 airfoils (353 blades and 419 vanes) with an average aspect ratio of 0.85 and an average gapchord ratio of 0.6. Figure 5 provides a summary of the baseline STS1046 ADP with the six-stage ATCC compressor.

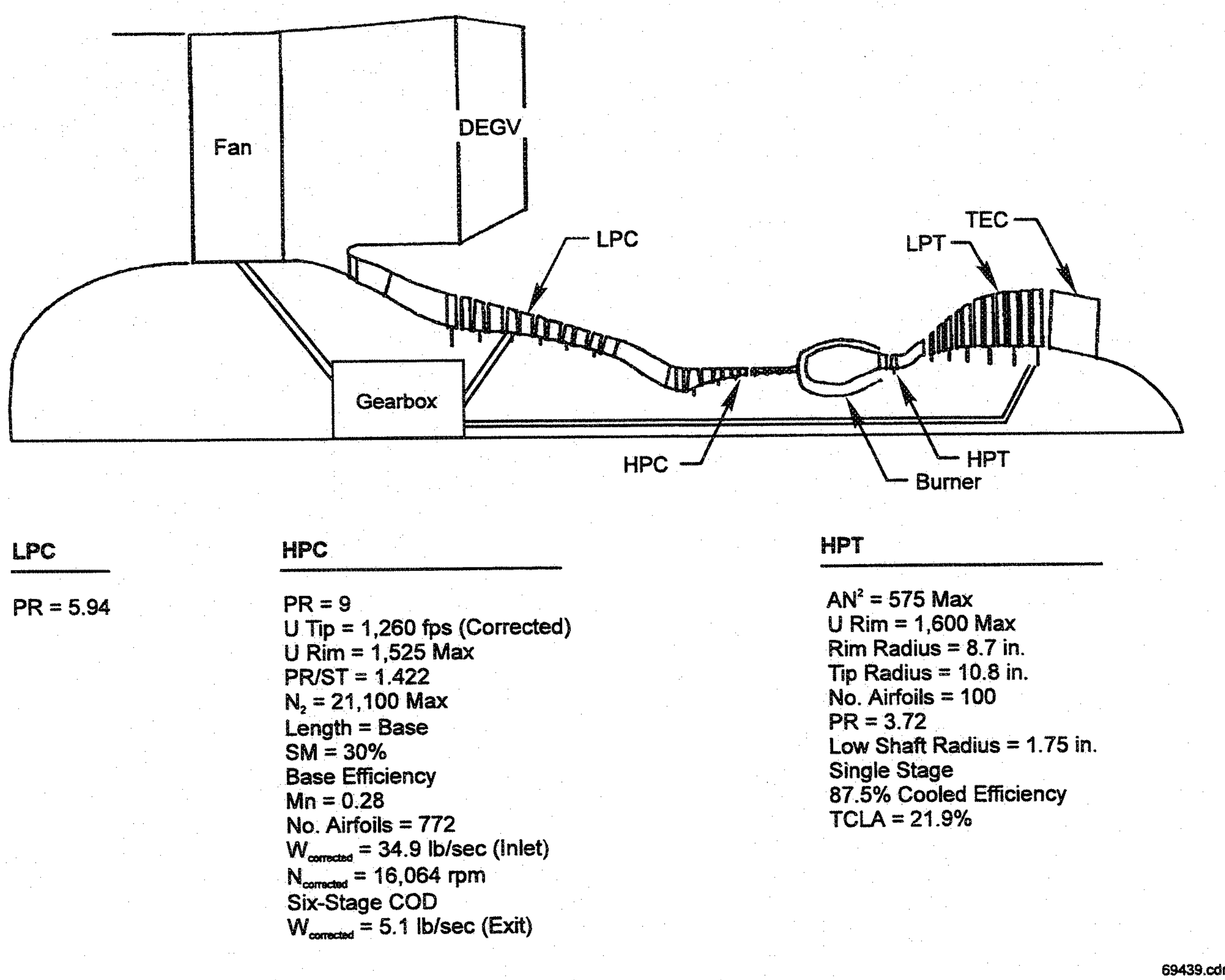
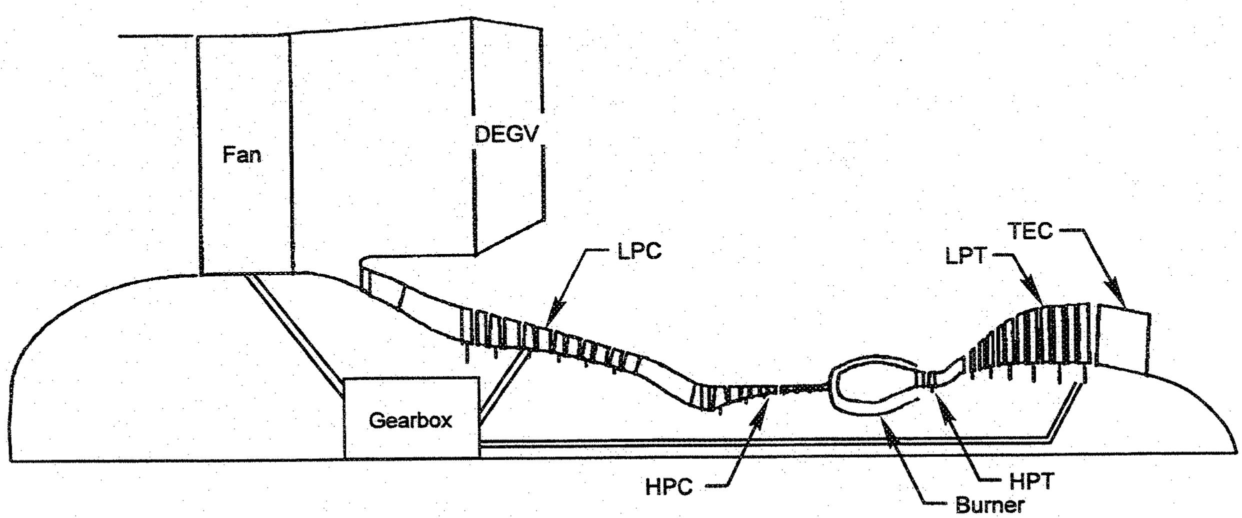


Figure 5. 2005 EIS ADP With Six-Stage High-Pressure Compressor

3.2.3.3.2. Eight-Stage High-Pressure Compressor

For the lower pressure ratio per stage HPC design, engine cycle parameters and low spool design characteristics were held fixed. Using the six-stage design as the starting point, high rotor speeds were reduced by 10 percent at all flight conditions and the compressor and turbine were resized. Pratt & Whitney's compressor and turbine meanline design analysis computer programs were exercised to determine the new design in terms of staging, airfoil count, length, and efficiency and other pertinent parameters. The analysis conducted on the compressor indicated that stall margin, pressure ratio, and airflow could be held constant if two additional stages were added to compensate for the lower wheel speed. As a result of lower shock loses, efficiency was projected to be increased by approximately 1 percent but at the expense of a slightly longer rotor (+1.5 in.) and substantially more airfoils (+573).

In the high-pressure turbine, approximately 22 additional airfoils were required to hold efficiency at 87.5 percent and turbine cooling and leakage air at 21.9 percent. The 10 percent drop in rotor speed was compensated by a 10-percent increase in rotor diameter that kept rim speed and work coefficient constant. Figure 6 provides a summary of the STS1046 modified with an eight-stage compressor.



LPC

PR = 5.95

HPC

PR = 9
U Tip = 1,134 fps (Corrected)
U Rim = 1,373 Max
PR/ST = 1.316
N_2 = 18,900 Max
Base Efficiency +1%
SM = 25%
Length = Base +1.5 in.
Mn = 0.28
No. Airfoils = 1345
$W_{corrected}$ = 34.9 lb/sec (Inlet)
$N_{corrected}$ = 14,457 rpm
Eight-Stage COD
$W_{corrected}$ = 5.1 lb/sec (Exit)

HPT

AN^2 = 460 Max
U Rim = 1,440 Max
Rim Radius = 9.65 in.
Tip Radius = 11.55 in.
No. Airfoils = 122
PR = 3.72
Low Shaft Radius = 1.75 in.
Single Stage
87.5% Cooled Efficiency
TCLA = 21.9%

69440.cdr

Figure 6. 2005 EIS ADP With Eight-Stage High-Pressure Compressor

Based on the added core length of 1.5 in. (increased weight) and the 595 additional airfoils (increased manufacturing and maintenance costs) required by the lower rotational speed, the six-stage high-pressure compressor was selected for the STS1046 ADP.

3.2.3.4. Diffuser/Combustor

The low emissions combustor employs float wall liners and a single row of fuel nozzles located in the dome area directly downstream of the diffuser. Maximum combustor exit temperature is 3100°F and the maximum compressor exit temperature is 1280°F. Overall component pressure loss is 5.7 percent which includes both the diffuser and burner liner. The diffuser is a conventional design with a design inlet Mach number of 0.28 and an area ratio of 1.31.

3.2.3.5. High-Pressure Turbine

The high work single stage high-pressure turbine has a design expansion ratio of 3.68 and a cooled efficiency of 87.5 percent. The efficiency includes 21.9 percent turbine cooling and leakage air. The high specific work and high efficiency are a result of the combination of high wheel speed and a large rotor annulus area that reduce losses in the turbine. However, these features also result in substantial mechanical and structural challenges that are being addressed under several government sponsored Integrated High Performance Turbine Engine Technology programs. Initial core engine testing of the design is scheduled for the first half of 1995 and is expected to validate a number of critical aerodynamic and structural turbine technologies. For the STS1046, maximum turbine rim speed is 1636 ft/sec at a mechanical speed of 21,000 rpm. The design results in a combination of high efficiency (low fuel burn) at a minimum number of parts (lower acquisition and maintenance costs). The HPT has 100 airfoils (40 vanes and 60 blades).

The HPT is followed by a transition duct that leads into the low-pressure turbine. An aerodynamic loading parameter was used as a sizing criteria to establish overall shape and length.

3.2.3.6. Low-Pressure Turbine

The low-pressure turbine (LPT) is a very high speed six-stage design, with a design expansion ratio of 12.72:1 and a specific work requirement of 251 Btu/lbm. The high work requirement is a result of the very large fan (high BPR) and multistage LPC (high OPR) that are both driven by the LPT component. Mean velocity ratio is 0.61 and the maximum rim speed is 810 ft/sec. Maximum inlet gas temperature is 2075°F and will require advanced single crystal materials for this conventionally shrouded uncooled design. Total cooling and leakage goals of 2.1 percent of core engine airflow allow only the transition duct, outer case, and disk bore areas to be cooled. Maximum LPT rotor exhaust gas temperature is approximately 1050°F. Because of the use of a high torque gearbox, the rotational speed of the low shaft can be set to maximize turbine efficiency while minimizing the number of airfoils and rotor stages. Turbine efficiency is 93.5 percent, which includes cooling, parasitic losses, and transition duct losses. The LPT has a total airfoil count of 933 (425 vanes and 508 blades). The LPT is followed by a turbine exit case with 15 exit guide vanes.

3.3. 1995 EIS TURBOFAN AND 2005 EIS ADP CYCLE COMPARISON

A comparison of the 1995 EIS baseline turbofan STF1043 to the 2005 EIS study ADP STS1046 cycle at several flight conditions is provided in Table 2. As can be readily seen, the two cycles are very different. The 2005 EIS STS1046 ADP operating temperatures and overall pressure ratios are higher at both climb and takeoff than the 1995 EIS STF1043 turbofan. The 10 years difference in EIS date enables developing technologies to achieve these differences in performance levels. The improvement in core cycle efficiency combined with the propulsive advantages that the ADP concept has over the turbofan cycle results in a smaller core size. The lower fan pressure ratio level of the ADP yields a larger fan diameter which, combined with the smaller core size, results in a higher engine bypass ratio.

Table 2. 1995 EIS Turbofan and 2005 EIS ADP Cycle Comparison

Includes Customer Bleed and Power Offtakes

	1995 EIS Turbofan STF1043	*2005 EIS ADP STS1046*
Max Climb (35k/0.85 Mn/Std + 18°F)		
CET, °F	2,320	2,985
CDT, °F	965	1,150
OPR	33.4	55.0
PR Split	2.85/11.7	6.18/8.9
Core Size, lb/sec	16.6	5.4
FPR Stage	1.78	1.40
BPR	4.6	16.7
Thrust, lb	12,645	10,385
Cruise Bucket (35k/0.85 Mn/Std)		
% Δ TSFC	Base	-14.6
Takeoff (SL/0.2 Mn/Std + 27°F)		
CET, °F	2,590	3,100
CDT, °F	1,130	1,280
OPR	31.5	48.4
Thrust, lb	51,430	43,200
Thrust Ratio	4.07	4.16
Takeoff (SLS/Std + 27°F)		
CET, °F	2,550	2,940
Thrust, lb	58,660	50,450

The levels of climb and takeoff thrusts are different between the two engines because the STS1046 ADP and the STF1043 turbofan were not sized or rated for the same application. The STS1046 was defined to meet the 50,000 takeoff thrust requirement of an advanced, long range, four engine commercial aircraft used in the study. The STF1043 turbofan is a current production engine being used *as rated for 60,000 takeoff*. Putting the two engines on a comparable thrust basis would involve cycle adjustments and/or engine scaling that was not within the scope of the study.

The OPR and combustor exit temperature (CET) levels are different between takeoff and climb because of the fundamental operating characteristics of an ADP versus a turbofan. A detailed explanation is provided in Section 3.5.

3.4. 1995 EIS TURBOFAN AND 2005 EIS ADP TSFC COMPARISON

A performance comparison between the STF1043 turbofan and the STS1046 ADP is shown in Figure 7. TSFC, which includes customer offtakes, is plotted versus thrust for both engines at 35,000 ft/0.85 Mn/standard day. Figure 7 shows the STS1046 ADP has a sizable TSFC advantage (14.6 percent) over the STF1043 turbofan at a bucket cruise flight condition. By definition, TSFC is a function of thermal and propulsive efficiency or, in other words, how efficiently an engine converts thermal energy into propulsive power. A breakdown of the TSFC difference is given in Table 3 and shows that of the total 14.6 percent delta, 7.6 percent results from thermal efficiency and 7.0 percent results from propulsive efficiency. The component comparison shown in Figure 7 indicates the component aerodesign points of the two engines, as well as the component efficiencies that are compared in Table 1.

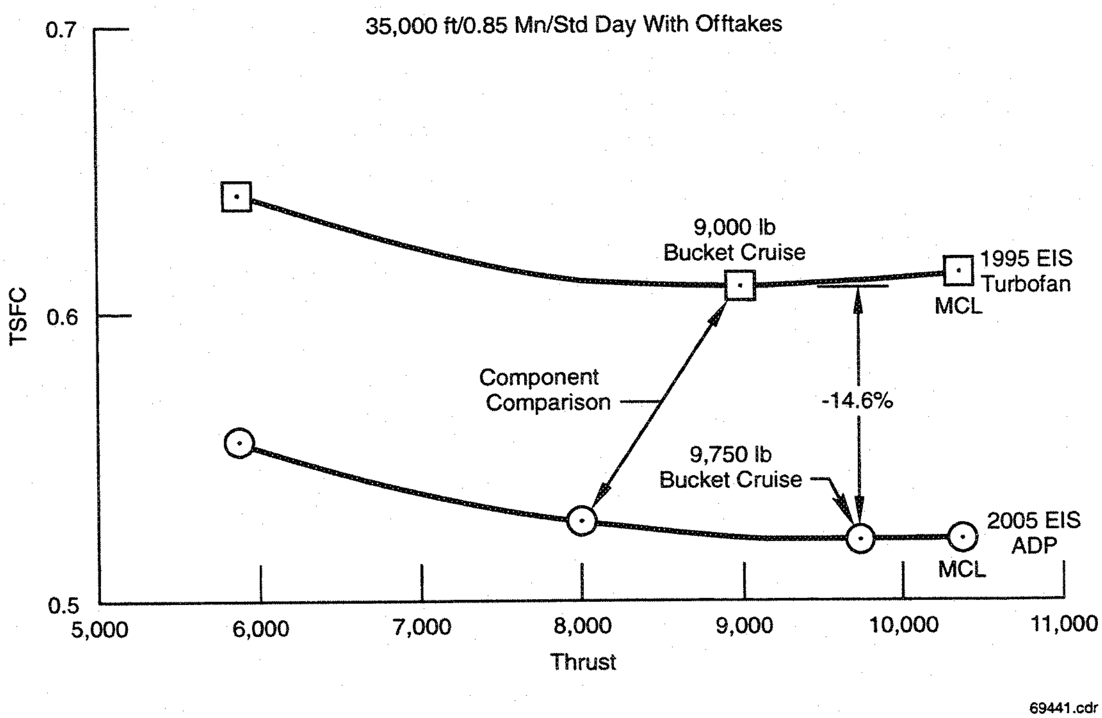


Figure 7. 2005 EIS ADP has Significantly Lower TSFC Than 1995 EIS Turbofan

Table 3. 2005 EIS ADP TSFC Benefit

Source	*% Δ TSFC*
Thermal	
Cycle (OPR & CET)	-12.2
Components	+4.6
Total	*-7.6*
Propulsive	
Cycle (FPR & VJR)	-3.1
Components	-3.9
Total	*-7.0*
Total Thermal + Propulsive	***-14.6***

The thermal and propulsive pieces can be further broken down into differences because of cycle and components. The thermal cycle benefit of the STS1046 ADP is 12.2 percent resulting from the high levels of OPR and CET. However, the single stage HPT plus the increased turbine cooling requirement in the ADP result in a 4.6 percent TSFC debit for thermal components. The net TSFC result resulting from thermal efficiency is 7.6 percent.

The 7 percent ADP propulsive cycle benefit consists of 3.1 percent because of the level of fan pressure ratio (FPR) and jet velocity ratio (VJR) and 3.9 percent because of higher fan and LPT efficiencies and no fan exit case strut or reverser losses. Of the 7.0 percent, 6.0 percent is a fundamental advantage for the ADP cycle. The remaining 1 percent is a result of technology differences from 1995 to 2005 EIS.

3.5. ADP AND TURBOFAN T_3 AND T_4 RATING COMPARISON

The STS1046 ADP and STF1043 turbofan rating temperatures are compared at takeoff and maximum climb in Table 4. Figure 8 shows how the compressor discharge temperatures (T_3) and combustor exit temperatures (T_4) for the STF1043 and STS1046 engines compare at takeoff and top of climb. Figure 9 is a plot of T_3 and T_4 maximum climb rating temperatures along the climb path from 1,500 ft to 35,000 ft. As can be seen from these data, the difference in T_3 and T_4 at comparable flight conditions is large. There are several reasons, ranging from fundamental ADP/turbofan relationships to technology level, for the magnitude of the difference.

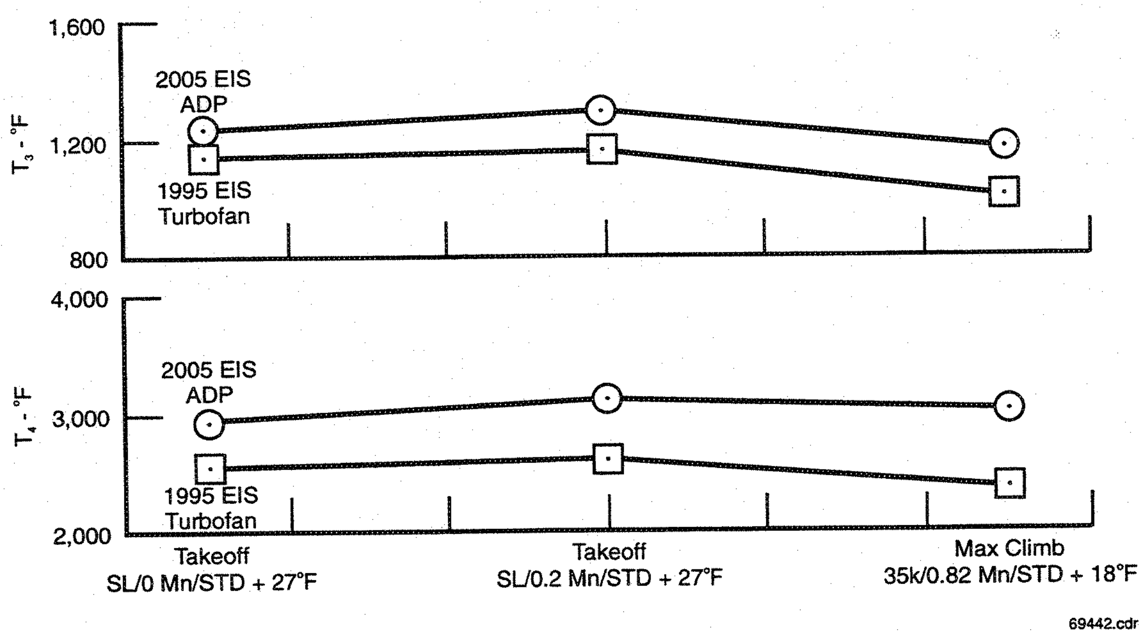


Figure 8. 1995 EIS Turbofan/2005 EIS ADP Takeoff to Climb Rating Comparison

Table 4. 1995 EIS Turbofan/2005 EIS ADP Cycle Comparison

	1995 EIS Turbofan STF1043	***2005 EIS ADP STS1046***	**Δ**
Cruise FPR (Stage)	1.63	1.32	
Fan Diameter, in.	94	119	
Core Size, lb/sec	16.6	5.4	
Takeoff SL/0.2 Mn/Std + 27°F			
Thrust, lb	51,400	43,200	-16%
OPR	31.5	48.4	+54%
T_3, °F	1,130	1,280	+150
T_4, °F	2,590	3,100	+510
Maximum Climb 35k/0.85 Mn/Std + 18°F			
Thrust, lb	12,600	10,400	-18%
OPR	33.4	55	+65%
T_3, °F	965	1,150	+185
T_4, °F	2,320	2,985	+665

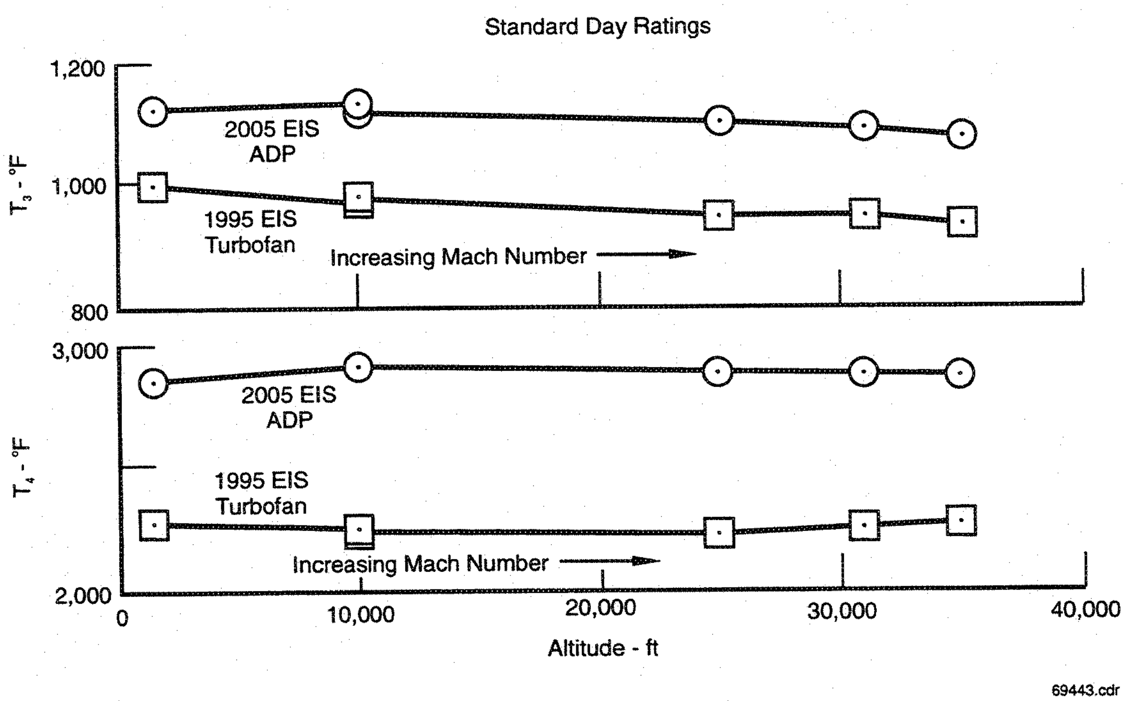


Figure 9. 1995 EIS Turbofan/2005 EIS ADP Rating Comparison Along Climb Path

Two Pratt & Whitney study engines were used for a T_3/T_4 rating temperature comparison to understand the contribution resulting from fundamental differences between a turbofan and an ADP. These T_3/T_4 study engines, unlike the STS1046 ADP and STF1043 turbofan, were consistently defined in terms of technology level, overall pressure ratio at takeoff, turbine airfoil lives and thrust requirements. A comparison of the rating temperatures for these two T_3/T_4 study engines is made in Table 5. Both engines were sized to provide the same takeoff and climb thrusts with the same maximum T_3 at takeoff. The data in Table 5 show the ADP's T_3, although the same at takeoff by definition, is greater than the turbofan at climb. The ADP's T_4 is 135°F lower than the turbofan's at takeoff but is 15°F greater than the turbofan's at climb.

The differences in takeoff and climb T_3 and T_4 levels between the STF1043 and STS1046 (Table 4) are significantly larger than those shown in Table 5 for the T_3/T_4 turbofan and ADP study engines. However, the relationship between takeoff and climb temperatures for each engine cycle is similar in both studies. The similarity is because the two ADP's have the same FPR design with variable geometry fans and LPC's, and the two turbofans have similar FPR design levels. Therefore, the large T_3 and T_4 differences in Table 4 are not a result of inherent differences between the ADP and turbofan cycles but rather are the result of differences in the specific STF1043 and STS1046 cycle definitions and 10 years difference in technology level.

Table 5. Cycle Effects On Rating Temperature

	T_3/T_4 Study Turbofan	***T_3/T_4 Study ADP***	Δ
Cruise FPR (Stage)	1.65	1.32	
Fan Diameter, in.	76	102	
Core Size, lb/sec	7.5	6.5	
Takeoff SL/0.2 Mn/Std + 27°F			
Thrust, lb	30,830	30,830	0
OPR	40	40	0
T_3, °F	1,240	1,240	0
T_4, °F	2,790	2,655	-135
Maximum Climb 35k/0.85 Mn/Std + 18°F			
Thrust, lb	8,230	8,230	0
OPR	46.9	49.4	+5%
T_3, °F	1,090	1,135	+45
T_4, °F	2,585	2,600	+15

It is important to note that an ADP cycle, when compared with a turbofan cycle, has characteristics that result in different takeoff-to-climb rating temperatures. To understand these differences, the remainder of the discussion in Section 3.5 will focus on the turbofan and ADP T_3/T_4 study engines since they are more consistently defined. It will be shown that it is the lower FPR design that causes the ADP to be pulled back at takeoff and pushed at climb relative to a turbofan.

Since the low FPR fan is designed to move more airflow at lower velocities, the ADP has a higher propulsive efficiency than the turbofan, and can produce thrust more efficiently. However, the effect of ram drag is greater with increasing flight speed since more total airflow is being moved. Therefore, the ADP must produce more gross thrust as flight speed increases. Figure 10 shows that for the same T_4 held at all Mach numbers, the ADP produces more net thrust at low flight speeds. However, the ADP's net thrust diminishes at a faster rate than the turbofan with increasing flight speeds because of the increasing ram drag. At 0.8 flight Mach number, the net thrusts are nearly identical, even though the ADP is producing far more gross thrust than the turbofan. Figure 11 shows that, for the same rated thrust, the ADP can run to a lower T_4 at takeoff and a higher T_4 at top of climb. The ADP has an advantage in the temperature relationship. The ADP's core size, already smaller than the turbofan's because of the propulsive efficiency benefit, can be further reduced by increasing both the climb and takeoff temperature levels. This has been included in Figure 11.

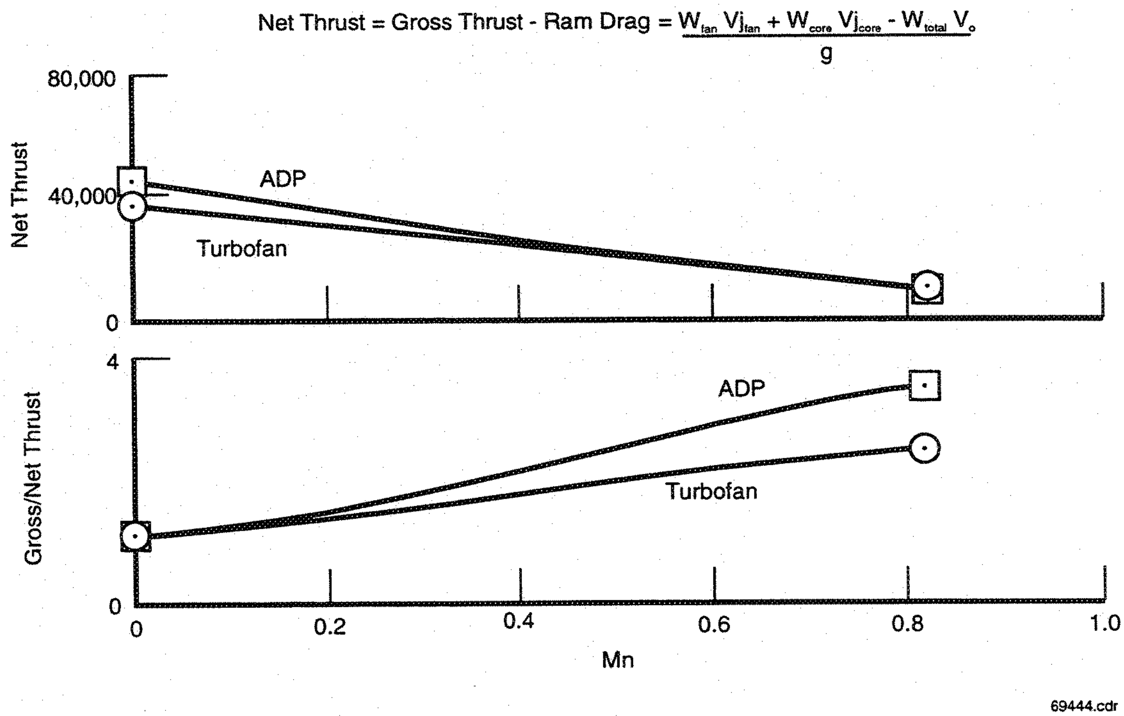


Figure 10. At Same T_4, Turbofan and ADP Thrust Lapse Rates Are Different

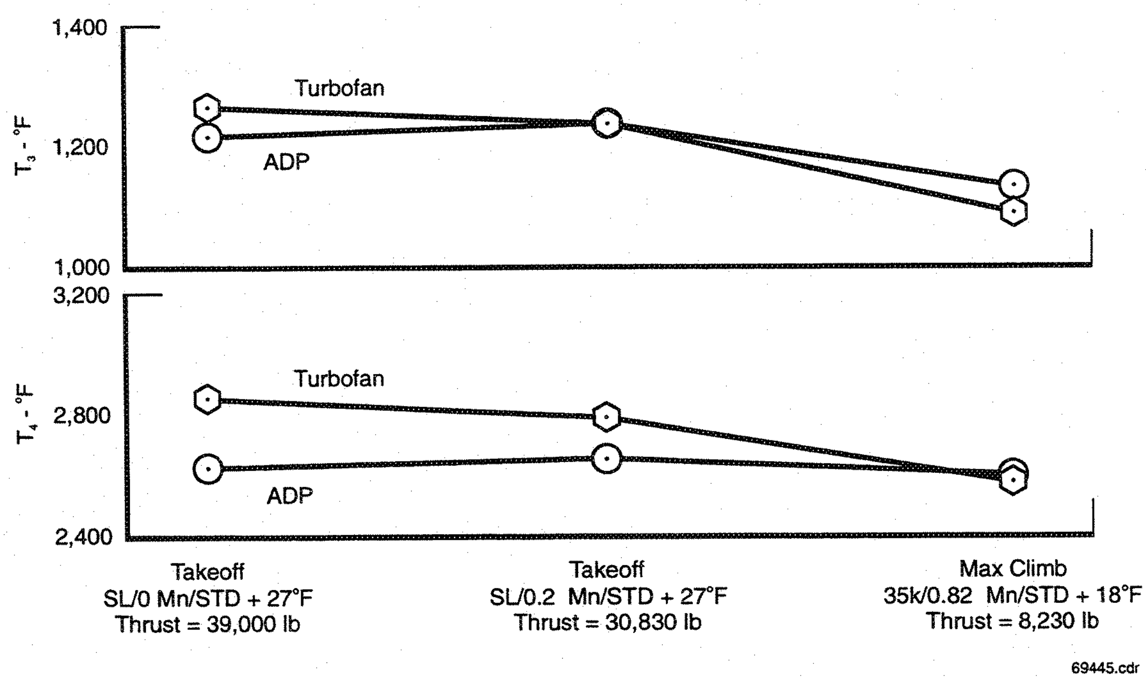


Figure 11. At Same Rated Thrust, Turbofan and ADP T_3 and T_4 Are Different

A detailed accounting of the T_3/T_4 difference can be broken down into the effects of FPR and the variable geometry in the fan and LPC required for surge-free operation. Figure 12 shows how the level of FPR affects the turbofan and ADP's T_3/T_4 relationships when there is no variable geometry. It should be noted that an FPR between the turbofan and ADP values would result in T_3 and T_4 levels between those shown in Figure 12. For example, a design FPR of 1.5, which is halfway between the turbofan and ADP design values, would result in T_3 and T_4 levels approximately midway between those plotted in Figure 12. These relationships show the FPR is responsible for the overall shape of the ADP's temperature rating schedule (Figure 12), while the variable geometry in the fan and LPC affects the final level (Figure 11).

The ADP design requires variable geometry in the fan because the lower FPR ADP fan nozzle unchokes more than the turbofan at takeoff. Figure 13 shows a plot of fan nozzle flow parameter versus fan nozzle expansion ratio with the ADP and turbofan levels indicated at climb and takeoff. The amount of nozzle unchoking causes a larger fan operating line shift in the ADP. Figure 14 shows how the fan operating line shifts at takeoff relative to climb for the ADP and turbofan. However, unlike the turbofan, the ADP's fan has inadequate surge protection at takeoff. Variable fan pitch is the solution, and Figure 15 shows how the variable fan pitch is used for surge control. At high altitude climb and cruise (flight Mach number greater than 0.75) the fan blades are set to the nominal (0 pitch angle) position to provide adequate fan surge margin. Under 0.75 flight Mach number, the fan blades close down by the schedule shown. Closing the fan pitch increases the fan speed and moves the surge line away from the operating line. The variable pitch provides surge protection while maximizing the fan efficiency, which minimizes the T_4 level.

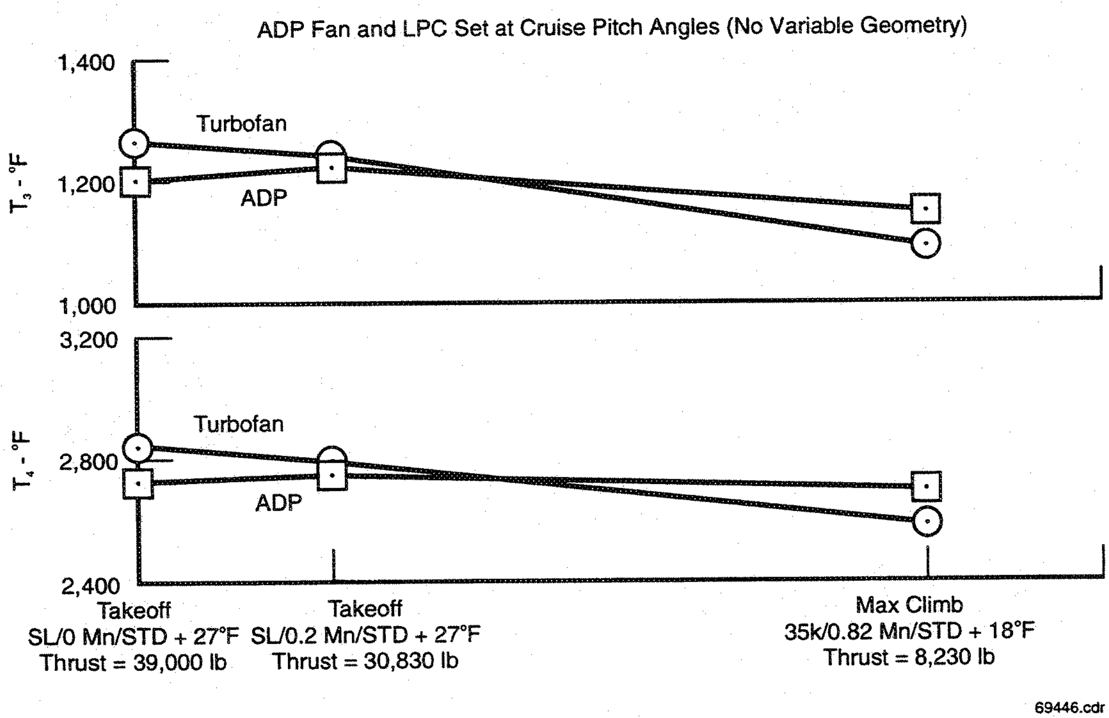


Figure 12. Fan Pressure Ratio Effect on T_3 and T_4

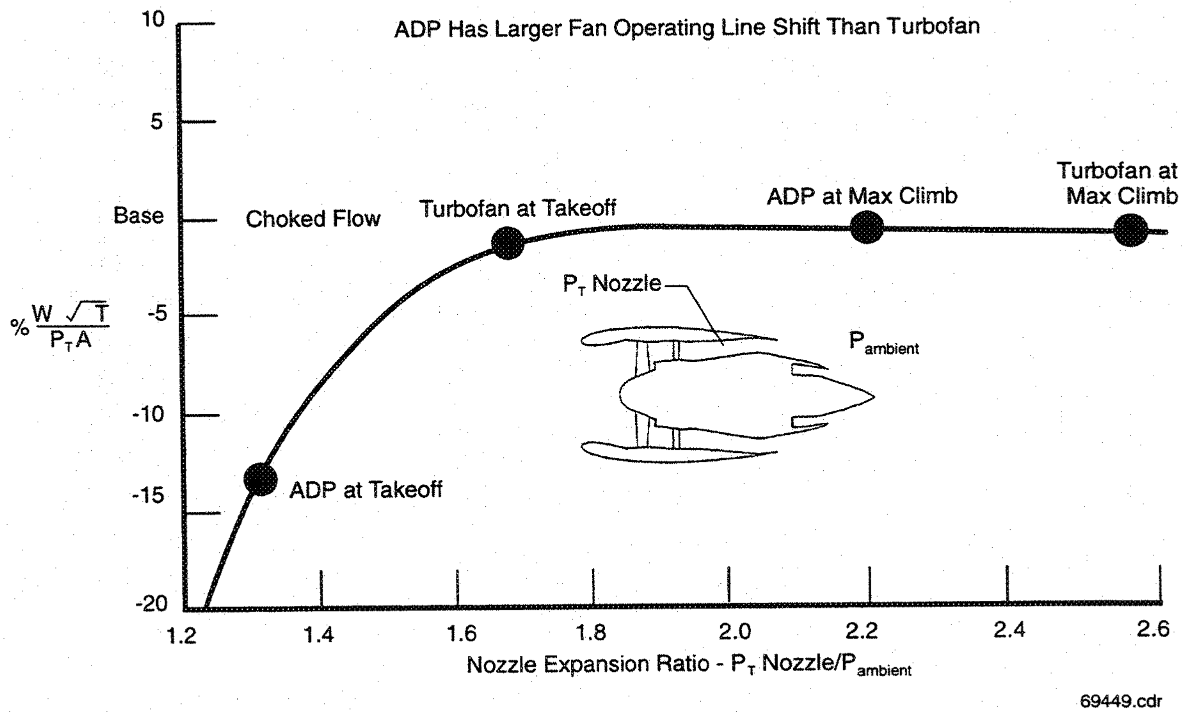


Figure 13. Lower Fan Pressure Ratio ADP Nozzle Unchokes More at Takeoff

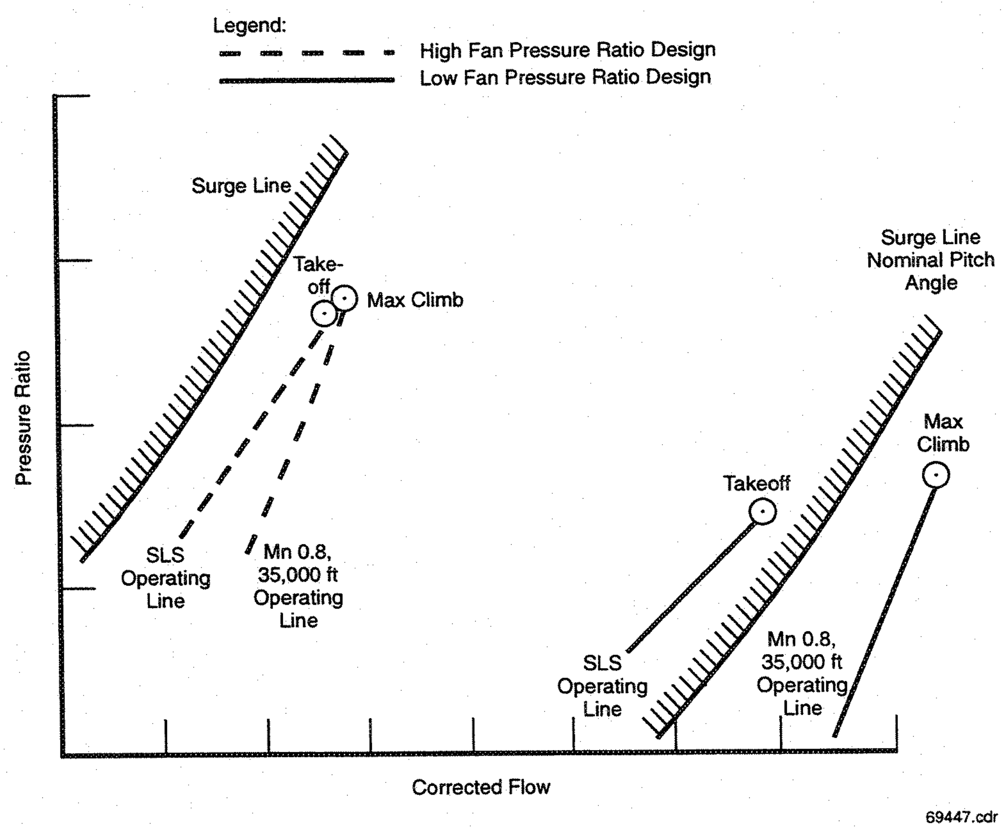


Figure 14. ADP Has Inadequate Surge Margin With Fixed Geometry Fan

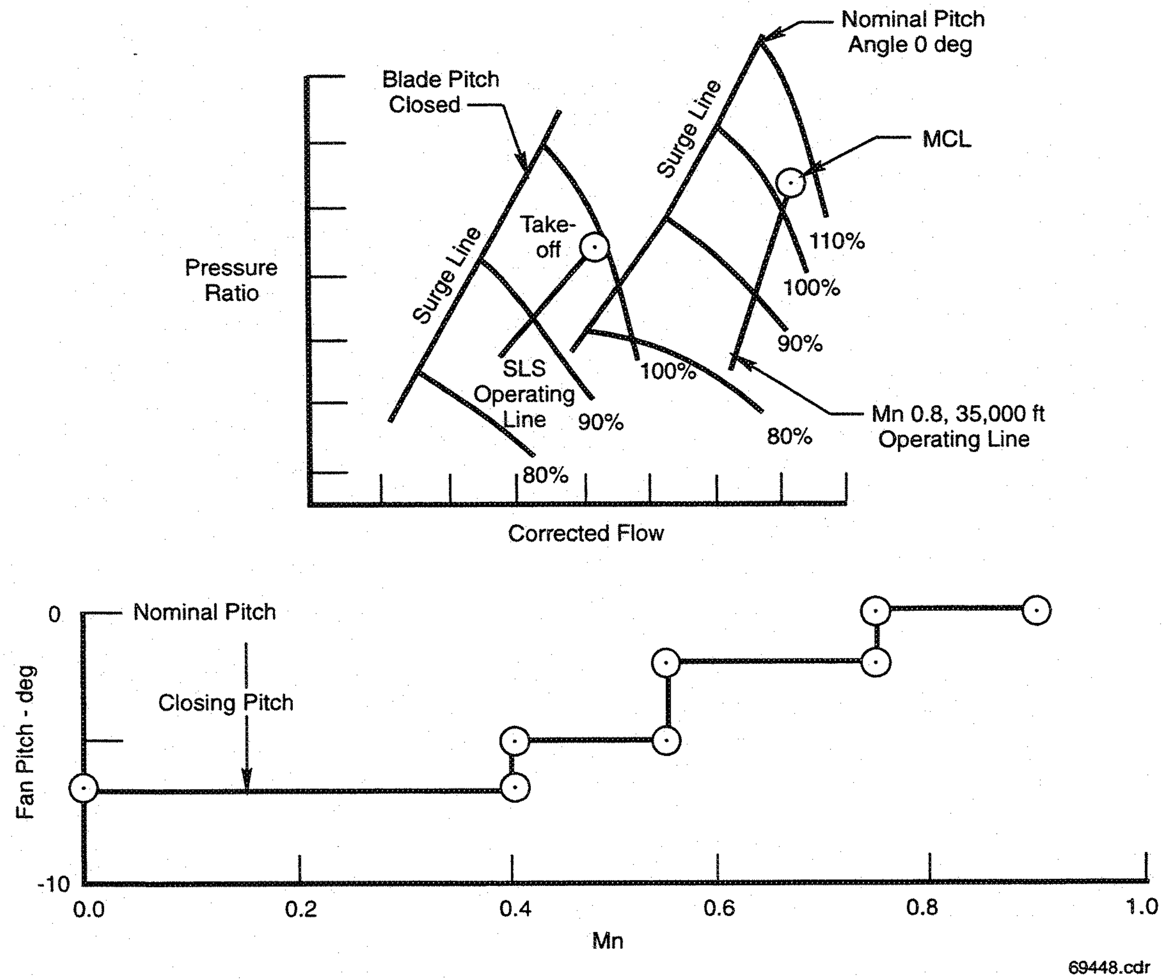


Figure 15. Fan Pitch Is Scheduled for ADP Surge Control

Variable geometry is also required in the ADP low compressor because of the large incidence changes brought about by the variable pitch fan. Figure 16 shows how changing fan pitch impacts the LPC and HPC operation. As the fan pitch closes down, the shaft speed increases and, since the fan and LPC are on the same shaft, the LPC speeds up. Because the HPC speed hasn't changed, the LPC pressure ratio and flow increase to the points labeled as Point 1 in Figure 16. The upmatching at constant T_4 produces excess thrust. As T_4 is reduced to hold thrust, both the LPC and HPC downmatch to the points labeled as Point 2. As can be seen in the figure, Point 2 does not have adequate surge margin on the LPC. As in the fan, variable geometry is the solution. The LPC stators are scheduled for surge control to move the surge line away from the operating line while maximizing the efficiency. Figure 17 shows how the variable geometry LPC is used for surge control. The line in Figure 17 labeled *variable fan pitch* represents where the LPC would be operating in response to the changing fan pitch and how the LPC pitch would change to insure surge free operation. Figure 18 shows how T_3 and T_4 are affected by the variable geometry in both the fan and LPC at several operating conditions. As can be seen, variable geometry in the fan and LPC result in a 10 to 20°F increase in T_3 because of the upmatching of the LPC, but a 100°F decrease in T_4 because of maximizing the efficiency on both components as well as LPC flow capacity.

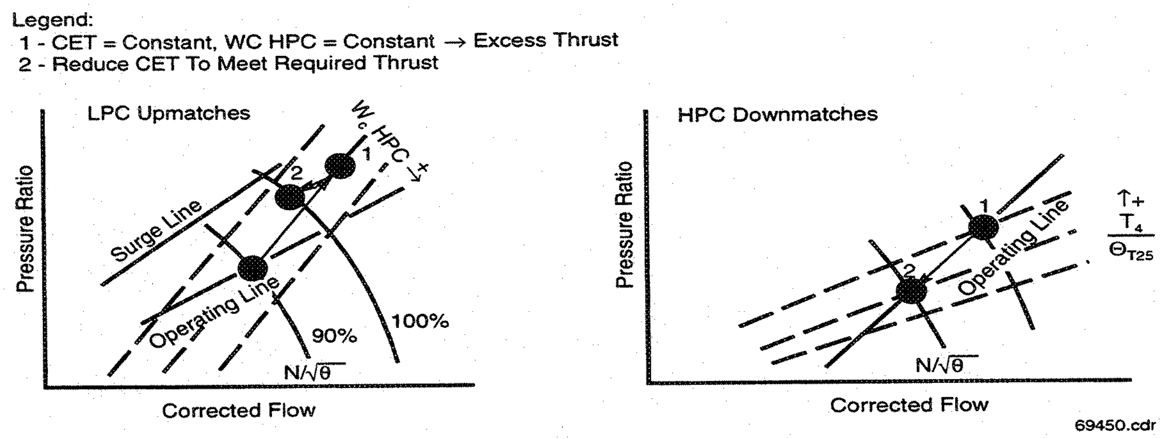


Figure 16. Changing Fan Pitch Impacts ADP LPC and HPC Operation

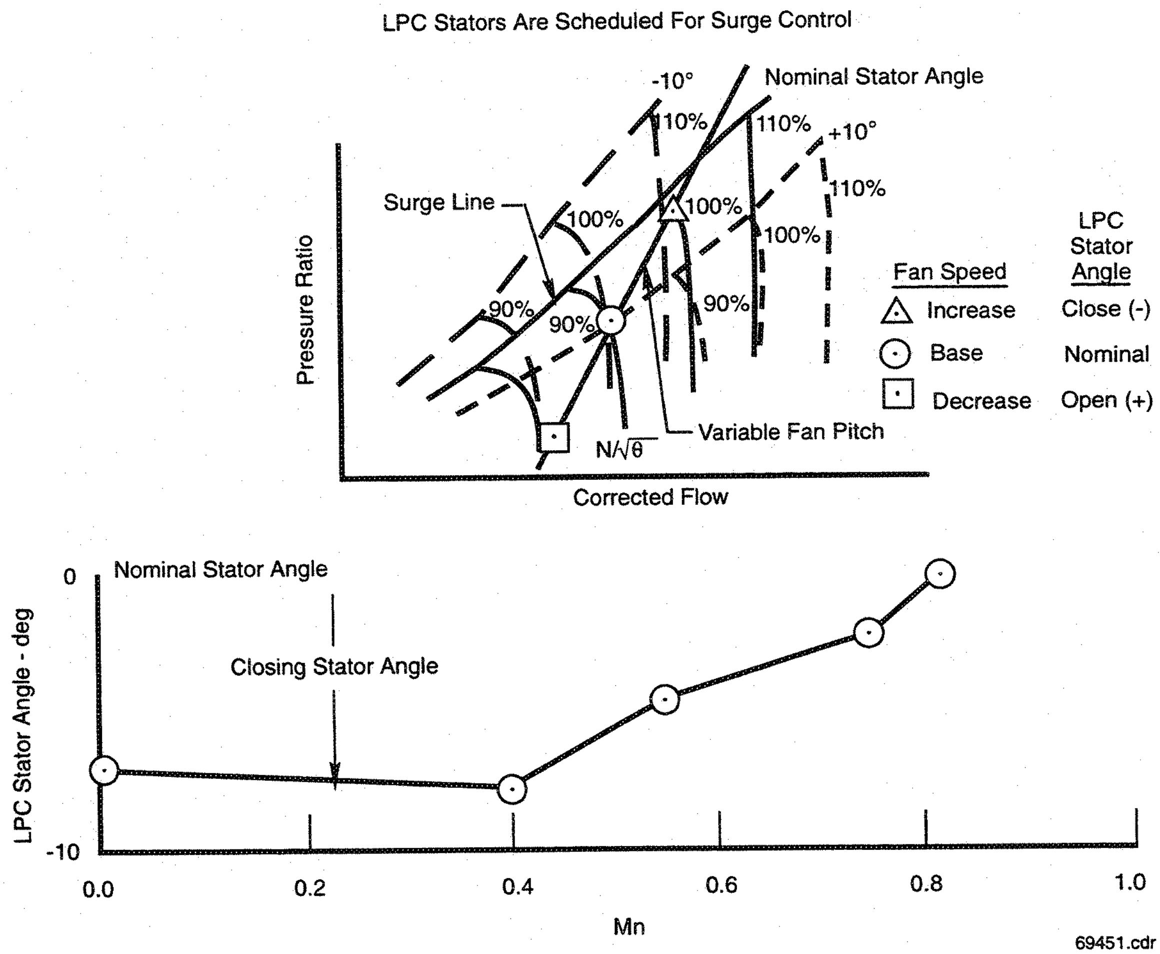


Figure 17. Variable Geometry Low Compressor Required for ADP

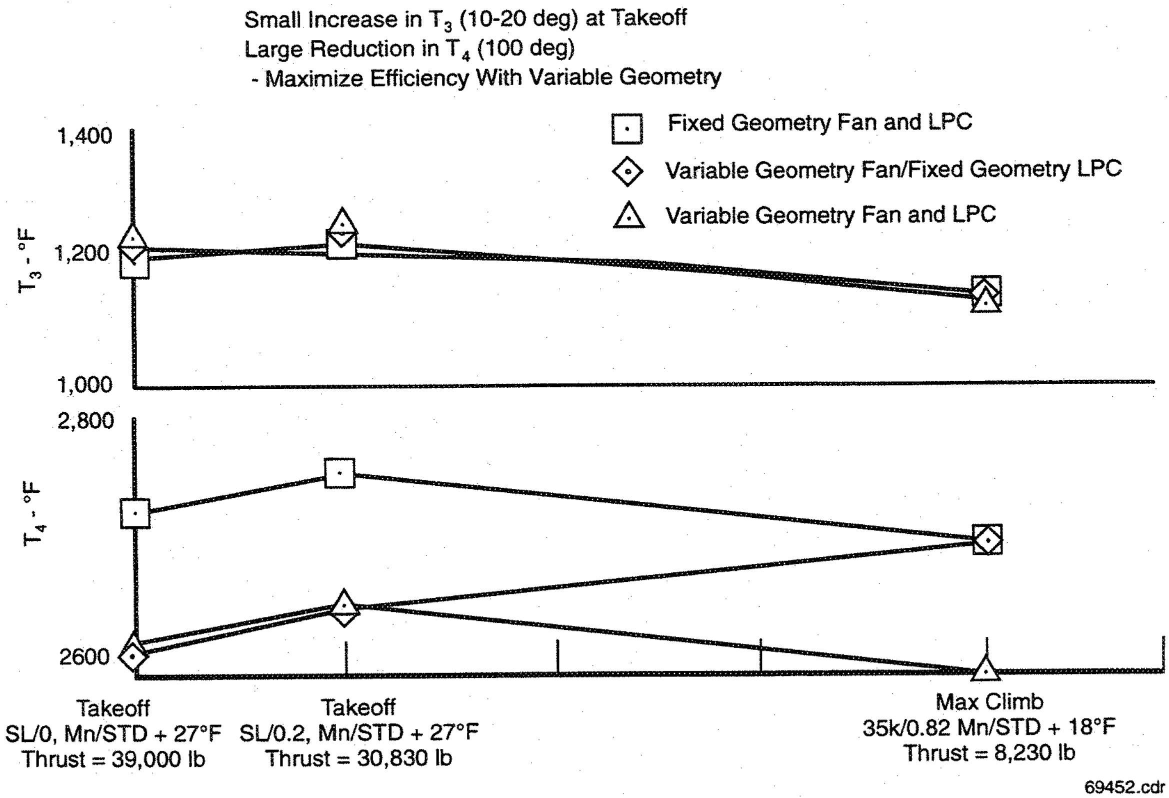


Figure 18. Effect of Fan and LPC Variable Geometry on ADP T_3 and T_4

Airplane thrust requirements can also impact rating differences between an ADP and a turbofan. For example, an airplane's growth path may lead to increased takeoff thrust requirements. An ADP is better able to respond to thrust growth because the low-pressure ratio fan has more throttling capability than the turbofan. The T_3/T_4 ADP and turbofan study engines were again used to assess this advantage. Figure 19 shows how the takeoff T_3 and T_4 for the ADP versus the turbofan change with increased takeoff thrust requirements. The takeoff/climb thrust ratio for the T_3/T_4 study ADP and turbofan was 3.75 and is noted on Figure 19. Takeoff (sea level/0.2 Mach number) thrust was then increased while holding climb (35,000ft/0.82 Mach number) thrust constant. As this was done, both the ADP and turbofan were throttle-bent (increased T_4) and the resulting differences in T_3 and T_4 between the two at takeoff were computed and plotted. As takeoff thrust increased, the ADP's T_3 and T_4 decreased relative to the turbofan. Figure 20 shows how fan and low compressor efficiencies are changing with thrust ratio for both the T_3/T_4 study ADP and turbofan engines. The ADP, with lower FPR and variable geometry, is able to retain a higher level of fan efficiency that translates to lower T_4. In addition, the ADP is able to hold the low compressor efficiency up, which contributes to the T_3 difference.

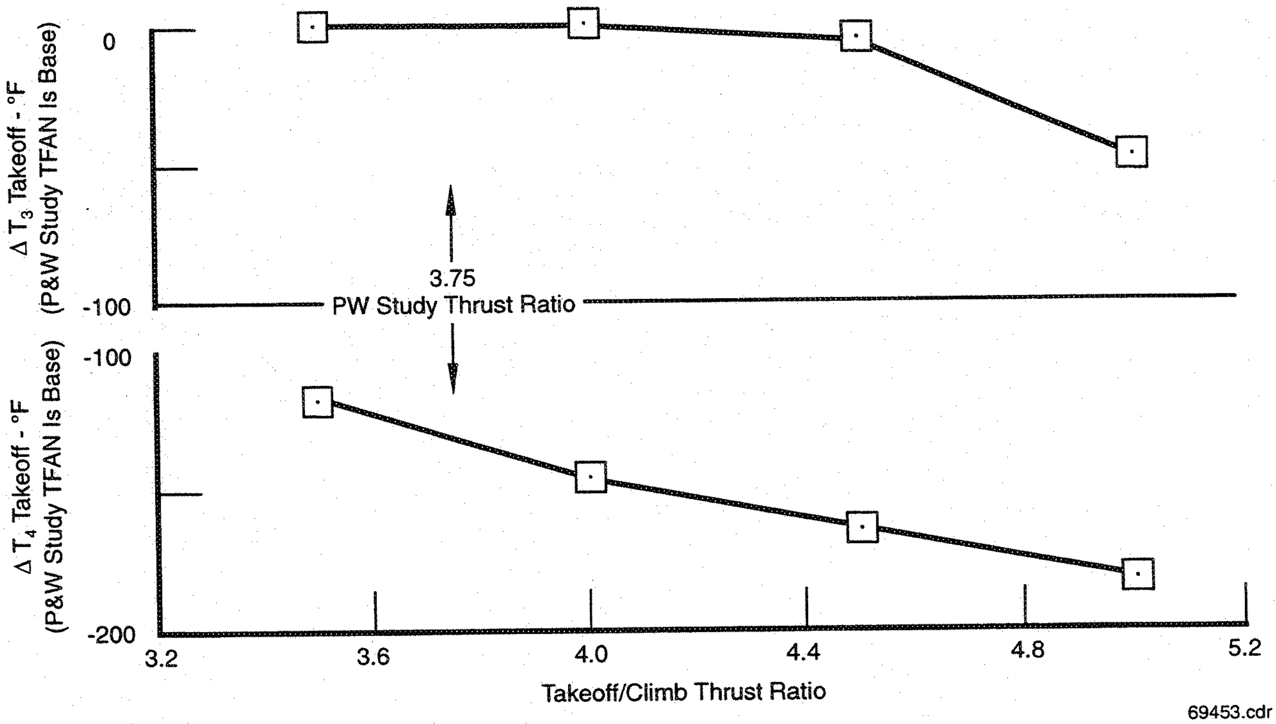


Figure 19. Airplane Thrust Requirements Impact Rating Differences

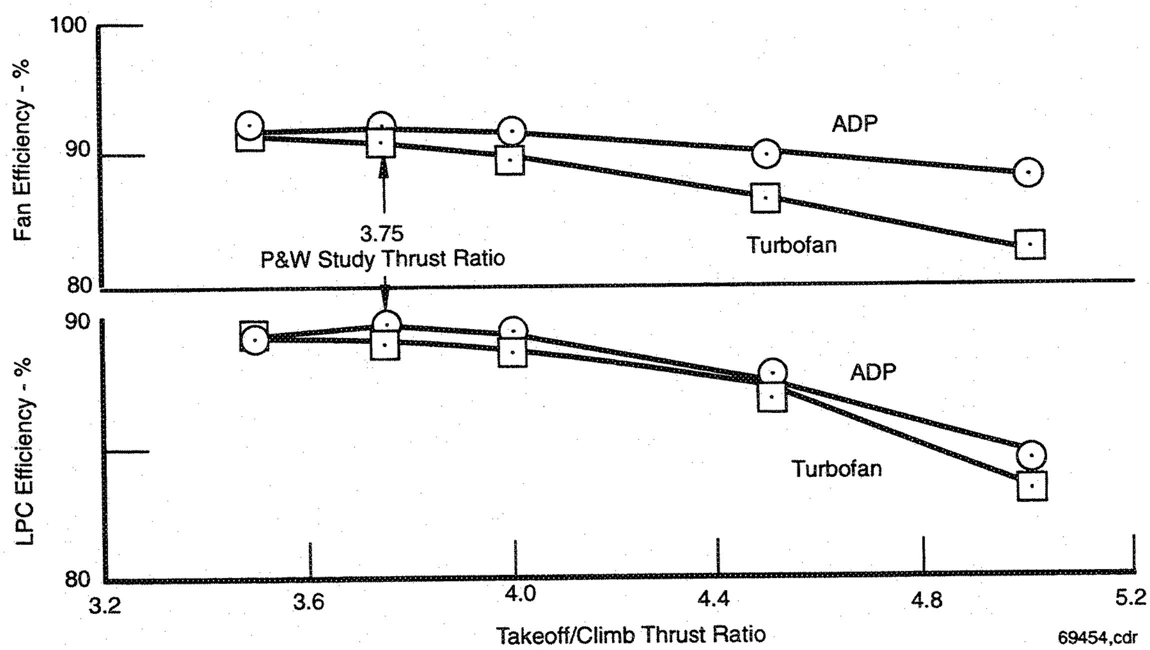


Figure 20. ADP FPR and Variable Geometry Provide Thrust Growth Advantage

In summary, the temperature rating structure of an ADP is different than a turbofan because of the propulsive advantage and different gross/net thrust lapse rate that the lower fan pressure ratio design brings, in addition to the variable geometry in the fan and LPC to make it work. The STS1046 ADP temperature rating structure is typical of other Pratt & Whitney study ADPs at that FPR design, even though the T_3 and T_4 levels seem to be very high when compared to the STF1043 turbofan.

3.6. 2005 EIS ADP ADVANTAGE

The ADP design has many advantages compared to a conventional turbofan. The lower FPR in the ADP translates to a propulsive advantage. The advantage results in lower TSFC at cruise and lower T_3/T_4 at takeoff, which offers lower NO_X emissions. The gear combined with the variable geometry fan and LPC in the ADP allows the fan, LPC and LPT to run at optimum speeds and efficiencies. The ADP has a takeoff noise advantage because of the lower duct jet velocity and lower fan tip speeds. Reduced T_4 at takeoff in the ADP, relative to a turbofan rated to similar thrusts, allows the ADP to have improved turbine airfoil life for the same climb T_4 or allows the ADP to run hotter climb T_4 for similar turbine airfoil life. The ADP's propulsive advantage allows for the option to have a smaller core engine than a turbofan for the same thrust requirements. Lower FPR design also gives the ADP a thrust growth advantage relative to a turbofan.

4. ECONOMIC BENEFIT ASSESSMENT

The economic figure of merit for Task XXXVIII was direct operating cost plus interest (DOC+I) that includes both engine and aircraft related operating costs and ownership costs (depreciation and interest). A mission analysis was performed to quantify the effects of the 2005 EIS STS1046 ADP engine on the economics of typical airline service.

4.1. AIRCRAFT SIMULATION

The Vehicle Analysis Modular Program (VAMP) aircraft performance simulation program was used for the analysis. The VAMP program has been in use and undergone continual development for approximately 20 years. The program is employed for a variety of uses in doing business with aircraft manufacturers and the airlines including thrust rating requirement evaluation, product line assessment, fuel burn, and other guarantee assessments. Experience with VAMP in working with both aircraft manufacturers and airlines has been excellent and the program is ideally suited for the requirements of Task XXXVIII.

The class of aircraft chosen for Task XXXVIII was a long-range quad (four engines) incorporating airplane technologies consistent with a year 2005 EIS. For consistency and convenience, the aircraft model developed with VAMP under the NASA funded High Technology UHBR Turbofan Propulsion Study (Contract NAS3-25952, Task 1) was employed for the study. The aircraft translated into a 470-passenger aircraft with today's three-class seating standards, which would represent the lower end of the anticipated new large aircraft. A takeoff field length requirement of 11,000 ft at sea level was chosen as representative for a large capacity long range aircraft operating from major large airports. This takeoff field length is also consistent with P&W-airframer studies involving this size aircraft. The aircraft performance requirements and characteristics are summarized in Tables 6 and 7.

The airplane technology improvements relative to today's airplanes represent modest evolutionary changes. The numbers in Tables 6 and 7 assume a general *cleaning up* of the airframe aerodynamically. It assumes selected light alloy or composite substitution for current aluminum alloy construction and some selected component design innovations for weight reduction. The wing loading is typical of the current 747's and is consistent with our aerodynamic assumptions. The span limitation and maximum takeoff gross weight (MTOGW) limitation reflect airport facility constraints. Gross weights over 1 million lb are envisioned as requiring new, increased strength runways and taxiways (thicker concrete and bases). The span is limited by gate facilities spacing and ground traffic interference. The airplane technology was kept constant for the study to isolate the effect of engine technology on aircraft performance and economics.

Table 6. Aircraft Performance Requirements

Passenger Capacity (Three-Class)	470 Passengers
Range (at Full Passengers + Baggage Payload)	8,000 nm
Cruise Speed	0.86 Mn
Takeoff Field Length (Sea Level, ISA + 27°F)	11,000 ft
Climb Requirements	
Maximum Time to 33,000 ft	30 min
Maximum Distance to 33,000 ft	225 nm
Minimum Rate of Climb	300 ft/min

Table 7. Aircraft Characteristics

Drag Technology Level	747-400 Less 5% Overall (Plus Aspect Ratio Increase)
Aspect Ratio	10
Quarter Chord Sweep	37.5 deg
Practical Span Limitation	240 ft
Wing Loading	150 lb/ft^2
Airframe Weight Technology Level	747-400 less 10%
MTOGW Limitation	1,000,000 lb

To recognize the full advantage of the performance and weight benefits of the advanced engine relative to the 1995 EIS STF1043 turbofan engine, the baseline airplane was simulated as a *rubber airplane*. In the rubberized simulation, the design range was fixed, wing loading (MTOGW/wing reference area) was held constant as were airplane performance requirements such as takeoff field length, rate of climb, and time to climb. The simulation not only represents installation of an advanced technology engine on a completely new aircraft but also recognizes the improved revenue potential economics related to improved payload ranges were the advanced engine to be installed on an existing fixed design aircraft. The engine performance, drag and weight of the STF1043 turbofan and the STS1046 ADP were then flown on the aircraft. The airplane weights, wing size, and engine thrust were then iterated on to match the design range as follows:

- The rubber airplane simulation assumes an initial input of MTOGW, fuselage configuration and engine performance, drag, and weight
- The wing area is then calculated based on a constant wing loading and the operating empty weight (OEW) and airplane drag is calculated
- The engine thrust is scaled to meet the airplane performance requirements.

Aircraft performance simulations assumed constant engine TSFC, weight and drag for each thrust class (STF1043 and STS1046) since thrust size iteration is quite modest within each class and it is assumed that fan diameter (nacelle size), weight and performance levels would not change. The small thrust changes involved would normally be accommodated within the basic engine configuration for each class. The range is compared to the desired range (8,000 nm) and iterated on until closure with the design range. At that point, the takeoff gross weight (TOGW) and associated airplane size, weight and drag required to fly 8,000 nm with 470 passengers when powered by either the STF1043 or STS1046 has been established.

In the study, the ADP provides performance improvements that allow the airplane to carry 470 passengers 8,000 nm at a 11.5 percent reduced TOGW. The reduced TOGW allows a reduction in aircraft empty weight in areas not associated with seat capacity (fuselage and passenger related systems). Operating empty weight was reduced by 27,890 lb (7.1 percent). The main contributors were the wing, tail, and landing gear that accounted for 94 percent of the operating empty weight reduction. The weight reduction in itself results in an additional significant fuel burn benefit that augments the fuel burn reduction from TSFC. Engine takeoff thrust for the STS1046 is 50,452 lb (3.9 percent less than the STF1043 because of the lower aircraft gross weight). The ADP engine thrust requirement was determined by time to climb rather than by takeoff performance. The higher lapse rate of ADP thrust with Mach number results in a higher takeoff thrust than a turbofan for the same aircraft weight. The STF1043 and STS1046 engine powered aircraft weight and performance characteristics are summarized in Table 8.

Table 8. Aircraft Weight and Performance Summary

	1995 EIS Turbofan (STF1043)	*2005 EIS ADP (STS1046)*	*2005 EIS Relative to 1995 EIS*
MTOGW, lb (8,000 nm)	858,668	759,953	-11.5%
Wing Reference Area, ft^2	5,724	5,066	-11.5%
Operating Empty Weight, lb	390,320	362,430	-7.1%
Manufacturing Empty Weight, lb	365,664	337,653	-7.7%
SLS Thrust/Engine, lb	52,531	50,452	-3.9%
Propulsion System Weight, lb	11,052	11,500	+4.1%
Begin Cruise Altitude, ft (4,000 nm)	35,000	35,000	No Change
End Cruise Altitude, ft (4,000 nm)	39,000	39,000	No Change
Average Cruise NAMS, nm/lb (4,000 nm)	0.02824	0.03415	+20.9%
Fuel Burn, lb (4,000 nm)	151,701	124,733	-17.8%

Potential benefits of takeoff weight reduction with a large long range aircraft would be increased revenue capability where MTOGW is limited by airport runway and taxiways. If, for instance, the perception is that a new large aircraft taxi weight is limited to 1 million lb unless current airport runways or taxiways were strengthened, an 11.5 percent TOGW savings would represent 115,000 lb. Therefore, the payload capability for an aircraft designed around a 1995 EIS engine would represent a TOGW of approximately 1.13 million lb but the aircraft would clear the 1 million lb limit when redesigned around an advanced 2005 EIS ADP; a very significant point. In addition, the reduced TOGW for the aircraft powered by the advanced engine may translate into significant noise benefits. A lighter TOGW aircraft, powered by a reduced thrust, smaller engine, is likely to be quieter than the base aircraft even with acoustically equivalent powerplants.

4.2. METHODOLOGY

Fuel burn, engine maintenance cost, and engine cost as reflected in engine price are the prime engine factors bearing on bottom-line economics. Airplane related maintenance costs as a function of manufacturer's empty weight and lower airframe price because of reduced weights of the wing, landing gear, tail, etc. are the prime airframe influences. Other cost reductions such as flight crew costs, landing fees, and navigation fees, are realized because of reduced MTOGW. The relationships employed to calculate direct operating costs for both the engines and the aircraft plus cost of capital or interest (DOC+I) are presented in Table 9. Discussions of the prime variables and the method of evaluating these variables are discussed in Section 4.3.

Table 9. Long-Range Quad Economics Groundrules and Cost Calculation Summary

OVERALL GROUND RULES		
Cost Year Dollars		1993 $
Type of Operation		International
Design Range, nm		8000
Economic Range, nm		4000
Economic Life, years		15
Residual Value After 15 Years, %		10
Annual Utilization, trips/year		480
Seating Capacity, three class		470
Passenger + Baggage Wt, lb		210
COST CALCULATION (DOLLARS/FLIGHT)		
Flight Crew Cost	=	\$482 + \$0.59 (MTOGW/1000)
Where		
MTOGW, lb	=	Maximum takeoff gross weight for 8000 nm design mission
Fuel Cost	=	$\frac{\text{(Fuel Burn)} \times \text{(Fuel Price)}}{\text{Fuel Density}}$
Where		
Fuel Density, lb/U.S. gal	=	6.7
Fuel Price, \$/U.S. gal	=	0.70
Fuel Burn	=	4000 nm flight with full passengers and baggage payload, assuming no other cargo
Engine Maintenance Material Costs	=	(EMMC) × (Number of Engines) × FH
Where		
EMMC, \$/EFH	=	Engine maintenance material cost/engine (input item)*
Number of Engines	=	4
FH, hr	=	Flight Hours for 4000 nm flight
** Engine maintenance cost is estimated for each engine configuration*		
Engine Maintenance Labor Costs	=	(EMLR) × (Labor Rate) x (Number of Engines) × FH
Where		
EMLR, hr/EFH	=	Engine Maintenance Labor Rate/Engine/EFH (input item)*
Labor Rate, \$/hr	=	(\$25) × (3.0) (Represents a base \$25/hour rate and 200% burden)
Number of Engines	=	4
FH, hr	=	Flight hours for 4000 nm flight
** Engine maintenance cost is estimated for each engine configuration*		
Airframe Maintenance Material Costs	=	(AFMC + AFMH × FH) × 1.042
Where		
AFMC	=	$15.20 + \left(\frac{97.33 \times AFW}{100{,}000}\right) - 2.862 \times \left(\frac{AFW}{100{,}000}\right)^2$
AFMH	=	$12.39 + \left(\frac{29.80 \times AFW}{100{,}000}\right) + 0.1806 \times \left(\frac{AFW}{100{,}000}\right)^2$

Table 9. Long-Range Quad Economics Groundrules and Cost Calculation Summary (Continued)

AFW	=	Operating empty weight less engine weight. It is recognized that AFW is often viewed as manufacturer's empty weight (MEW) less engine weight but OEW was used for convenience and the effect on cost differential between the base and year 2005 EIS engine powered aircraft is insignificant
FH, hr	=	Flight hours for 4000 nm flight
Airframe Maintenance Labor Costs	=	(Labor Rate) × (AFLC + AFLH x FH)
Where		
Labor Rate, $/hr	=	($25) × (3.0) (Represents a base $25/hr rate and 200% burden)
AFLC	=	$1.614 + \left(\frac{0.7227 \times AFW}{100,000}\right) + 0.1024 \times \left(\frac{AFW}{100,000}\right)^2$
AFLH	=	$1.260 + \left(\frac{1.774 \times AFW}{100,000}\right) - 0.1071 \times \left(\frac{AFW}{100,000}\right)^2$
AFW	=	Operating empty weight less engine weight
Depreciation	=	$\frac{(\text{Investment}) \times (1 - \text{Residual Value})}{(\text{Depreciation Pd}) \times (\text{No. Flights})}$
Where		
Investment	=	Airframe Price + Airframe Spares + Engine Price + Engine Spares
Where		
Airframe Spares	=	6% of Airframe Price
Engine Spares	=	23% of Engine Price
Residual Value	=	Value after 15 years = 10%
Depreciation Pd.	=	Economic Life = 15 years
No. Flights	=	480 Flights Per Year
Interest*	=	4.13% of Investment Per Year
	=	$\frac{0.0413\ (\text{Investment})}{(\text{No. Flights/Year})}$
** Interest calculation is presented in Table 10*		
Insurance	=	0.35% of Flyaway Price Per Year
	=	$\frac{0.0035\ (\text{Flyaway Price})}{(\text{No. Flights/Year})}$
Cabin Crew	=	$\frac{\$78 \times \text{Seats} \times \text{Block Hours}}{30}$
Where		
Block Hours	=	Block hours (gate-to-gate) for 4000 nm. flight
	=	Flight hours + 18 minute taxi
Landing Fees	=	$\frac{\$4.25 \times \text{MTOGW}}{1000}$
Navigation Fees	=	$(\$0.136) \times (\text{OLD}) \times \left(\frac{\text{MTOGW}}{1000}\right)^{\frac{1}{2}}$
Where		
OLD, nm	=	Overland Distance = 500

Table 10. Calculation of Interest Expenses

$$\text{Average Annual Interest} = \frac{\text{Loan Value}}{\text{Depreciation Period}} \times \left[\frac{(\text{Loan Period} \times \text{Payments / yr}) + 1}{2 \times \text{Payments / yr}}\right] \times \text{Interest Rate}$$

Where

Loan Value	=	Investment = Flyaway Price + Spares
Depreciation Period	=	15 Years
Loan Period	=	15 Years
Interest Rate	=	8%

$$= \frac{\text{Investment}}{15} \times \left[\frac{(15 \times 2) + 1}{2 \times 2}\right] \times 0.08$$

$$= \text{Investment x } 0.0413$$

Note: The above is analogous to averaging the annual interest payments for a 15 year loan with two payments per year on a loan for the investment less a residual value at the end of the 15 years of 10% of investment.

4.3. PRIME ECONOMICS VARIABLE EVALUATION

There are certain prime influences on the economic impact of an advanced technology engine that warrant detailed discussion. The purpose of the section is to provide insight into these variables. The following will be discussed:

- Takeoff gross weight, engine thrust, and fuel burn
- Engine weight
- Engine price
- Engine maintenance cost
- Airplane and airframe price.

4.3.1. Takeoff Gross Weight, Engine Thrust, and Fuel Burn

The most basic parameter that reflects the effect of engine technology is probably aircraft takeoff gross weight required for the design mission (in the study 8,000 nm). Engine improvements allow the design mission to be satisfied with a much lighter MTOGW. The lower MTOGW allows for a wing area reduction and lighter structural weight that increases the fuel burn benefit and should reduce the cost of producing the aircraft. MTOGW reduction also results in a smaller engine that should reduce engine price and maintenance cost. A review of Table 9 shows that MTOGW, aircraft weight, engine and airplane price, and maintenance cost and fuel burn are all related to MTOGW and affect all DOC+I cost categories with the exception of cabin crew costs. Crew costs are a function of seating capacity that was held constant for the study. MTOGW is the summation of aircraft operating weight empty, payload, and fuel load to meet design requirements. Table 11 summarizes the MTOGW composition of the STF1043 turbofan and STS1046 ADP powered aircraft. The data in Table 11 show that changes in OEW reduce MTOGW by 28.2 percent, while savings in flight fuel and reserves account for the remaining 71.8 percent. Of the 28.2 percent MTOGW reduction from OEW, 94 percent results from wing, tail, and landing gear weight reductions. Changes in OEW also contribute to the reduced fuel burn. (Less airplane weight to carry means less fuel to fly 8,000 nm.)

Table 11. Maximum Takeoff Gross Weight Composition

	1995 EIS Turbofan STF1043 (lb)	*2005 EIS ADP STS1046 (lb)*	*STS1046 Versus STF1043 (%)*	*Δ as of % of MTOGW Δ (%)*
Wing	142,269	120,904	-15.0	-21.6
+ Fuselage	70,392	70,784	+0.6	+0.4
+ Tail	8,186	6,995	-14.6	-1.2
+ Landing Gear	36,434	32,641	-10.4	-3.8
+ Other	108,383	106,329	-1.9	-2.1
= Manufacturing Empty Weight	***365,664***	***337,653***	***-7.7***	***-28.3***
+ Operator Items	24,656	24,776	+0.5	+0.1
= Operating Empty Weight	***390,320***	***362,430***	***-7.1***	***-28.2***
+ Payload	98,700	98,700	N/C	0
+ Flight Fuel Burn	334,030	269,695	-19.1	-65.2
+ Reserves	35,618	29,128	-20.5	-6.6
= MTOGW	***858,688***	***759,953***	***-11.5***	***100.00***

Fuel burn and MTOGW are directly related. Table 11 shows the relationship between MTOGW and OEW. The OEW reduction effects the fuel burn for the 4,000 nm economics mission by about 0.15 percent/1,000 lb OEW. Therefore, the 27,890 lb OEW benefit for the advanced ADP shown in Table 11 results in about a 4 percent fuel burn reduction that augments TSFC benefits and more than offsets weight and drag increase that may be incurred with a high bypass larger diameter ADP engine. Figure 21 presents the relationship between fuel burn for a 4,000 nm flight and MTOGW for an 8,000 nm design mission. The cases shown were run to establish TSFC, weight and drag influence factors. The approach was to improve the base engine and degrade the advanced engine to be able to couple the two trends to show continuity between the two. Figure 21 shows a direct relationship between TSFC and drag effects on fuel burn as a function of TOGW. Engine weight effects are offset from the line drawn between the base and advanced engine because engine weight changes MTOGW so directly.

Engine thrust is also directly related to MTOGW for an aircraft incorporating the same airplane technology such as was done for the study. Figure 22 shows the relationship between engine maximum sea-level takeoff thrust and MTOGW and illustrates an interesting aspect of the very high bypass ratio ADP. If both the base STF1043 turbofan and the advanced technology STS1046 ADP engines were a similar bypass ratio exhibiting similar thrust lapse rates with Mach number, thrust sizing would be determined by takeoff and the thrust, as a function of MTOGW, would be continuous. However, the very high bypass ratio ADP has a greater net thrust lapse rate with Mach number than the base turbofan requiring the ADP thrust to be sized by climb requirements, which was maintained at 30 minutes time to climb to 33,000 ft. Distance to climb to 33,000 ft was under 225 nm and rate of climb at top of climb was well above 300 ft/min , which are both acceptable. Sizing the ADP to climb resulted in a thrust level at sea level 8.6 percent above the STF1043 turbofan for the same airplane MTOGW. The effect is consistent with results from other Pratt & Whitney studies for specific airplane applications. Despite the above effect, the STS1046 ADP thrust required was still 3.9 percent lower than that of the base turbofan engine as shown in Table 8.

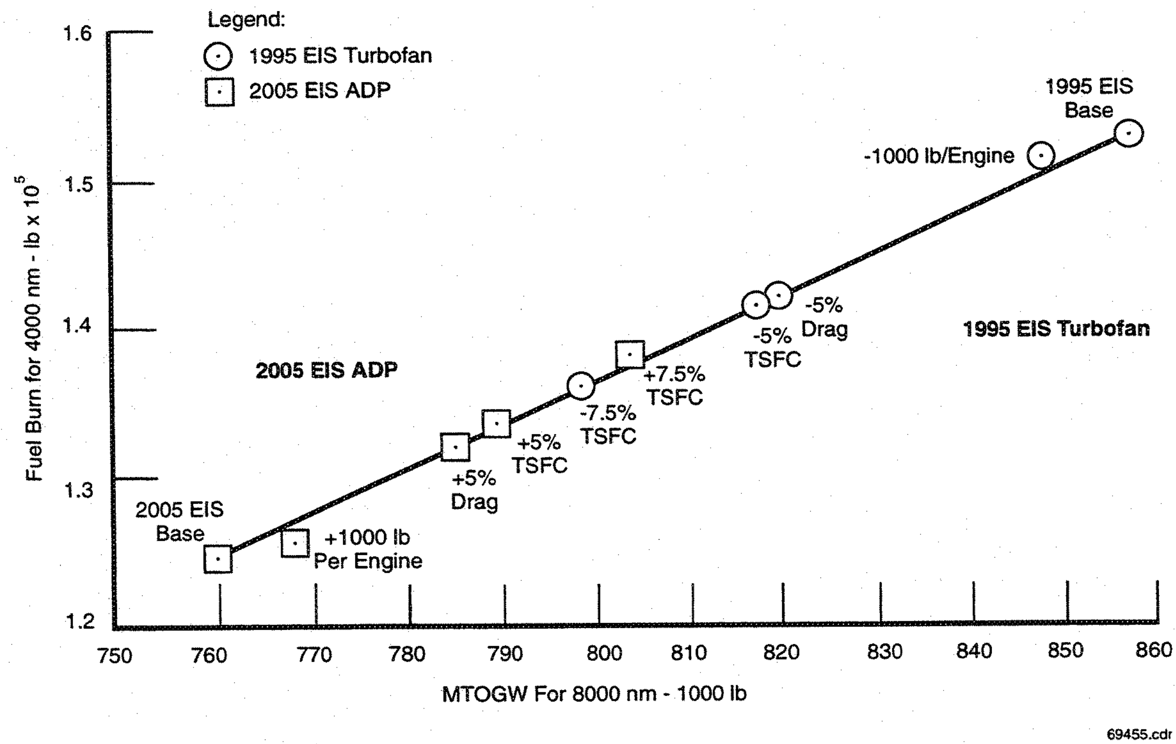


Figure 21. Fuel Burn Reflects Technology Effect on Aircraft Size

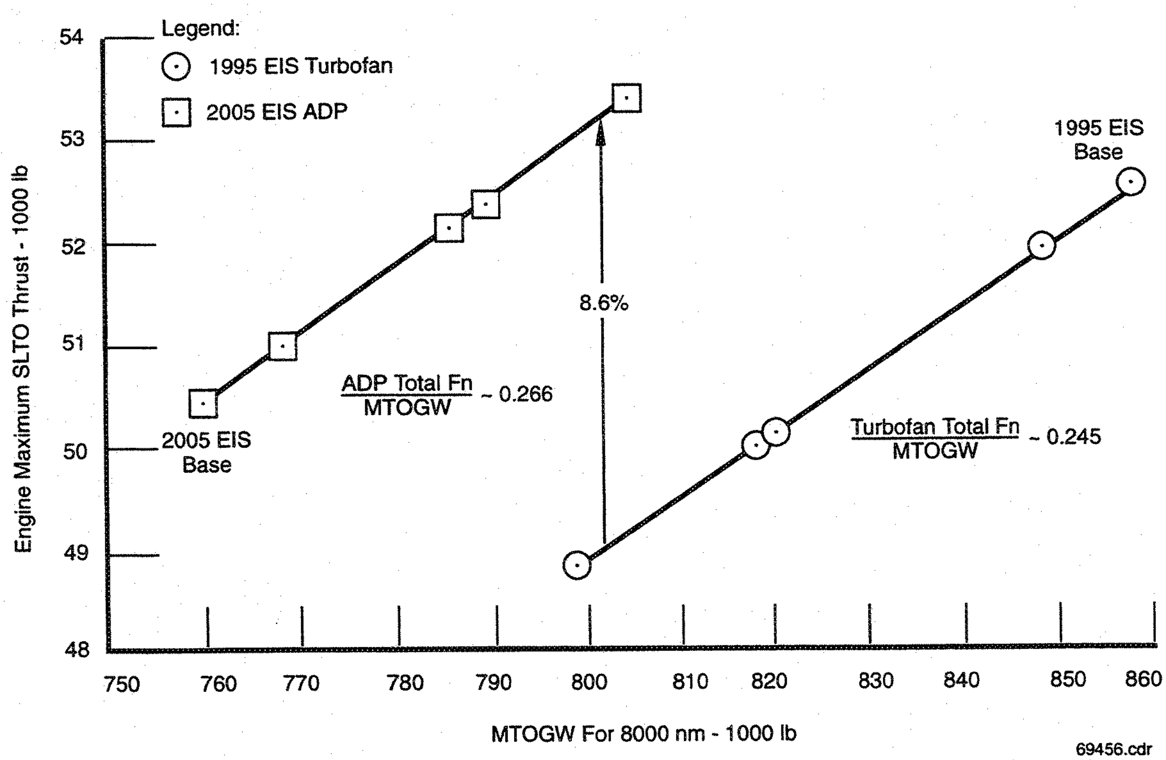


Figure 22. Takeoff Thrust Advantage of 2005 EIS ADP

4.3.2. Engine Weight

Propulsion system weight was estimated employing a methodology developed over years of assessing weight for current and advanced engines. The STF1043 is representative of the PW4000 engine family. For the purposes of economic assessment and the calculation of airframe weight to be used to calculate airframe maintenance, a constant thrust/lb. weight of 52,521 lb/11052 lb or 4.75 was employed for the base case and trade factors related to the STF1043.

The methodology employed to estimate propulsion system weight uses one or more of the following weight group methods:

- Geometric Scaling
- Classical Scaling
- Detailed Weight Analysis
- Weight Trend Charts.

The weight for the STS1046 ADP propulsion system was estimated using primarily the geometric scaling and detailed weight analysis methods, except for the core (HPC through HPT). Current ADPs use an existing core (V2500, PW2040, PW4000) so the weight for this section of the engine represents existing hardware. The core weight for the advanced engine was estimated based on the ATCC.

The low spool (LPC, low shaft, LPT and bearings), externals and accessory gearbox weights were estimated using geometric scaling and detailed weight analysis methods. The geometric scaling method works very well for estimating weights of conventional engine hardware, which is the case for these sections of the engine. The geometric scaling method uses existing engine/nacelle hardware weight and size (e.g. PW4000, PW2000, V2500) as a basis. These weights are scaled geometrically to the study engine size and adjusted using standard structural methods and criteria for engine loads, pressures, temperature, and material changes relative to the base hardware.

The ADP propulsor modules are the fan rotor, fan rotor support, fan variable pitch system, fan case, inlet case, fan drive gearbox, and nacelle. The fan case and inlet case are conventional turbofan structures and geometric scaling is used for estimating the weights of these items. The fan rotor and fan rotor support, fan exit case and nacelle have unique features relative to conventional turbofan hardware. Extensive analytical work, including finite element analysis, has been completed and is ongoing to understand and size these components relative to conventional turbofan engines. Weights are based on the results of the continuing analytical work. The fan variable pitch system and fan drive gearbox are unique to the ADP propulsion system. The variable pitch system weight is based on extensive analytical analysis combined with component fabrication and testing. A full variable pitch rig is currently being built to substantiate the design system. The fan drive gearbox system weight comes from a Rules Based Design System that was developed for the fan drive gearbox. Follow-on rig testing correlated very well with analytical predictions.

The weight for the 50,452 lb thrust STS1046 ADP was 11,500 lb resulting in a thrust to weight value of 4.39. As with the STF1043 turbofan, the thrust to weight for the advanced engine of 4.39 was held constant in the economic assessment for trade factors related to the STS1046.

4.3.3. Engine Price

Engine price, for the purposes of Task 38, is assumed to be full price without the discounts that would normally be offered in a marketing campaign. The assumption is typical of product line economic studies. The STF1043 engine price was assumed to be $115/lb of takeoff thrust, which is representative of the PW4000 family. Using Pratt & Whitney experience, nacelle and engine build-up was assumed to add about 35 percent, which increased the turbofan propulsion system price to $155/lb of thrust. Previous Pratt & Whitney studies have shown that an ADP configuration, such as the STS1046, is estimated to add about 10 percent to the propulsion system price resulting in a rate of $170/lb of thrust for the ADP propulsion system. Figure 23 presents the above propulsion system prices as a function of takeoff thrust and shows the various cases employed for the study. The overall result is that the STS1046 ADP powered airplane requires 3.9 percent less thrust than the STF1043 turbofan powered aircraft but the ADP is 10 percent more expensive per pound of thrust resulting in a 5.4 percent overall more expensive powerplant for the STS1046 case ($8.577M versus $8.1408M).

4.3.4. Engine Maintenance Cost

The maintenance cost estimates for commercial engines are evaluated using a model developed for modern subsonic commercial engines. The model is based on a methodology developed over years of assessing maintenance cost for product line studies, marketing campaigns involving comprehensive maintenance cost guarantees, and evaluations to help airline operators manage their maintenance costs. Parametric maintenance cost analysis is facilitated by the use of a computerized maintenance cost estimating system. The estimating system uses a bottom-up method whereby total engine material and labor is built up from the individual parts and modules. Material cost is determined from predicted part scrap lives combined with estimated spare parts prices. Labor is determined by parts counts, features, and size combined with frequency of repair of key parts and modules. Spare parts price information is derived from the manufacturing cost estimate (or actual spare part catalog prices if available). Part life and maintenance labor data is derived through comparisons to Pratt & Whitney's data base of part lives and module labor for existing commercial and military engines incorporating factors unique to the engine mission, operating parameters, configurations, size, and complexity.

Total bare engine maintenance cost (labor and material) for the turbofan engine representative of PW4000 technology can be represented as 1.5 (takeoff thrust) + 5, where takeoff thrust is in thousands of pounds and maintenance cost is in 1993 $/engine flight hours/engine. Using this formula, maintenance cost for the 52,531 lb thrust STF1043 turbofan is estimated to be $83.80. The maintenance cost for an advanced core ADP was estimated as 5 percent higher than the base turbofan employing the above described methodology and accounting for the addition of a fan drive gear system and variable pitch mechanism balanced somewhat by the elimination of a traditional thrust reverser. Thus, the total maintenance cost for the 50,452 lb. thrust STS1046 would be $84.71. The overall result is that, even though the advanced ADP powered airplane requires 3.9 percent less thrust than the turbofan powered aircraft, the 5 percent higher maintenance cost for the ADP results in a 1.1 percent higher maintenance cost for the STS1046 ADP. Figure 24 illustrates the above.

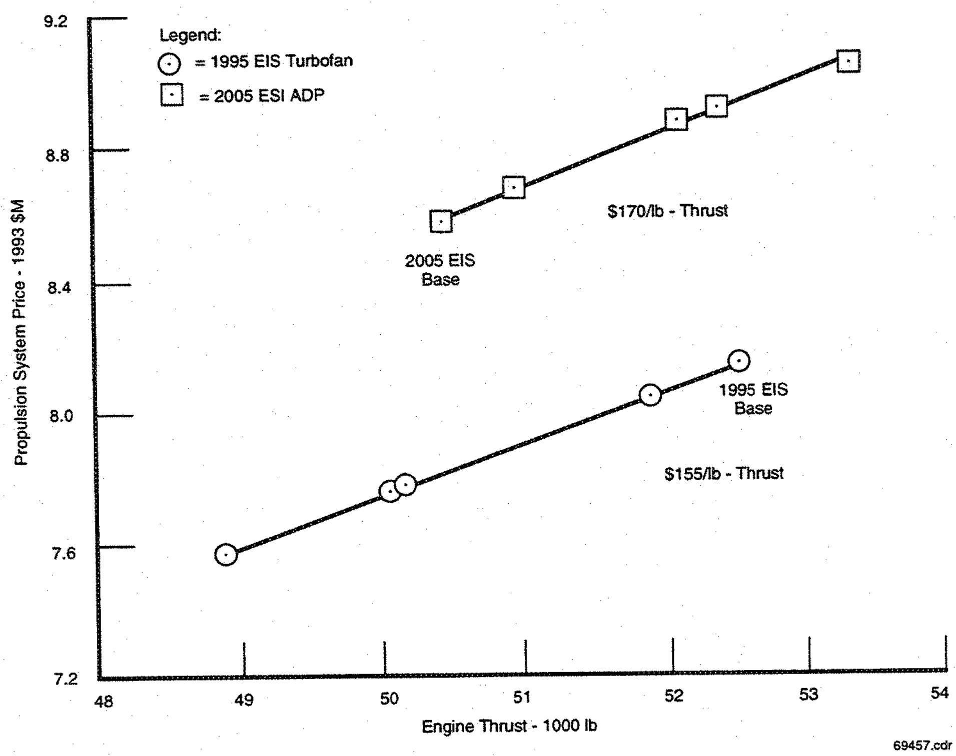


Figure 23. Effect of Thrust on Propulsion System Price

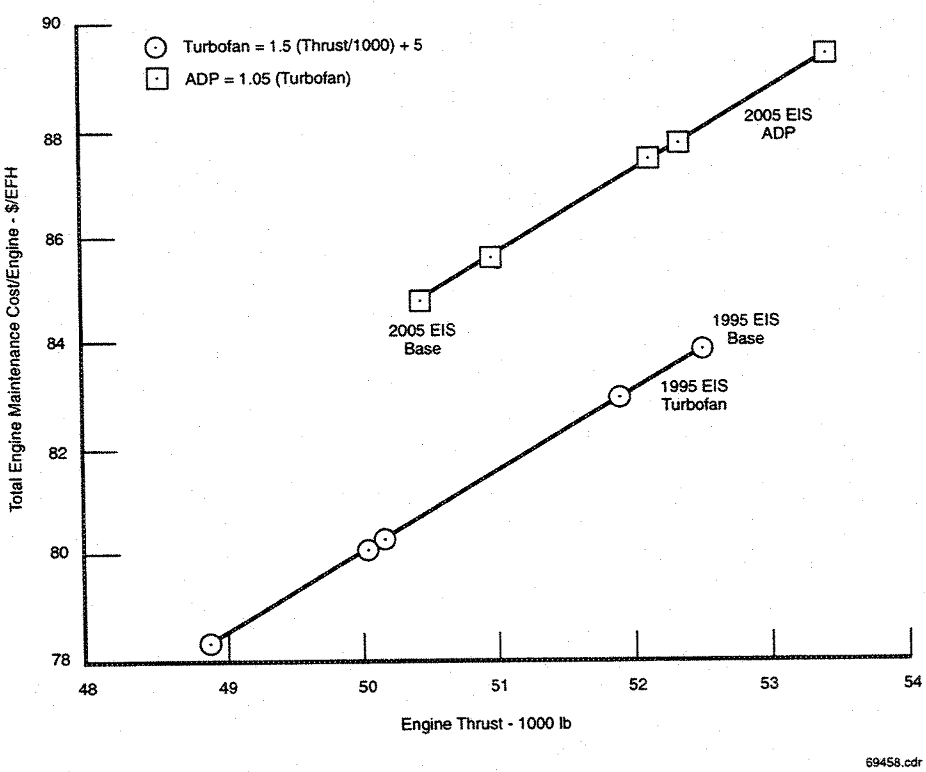


Figure 24. Effect of Thrust on Engine Maintenance Cost

4.3.5. Airplane and Airframe Price

Airplane price, like engine and propulsion system price, is viewed as being an undiscounted price. Pratt & Whitney maintains an awareness of airplane prices as part of the process of assessing product line opportunities from an economic/market viewpoint. Normally, aircraft can be viewed as being priced as a function of seating capacity with a small bias for range capability. A regression of long range aircraft resulted in a flyaway price of $170M as representative for a 470 seat airplane. It should be noted that the aircraft price chosen will not effect the results of this study as long as it is representative. The important facet is how airplane price is varied with engine changes that effect TOGW and, therefore, airplane size and weight to meet the 8,000 nm range requirements. While acknowledging that, in the marketplace, aircraft price is based on seats (a measure of airplane productivity), airplane price was changed from the $170M base case to recognize airplane weight changes mostly because of wing, landing gear, tail size, and other weights related to TOGW. Since airplane technology was maintained constant in the study, a constant cost or price per pound of airframe weight was assumed. This significantly effects the economic assessment of advance engine technology because advanced engine technology reduces airframe weight and price as illustrated in Table 12.

Table 12. Effect of Engine Technology on Airframe Weight and Price

	1995 EIS Turbofan STF1043	*2005 EIS ADP STS1046*	*Effect of Engine Technology*
MTOGW, lb	858,668	759,953	-11.5%
Manufacturing Empty Weight, lb	365,664	337,653	-7.7%
Propulsion System Weight, lb	11,052	11,500	
MEW - Propulsion System, lb	321,456	291,653	
Add 6,500 lb for ADP Installation	0	+6,500	
Airframe Weight	321,456	298,153	-7.2%
Airframe Price, $M	137.437	127.472	-7.2%
			~ 10M

The $10M or 7.2 percent reduction in airframe price increases the effect on DOC+I of the STS1046 ADP by 2.5 percentage points, which is significant. Inclusion of this effect is considered appropriate since an airframe manufacturer with a lighter aircraft resulting from advanced propulsion technology should be more competitive in the marketplace and maintaining a constant price per pound if airframe weight is a method of recognizing this advantage.

4.4. PERFORMANCE AND PRICE RELATED INFLUENCE FACTORS

An objective of the AST Technology study was to provide appropriate influence factors to illustrate the relative importance of selected propulsion system characteristics. Table 13 provides a summary of the influence of propulsion system TSFC, drag, weight, maintenance cost, and price on DOC+I. Also included are the effects of airframe price on DOC+I.

Table 13. Performance and Price-Related Influence Factors

Change	*Δ Fuel Burn*	*Δ DOC + I*
1% TSFC	1.32%	0.65%
1% Drag	1.13%	0.58%
1000 lb/Engine Weight	0.81%	0.65%
10% Engine Maintenance Cost	0.0	0.34%
10% Engine Price	0.0	1.11%
1% Airframe Price	0.0	0.35%

4.5. 2005 EIS ADP ECONOMIC ADVANTAGE

The STS1046 2005 EIS ADP propulsion system provides a 6.6 percent reduction in DOC+I compared to the base STF1043 1995 EIS turbofan engine, which is very significant. Although the assessment of an economic hurdle for a new product is often subjective, industry discussions generally assessed 3-5 percent improvement as significant. If a 10 percent improvement in DOC+I is viewed as required to justify the launch of a new airplane then 6.6 percent from the propulsion system represents two-thirds of that goal. Table 14 summarizes the economic results and Table 15 provides a detailed input and output summary for the cases considered.

Table 14. Summary of 2005 EIS ADP Economics

			Constant Airframe Price		*Constant Airframe Price/lb*	
Cost Category	*1995 EIS Turbofan*	*(A) Percent of Total*	*(B) Percent Change*	*(A) × (B) Percent Δ DOC + I*	*(C) Percent Change*	*(C) × (B) Percent Δ DOC + I*
Flight Crew	8,588	9.6	-5.9	-0.56	-5.9	-0.56
Fuel	15,849	17.8	-17.8	-3.17	-17.8	-3.17
Engine Maintenance	2,811	3.1	+1.1	+0.04	+1.1	+0.04
Airframe Maintenance	5,330	6.0	-5.1	-0.31	-5.1	-0.31
Depreciation	23,217	26.0	+1.1	+0.29	-4.5	-1.17
Interest	15,981	17.9	+1.1	+0.20	-4.5	-0.81
Insurance	1,240	1.4	+1.1	+0.02	-4.8	-0.07
Cabin Crew	10,615	11.9	N/C	0.0	N/C	0.0
Landing Fees	3,649	4.1	-11.5	-0.47	-11.5	-0.47
Navigation Fees	1,993	2.2	-5.9	-0.13	-5.9	-0.13
DOC + I	89,273	100.0		-4.09		-6.65

Year 2005 EIS ADP DOC + I = $85,641/Flight

Year 1995 EIS Turbofan DOC + I = $89,293/Flight

Year 2005 EIS ADP DOC + I Advantages = 4.09% (Airframe Price = Constant)

Year 2005 EIS ADP DOC + I Advantages = 6.65% (Airframe Price/lb = Constant)

Table 14 shows a breakdown by cost category and the effect in each category for the STS1046 ADP. The major influences are fuel burn (-3.17 percent DOC+I), price related costs such as depreciation, insurance, and interest (-2.05 percent), and TOGW related costs such as flight crew, navigation and landing fees (-1.16 percent). Engine and airframe maintenance effects are relatively small. As a matter of perspective, it should be mentioned that although engine maintenance costs appear to be a relatively small ingredient in DOC+I, acceptable product introduction risk is extremely important, especially for extended twin over-water operation. Delays and cancellations, diversions to alternate airports etc. are very important to avoid in airline operation and are not adequately reflected in DOC+I. Technology insertion into product lines must be at low risk that accentuates the importance of technology focus well through the development cycle.

Table 15. Economic Analysis Input/Output Summary

Variable	Units	ECONOMIC ANALYSIS WITH AIRFRAME PRICE/WEIGHT HELD CONSTANT										ENG/AC PRICE & TOGW EFF.		
		Base	*-5% SFC*	*-7.5% SFC*	*-1K/Engine*	*-5% Drag*	*Base*	*+5% SFC*	*+7.5% SFC*	*+1K/Engine*	*+5% Drag*	*+1% E/PR*	*+1% AFP*	*+1% TOW*
Aircraft		LR Quad	LR Quad	LR Quad	LR Quad	LR Quad	LR Quad	LR Quad	LR Quad	LR Quad	LR Quad	LR Quad	LR Quad	LR Quad
Engine		1995 EIS	1995 EIS	1995 EIS	1995 EIS	1995 EIS	2005 EIS	2005 EIS	2005 EIS	2005 EIS	2005 EIS	2005 EIS	2005 EIS	2005 EIS
Operation		Int'l	Int'l	Int'l	Int'l	Int'l	Int'l	Int'l	Int'l	Int'l	Int'l	Int'l	Int'l	Int'l
Maximum TOGW	1000 lb	858.668	818.226	799.161	848.671	820.191	759.953	789.183	804.404	768.124	785.425	785.425	785.425	793.2793
Maximum Landing Weight	1000 lb	557.889	567.138	562.161	570.879	567.654	552.708	560.173	564.117	559.131	559.205	559.205	559.205	559.205
Manufacturer Empty Weight	1000 lb	365.664	353.902	348.401	359.288	354.471	337.653	346.008	350.385	343.456	344.93	344.93	344.93	344.93
Propulsion System Weight/Engine	1000 lb	11.052	10.533	10.288	10.925	10.558	11.5	11.942	12.173	11.624	11.885	11.885	11.885	11.885
Airframe Weight = MEW-PS Weight (+6500 lb ADP)	1000 lb	321.456	311.77	307.25	319.06	312.239	298.153	304.74	308.393	299.46	303.89	303.89	303.89	303.89
Seat Class		3 Class	3 Class	3 Class	3 Class	3 Class	3 Class	3 Class	3 Class	3 Class	3 Class	3 Class	3 Class	3 Class
Number of Seats		470	470	470	470	470	470	470	470	470	470	470	470	470
Payload	1000 lb	98.7	98.7	98.7	98.7	98.7	98.7	98.7	98.7	98.7	98.7	98.7	98.7	98.7
Economic Range	nm	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
Flight Time	Hours	8.3868	8.3811	8.3785	8.3856	8.389	8.3868	8.3916	8.3926	8.3877	8.3807	8.3807	8.3807	8.3807
Block Time	Hours	8.6868	8.6811	8.6785	8.6856	8.689	8.6866	8.6916	8.6926	8.6877	8.6807	8.6807	8.6807	8.6807
Engine SLS To Thrust	1000 lb	52.51	50.055	48.889	51.917	50.175	50.452	52.393	53.403	50.994	52.143	52.143	52.143	52.143
Number of Engines		4	4	4	4	4	4	4	4	4	4	4	4	4
Propulsion System Price/Position	$M	8.1406	7.7585	7.5778	8.0471	7.7771	8.577	8.907	9.079	8.669	8.664	8.95264	8.864	8.864
Airframe Price	$M	137.4368	133.2941	131.3617	136.419	133.494	127.472	130.306	131.85	128.031	129.925	129.925	131.224	131.224
FlyawayPrice	$M	170	164.328	161.6729	168.607	164.605	161.78	165.934	168.168	162.709	165.381	165.734	166.68	168.68
Engine Spares	DEC %	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Airframe Spares	DEC %	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Total Investment	$M	185.7357	179.483566	176.5262	184.19587	179.766972	177.3192	181.9468	184.42968	178.3643	181.33138	181.7675	182.7083	182.70832
Depreciation Period	Years	15	15	15	15	15	15	15	15	15	15	15	15	15
Residual Value	DEC %	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Fuel Burn/Flight	Lb	151701	140603	135325	150186	141285	124733	132929	137178	125747	131769	131769	131769	131769
Fuel Density	Lb/USG	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7
Fuel Price	$/USG	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Engine MMC/Engine	$/EFH	38.78	35.06	33.33	37.88	35.26	39.74	42.77	44.36	40.57	42.38	42.38	42.38	42.38
Engine MLR/Engine	MH/EFH	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Base Labor Rate	$/MH	25	25	25	25	25	25	25	25	25	25	25	25	25
Burden	DEC %	2	2	2	2	2	2	2	2	2	2	2	2	2
Utilization	Flights/Yr	480	480	480	480	480	480	480	480	480	480	480	480	480
Annual Insurance	FAP %	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035
Annual Interest	Inv %	0.0413	0.0413	0.0413	0.0413	0.0413	0.0413	0.0413	0.0413	0.0413	0.0413	0.0413	0.0413	0.0413
Results														
Flight Crew	$/Flight	8587.70	8375.12	8274.99	8535.48	8392.82	8081.77	8236.32	8315.33	8124.68	8206.74	8206.74	8206.74	8246.97
Fuel	$/Flight	15849.36	14689.68	14138.43	15691.07	14761.12	13031.81	13888.10	14332.03	13137.75	13766.91	13766.91	13766.91	13766.91
Engine Maintenance Material Costs	$/Flight	1300.93	1176.04	1117.02	1270.59	1183.18	1333.13	1435.63	1489.18	1361.16	1420.70	1420.70	1420.70	1420.70
Engine Maintenance Labor Costs	$/Flight	1509.59	1508.6	1508.13	1509.41	1510.02	1509.59	1510.49	1510.67	1509.79	1508.53	1508.53	1508.53	1508.53
AFMC	$/Flight	298.5	290.83	287.23	296.62	291.2	279.95	285.23	288.14	281	284.55	284.55	284.55	284.55
AFMH	$/Flight	110.05	107.05	105.66	109.31	107.2	102.85	104.88	106.01	103.25	104.62	104.62	104.62	104.62
Airframe Maintenance Material Costs	$/Flight	1272.75	1237.95	1221.71	1264.25	1240.48	1190.45	1214.28	1227.3	1195.19	1210.08	1210.08	1210.08	1210.08
AFLC	MH/Flight	5	4.86	4.8	4.96	4.87	4.68	4.77	4.82	4.7	4.76	4.76	4.76	4.76
AFLH	MH/FH	5.86	5.75	5.7	5.83	5.75	5.6	5.67	5.71	5.61	5.66	5.66	5.66	5.66
Airframe Maintenance Labor Costs	$/Flight	4057.99	3978.90	3941.82	4038.84	3988.05	3871.52	3927.01	3956.83	3882.61	3915.52	3915.52	3915.52	3915.52
Depreciation	$/Flight	23216.97	22432.95	22065.77	23024.48	22470.87	22164.9	22743.35	23053.71	22295.54	22666.42	22720.94	22838.54	22838.54
Interest	$/Flight	15981.01	15441.34	15188.81	15848.52	15467.45	15258.84	15655.01	15868.64	15346.77	15602.05	15639.58	15720.53	15720.53
Insurance	$/Flight	1239.58	1198.23	1178.86	1229.43	1200.24	1179.65	1209.94	1226.21	1186.42	1205.9	1206.49	1215.38	1215.38
Cabin Crew	$/Flight	10615.03	10608.30	10605.13	10613.80	10617.96	10615.03	10621.14	10622.36	10616.37	10607.82	10607.82	10607.82	10607.82
Landing Fees	$/Flight	3649.34	3477.46	3396.43	3606.85	3485.81	3229.80	3354.03	3418.72	3264.53	3338.06	3338.06	3338.06	3371.44
Navigation Fees	$/Flight	1992.61	1945.12	1922.32	1980.97	1947.45	1874.57	1910.28	1928.62	1884.62	1905.73	1905.73	1905.73	1915.23
Direct Operating Costs Plus Interest	$/Flight	89272.85	86069.86	84559.03	88613.69	86263.46	83339.05	85705.57	86949.58	83805.42	85364.46	85449.09	85654.53	85737.64

5. CRITICAL TECHNOLOGIES

The ADP represents significant technology advances compared to present day engines because the ADP's components assume 10 years technology advancement. Examples of such advances are a low noise fan and nacelle configuration, a low emissions combustor configuration, and significant reductions in weight, price, and maintenance cost in the HPC and HPT. Development of this technology must be initiated in the near term in order to meet 2005 EIS. This is illustrated in Figure 25, which shows a typical schedule for developing technology for transitioning into an engine development program ending in engine certification.

Pratt & Whitney used a planning process to identify those technologies critical or enabling to the 2005 EIS ADP. The results of this process were presented to NASA Lewis on October 10, 1994, and are provided in Appendix A.

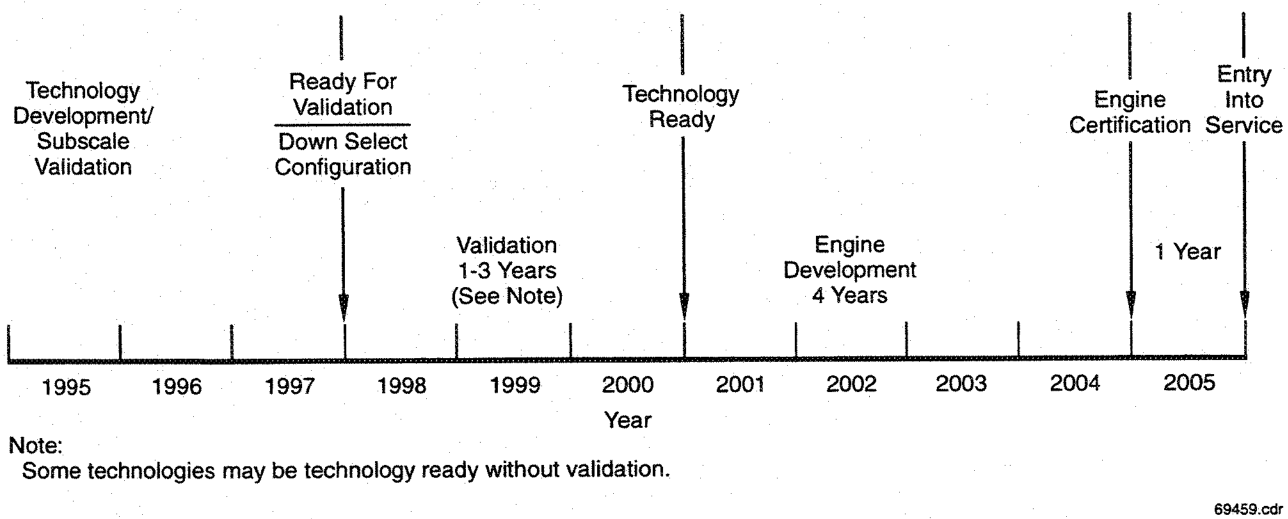


Figure 25. Typical Technology Development and Transition Path

6. CONCLUSIONS

A study was conducted to define and assess critical or enabling technologies required for a 2005 entry into service (EIS) engine for subsonic commercial aircraft, with NASA Advanced Subsonic Transport goals used as benchmarks. Two engines were selected for use in this study — a baseline current technology engine and an advanced technology engine. The baseline engine is a turbofan based on 1995/96 EIS technology, e.g., PW4084. The advanced engine is a 2005 EIS Advanced Ducted Propulsor (ADP) engine using a derivative of the Advance Technology Common Core (ATCC) for the high spool.

The performance analysis conducted as part of this study showed the high technology ADP design has many advantages over a conventional turbofan. The two primary reasons for this are the 10 year difference in technology level and the inherent propulsive efficiency advantage of the ultra high bypass ratio (lower fan pressure ratio) ADP configuration. The variable geometry in the fan and low-pressure compressor (LPC) required to make the low spool work contribute to this advantage. The propulsive advantage of the lower fan pressure ratio (FPR) results in lower thrust specific fuel consumption at cruise (14.6 percent) and significantly lower compressor discharge temperatures (T_3) and combustor exit temperatures (T_4) at takeoff. The ADP's reduced T_4 at takeoff, relative to a turbofan rated to similar thrusts, allows the ADP to have improved turbine airfoil life for the same climb T_4 or allows the ADP to run a hotter climb T4 for the same turbine airfoil life. The fan drive gear combined with the variable geometry fan and LPC in the ADP allows the fan, LPC, and low-pressure turbine to run at optimum speeds and efficiencies. The ADP's propulsive advantage allows for the option to have a smaller size core engine than a turbofan for the same thrust requirements. The lower FPR design also gives the ADP a thrust growth advantage relative to a turbofan.

An airplane/engine mission analysis was performed to quantify the effects of the ADP engine on the economics of typical airline operation. The economic figure of merit for this study was direct operating cost plus interest (DOC+I), which includes both engine and aircraft related operating costs and ownership costs. The baseline airplane was simulated as a rubber airplane with design range fixed and wing loading, takeoff field length, and time to climb to dispatch altitude held constant. The class of aircraft chosen for this study was a long-range quad engine passenger aircraft. The turbofan weight used in this analysis was representative of the PW4000 engine family. The ADP weight was estimated using geometric scaling and detailed weight analysis methods, except for the core which was based on the ATCC. Engine and airplane prices were assumed to be full price without the discounts. Relative to the turbofan, the ADP configuration was estimated to add 10 percent to the propulsion system price and 5 percent to the maintenance cost at constant thrust.

Results from the mission analysis show the ADP propulsion system provides a 6.6 percent reduction in DOC+I compared to the base turbofan engine. The major influences are fuel burn (-3.17 percent DOC+I), price related costs (-2.05 percent), and takeoff gross weight related costs (-1.16 percent). Engine and airframe maintenance effects are small. Propulsion system influence factors effecting TSFC, drag, weight, maintenance cost, and price on DOC+I were determined including the effects of airframe price on DOC+I.

Critical and enabling technology for the 2005 EIS ADP were identified and prioritized. Critical technology paths were identified.

APPENDIX A. CRITICAL TECHNOLOGIES

Pratt & Whitney went through a planning process to identify those technologies critical or enabling to 2005 EIS ADP. This technology planning process resulted in a component-by-component identification of 39 technology improvements along with the attendant characteristic and system benefits. Ten of the most critical of these technologies were identified, program objectives determined, and risk levels assessed. The results of this process were presented to NASA Lewis on 10 October 1994, and are provided in this Appendix. The component-by-component improvements are presented in Table 16, and the recommended technology programs are shown in Table 17.

Table 16. Year 2005 EIS Engine Overall Technology Study Summary

Components	*Technology*	*Characteristic Benefit*	*System Benefit*
Nacelle	Composite outer cowl (aft of inlet to aft of fan exit case)	Weight reduction	
Nacelle	Advanced acoustic treatment	Noise absorption	Reduced noise and maintenance cost
Nacelle	Laminar flow control	Improved internal and external flow	Drag reduction, lower distortion
Fan and Nacelle **	Optimized fan exit case and duct (improved CFD analysis technique)	Decrease FEGV and duct pressure loss	0.4% FEGV and duct pressure loss
Fan *	Low noise/high performance fan blade including aeromechanics	Noise reduction performance improvement (included in geared fan fuel burn benefit)	Noise reduction 2% fan efficiency
Fan *	Advanced fan noise prediction system	Noise reduction and aeroelastic insight optimized vane spacing and position	Noise reduction and wave interaction with rotating and static structures for improved durability
Fan *	Optimized advanced fan tip casing treatment (VPCT)	Increased fan surge margin with minimum impact on cruise performance	Allows low speed fan with improved noise and performance 1% fan efficiency
Fan **	Fan blade retention bearing	Low friction dry lubricated durable bearing	Reduced complexity and cost
Fan	Composite fan exit case	Weight reduction	
Fan	Geared variable pitch fan	Reduced fan speed No reverser Improved fan efficiency over flight cycle	Improved propulsion efficiency
Fan	Active noise control	Control noise at the source	Reduced noise
Fan	Composite containment case	Weight reduction	

* *NRP AST Noise Reduction Program*

** *AST Propulsion Element*

Table 16. Year 2005 EIS Engine Overall Technology Study Summary (Continued)

Components	***Technology***	***Characteristic Benefit***	***System Benefit***
Control	High temperature pressure sensor	Allows sensing of compressor pressures at temperatures above 1000°F	Facilitates active stability control on high OPR engines
Control	High band width actuator	Provides bleed actuator response 10X + faster than available today	Facilitates active stability control
Control	Microwave blade tip clearance sensor	Provide blade tip clearance measurements at high temperature locations in the engine	Facilitates active clearance control
Compressor	Improve multi-stage CFD capability	Swept rotor bowed vanes	Improved efficiency
Compressor	Improved disk material	+50°F capability	Improved cycle efficiency
Compressor	Advanced seals	Leakage reduction	Improved efficiency
Compressor	Erosion coating for IBRs	Longer life	Reduced maintenance costs
Compressor	IBR blade repair procedure	Repair instead of replacing assembly	Reduced maintenance costs
Compressor **	Composite LPC stators (includes lifing and long term durability)	Weight reduction	Improved fuel burn and composite durability and maintainability
Combustor **	Enhanced fuel preparation/injection	Lean stability enhancements, mixing and soot retardation	Low emissions combustor
Combustor **	Component surface treatments/bulk fuel treatments	Fuel system coke avoidance	Low emissions combustor
Combustor	High performance fuel pumps	High pressure rise capability and reduced temperature rise	Low emissions combustor
Combustor **	Practical variable geometry	Staged air introduction replacing assembly	Low emissions combustor
Combustor **	Stoichiometry management	Mixing of injector fuel-air flow with secondary streams	Low emissions combustor

* *NRP AST Noise Reduction Program*

** *AST Propulsion Element*

Table 16. Year 2005 EIS Engine Overall Technology Study Summary (Continued)

Components	*Technology*	*Characteristic Benefit*	*System Benefit*
Turbine **	Tip clearance desensitation	Improved efficiency	Reduced fuel burn
Turbine **	Rim cavity loss reduction	Improved efficiency	Reduced fuel burn
Turbine **	High Mn HPT/LPT interaction loss reduction	Reduced HPT/LPT transition duct pressure loss	Reduced fuel burn
Turbine	Improved thermal barrier coating	Increased T_4 and maintain life	Reduced fuel burn and maintenance cost
Turbine	Improved secondary flow management	Improved efficiency	Reduced fuel burn
Turbine	Increased strength shaft material	Allows higher HPT AN^2	Single stage HPT
Turbine	Improved disk material (2 da/dn nickel disk)	Allows higher HPT AN^2	Single stage HPT
Turbine	Advanced turbine blade attachment	Allows higher HPT AN^2	Single stage HPT
Turbine	Improved outer air and shaft seals	Reduced leakage	Reduced fuel burn
Turbine	High cooling effectiveness blade and vane	Reduced cooling air	Reduced fuel burn
Jet	Jet exhaust noise assessment for high bypass ratio engines	Ensure prediction models are representative for UHBR engines	Low noise
Systems **	Advanced lubrication system	Reduced size/lower weight lubrication system	Reduced cost and weight/fuel burn
Systems **	Lubrication system debris monitoring	Dependable/accurate condition monitoring	Improved reliability

* *NRP AST Noise Reduction Program*

** *AST Propulsion Element*

Table 17. Recommended Technology Programs

Fan/Propulsor Aero:	**Fan Duct Design Optimization**
Requirement:	The sensitivity of TSFC to fan exit guide vane and fan duct pressure loss significantly increases with engine bypass ratio. The sensitivity for an advanced ducted propulsor is in the neighborhood of 2.5% TSFC to 1% pressure loss. The ADP requires a very low loss duct system to optimize its propulsive cycle benefits.
Program Objectives:	Develop improved CFD capability and design methodology for a low loss fan EGV/pylon/duct system. Design, fabricate and demonstrate test configurations to validate improvements.
Risk:	Moderate
Propulsor:	**Advanced Lubrication System**
Requirement:	Studies identified the need for two full size lubrication systems for an ADP (one for core and one for the propulsor). These two systems ***must*** be of reduced size to fit in available space and also meet maintainability and weight goals.
Program Objectives:	Acquire necessary lube system component size reduction technology addressing such areas as oil aeration, dwell time in oil tanks, filtration, high pump flow rates and high supply pressures.
Risk:	Moderate
Fan:	**Retention Bearing**
Requirement:	A variable pitch fan requires a long life, very high strength bearing having a low coefficient of friction.
Program Objectives:	Conduct candidate screening tests to define the most promising bearing concepts. Evaluate effect of flexible disk (disk distortion) criteria. Perform cyclic endurance testing in flexible disk.
Risk:	Moderate

Table 17. Recommended Technology Programs (Continued)

Propulsor:	**On-Line Health Monitoring**
Requirement:	Potential ADP airline customers have insisted on high dependability of a fan drive gear system at entry into service. We view a reliable on-line health monitoring system as required to achieve dependability goals.
Program Objectives:	Define applicability of debris monitor to propulsor component failures (gears and ball, roller and tapered roller and journal bearings).
Risk:	Moderate
Materials:	**PMC Long-Term Lifing and Durability**
Requirement:	Weight reduction is very important especially for large diameter, very high bypass engines. Durability and maintenance remain a strong customer concern and potential inhibitor to the use of composites. This needs to be addressed and other composite programs are either not addressing this issue or are doing very little.
Program Objectives:	Evaluate high temperature polymer matrix composite (PMC) materials and develop methods to predict durability of PMC engine components in long term service and the methodology to structurally tailor PMC engine components for life-cycle cost requirements.
Risk:	Moderate
Controls:	**Microwave Blade Tip Clearance**
Requirement:	Advanced operating modes, such as active clearance control, require blade tip clearance measurements at high temperature locations in the engine. Current optical and capacitive sensor have limited transition capability.
Program Objectives:	Develop and demonstrate an engine quality microwave blade tip clearance sensor.
Risk:	Moderate
Controls:	**High Bandwidth Actuator**
Requirement:	Advanced operating modes, such as active stability control, require actuators that operate 10× + faster than today's hardware.
Program Objectives:	Develop and demonstrate an engine quality actuator capable of operation between 100 and 300 Hz.
Risk:	Moderate

Table 17. Recommended Technology Programs (Continued)

Controls:	**High Temperature Pressure Sensor**
Requirement:	Advanced operating modes, such as active stability control, require pressure measurement capability at high temperature locations of the engine.
Program Objectives:	Develop and demonstrate an engine quality pressure sensor with signal conditioning electronics, capable of operation at temperatures above 1000°F.
Risk:	Moderate
Turbine:	**Rim Cavity Program**
Requirement:	The management of secondary flow to prevent leakage, improve cooling effectivity and minimize losses as this flow is introduced into the gas path is important for engine performance and parts life. Advanced high pressure/high temperature cycles increase the need for improvements in this area.
Program Objectives:	Experimentally obtain time-averaged and time-resolved pressure distribution and velocity data to evaluate codes modeling the ingestion process. Develop improved modeling and rim seal concepts.
Risk:	Moderate
Turbine:	**Tip System Desensitization**
Requirement:	High performance turbines, which obtain ***and retain*** maximum efficiencies, require efficient flow management in the tip area.
Program Objectives:	Improve tip area flow modeling capabilities to investigate clearance insensitive design concepts and more effective airfoil and blade outer air seal cooling concepts.
Risk:	Moderate

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13. ABSTRACT ***(Maximum 200 words)***
A study was conducted to define and assess the critical or enabling technologies required for a year 2005 entry into service (EIS) engine for subsonic commercial aircraft, with NASA Advanced Subsonic Transport goals used as benchmarks. The year 2005 EIS advanced technology engine is an Advanced Ducted Propulsor (ADP) engine. Performance analysis showed that the ADP design offered many advantages compared to a baseline turbofan engine. An airplane/engine simulation study using a long range quad aircraft quantified the effects of the ADP engine on the economics of typical airline operation. Results of the economic analysis show the ADP propulsion system provides a 6% reduction in direct operating cost plus interest, with half the reduction resulting from reduced fuel consumption. Critical and enabling technologies for the year 2005 EIS ADP were identified and prioritized.

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