NASA CR165330

R80AEG068

(NASA-CR-165330) PROPULSION SYSTEM STUDY FOR SMALL TRANSPORT AIRCRAFT TECHNOLOGY (STAT) Final Report (General Electric Co.) HC A10/MF A01 CSCL 21A

N81-25078

Unclas
G3/07 26510

PROPULSION SYSTEM STUDY FOR SMALL TRANSPORT AIRCRAFT TECHNOLOGY (STAT)

FINAL REPORT

by

C.E. Smith

R. Hirschkron

R.E. Warren

GENERAL ELECTRIC COMPANY

Lynn, Massachusetts

Prepared For

National Aeronautics and Space Administration

NASA Lewis Research Center

Contract NAS3-21996

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-165330		
4. Title and Subtitle Propulsion System Study for Small Transport Aircraft Technology (STAT), Final Report		5. Report Date May 1981
		6. Performing Organization Code
7. Author(s) C.E. Smith, R. Hirschkron and R.E. Warren		8. Performing Organization Report No. R80AEG068
		10. Work Unit No.
9. Performing Organization Name and Address General Electric Company Aircraft Engine Group Lynn, Massachusetts 01910		11. Contract or Grant No. NAS3-21996
		13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Project Manager, William C. Strack, Low-Speed Vehicle Section, NASA Lewis Research Center, Cleveland, Ohio 44135

16. Abstract

Propulsion system technologies applicable to the generation of commuter airline aircraft expected to enter service in the 1990's are identified and evaluated in terms of their impact on aircraft operating economics and fuel consumption. The most promising technologies in the areas of engine, propeller, gearbox, and nacelle design are recommended for future research. Each item under consideration is evaluated relative to a modern baseline engine, the General Electric CT7-5, in a current technology aircraft flying a fixed range and payload. The analysis is presented for two aircraft sizes (30 and 50 passenger), over a range of mission lengths (100 to 1100 km) and fuel costs (\$264 to \$396 per m^3).

17. Key Words (Suggested by Author(s))		18. Distribution Statement
Commuter Aircraft Aircraft Engines Turboprop Propeller	Gearbox CT7-5 STAT DOC	Unclassified - Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21.	22. Price*
Unclassified	Unclassified		

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-C-168 (Rev. 10-75)

TABLE OF CONTENTS

Preceding page blank

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES - Continued

LIST OF TABLES

LIST OF TABLES - Continued

SUMMARY

The primary objective of this study was to identify the propulsion system technology which should be pursued for the generation of commuter airline aircraft which might go into service in the 1990 time period. The first step in the analysis was to define the aircraft which were to serve as a basis for the propulsion system study. Ground rules established for the aircraft were as follows:

1. 30-and 50-passenger sizes.

2. Design range of 1111 km (600 nmi), average stage length of 185.2 km (100 nmi).

3. 1219m (4000 ft) field length at sea level on a 32.2°C (90°F) day.

4. Cruise speed capability of 129.6 m/sec (250 knots) indicated air speed at 3048 m (10,000 ft) altitude.

The aircraft were defined with modern (1980) aircraft technology and were first laid out with a modern engine to serve as a bench mark for later studies. The General Electric CT7-5 was selected as the reference engine and was scaled as necessary to satisfy the mission. The characteristics of the two aircraft which resulted are as follows:

Number of Passengers	30	50
Design TOGW - kg (lbm)	10,840 (23,900)	17,820 (39,300)
Wing Loading - N/m^2 (lb/ft^2)	2873 (60)	2873 (60)
Aspect Ratio	12	12
Number of Engines	2	2
Takeoff Power		
Std Day* - kW (hp)	1208 (1620)	2095 (2810)
32.2°C (90°F) Day - kW (hp)	1059 (1420)	1834 (2460)

* Standard day output power at rated turbine inlet temperature. This is provided for reference only; the CT7-5 engine is flat rated to 30°C (86°F).

Note that in studies of the advanced engines and their technology, the aircraft technology was maintained the same but the aircraft were resized and re-optimized as appropriate to satisfy the mission.

The next phase of the study was to identify and evaluate specific technologies for an advanced engine. After an initial screening, the features listed in Table 1 were evaluated in a reference advanced engine with effects on Direct Operating Cost (DOC) as illustrated. A few optional design features not limited by technology were also evaluated with the results shown in Table 2. The technology features with payoff, along with other technology appropriate to the 1990 time period, were then incorporated into the advanced engines described later. The effect on DOC for a 185.2 km (100 nmi) stage length mission was the primary factor used in deciding which features to include.

TABLE 1
MERIT FACTOR SUMMARY

Advanced Engine Technology Features	Change in Direct Operating Cost: Favorable	Unfavorable
Highly Loaded Axial Compressor	X	
Multi-Blade Centrifugal Impeller	X	
Two-Material Centrifugal Impeller		X
Advanced Centrifugal Diffuser	X	
Advanced Combustor		
Advanced Material	X	
Thermal Barrier Coating	X	
Active Clearance Control for HP Turbine	X	
Advanced HP Turbine Blade		
Advanced Material		X
Advanced Cooling Technique	X	
Cast Blisks for LP Turbine	X	
Metal Matrix LP Shaft	X	
Closed Loop Accel Schedule and Reduced Stall Margin	X	
Composite Materials for Nacelle	X	

TABLE 2
MERIT FACTOR SUMMARY

Design Factors	Change in Direct Operating Cost: Favorable	Unfavorable
Modular Construction		X
Inlet Protection Systems*		
Vaned IPS with Blower		X
Vaneless Foreign Object Protector		X
Diagnostic Data Recording	X	
Alternate Ratings		
10% Derate Option when Allowed	X	
Automatic Provisional Rating with 5% Reduction in Engine Size	X	

* May be required to pass certification tests.

A parametric cycle study was carried out based on advanced engine technology to show the effects of cycle pressure ratio, turbine rotor inlet temperature (T41) and engine arrangement. As a result, the following cycles were selected for the advanced engines in this study.

Number of Passengers	30	50
Takeoff Power		
Std Day - kW (hp)	1107 (1485)	1831 (2455)
32.2°C (90°F) Day - kW (hp)	943 (1265)	1510 (2025)
Corrected Airflow - kg/s (lbm/sec)	3.55 (7.8)	5.35 (11.8)
Cycle Pressure Ratio	17	20
Turbine Rotor Inlet Temperature (T41) - °C (°F)	1260 (2300)	1315.6 (2400)
Compressor Stages on LP Spool	None	1
Core Compressor Stages	3 Axial 1 Centrifugal	3 Axial 1 Centrifugal
HP Turbine Stages	1	1
LP Turbine Stages	2	3

SUMMARY - Continued

A number of gearbox technology advances were identified by Hamilton Standard, including high contact ratio gearing, advanced materials and lubricants. Together with several design features, these were collectively evaluated to provide a 1.2 to 1.7% improvement in DOC and a 1.0 to 1.3% reduction in fuel usage. (The payoff varies with aircraft size and fuel cost.)

Propeller advances identified by Hamilton Standard during this study included double acting pitch change, composite blades, and proplets. These resulted in a 1.0 to 1.6% improvement in DOC and 2.7 to 3.0% reduction in fuel usage. The effects of reduced cabin noise treatment which might be possible due to the lower noise projected for incorporating a precision syncrophaser would increase this payoff. After the study was completed, additional input showing greater propeller technology improvements was received. This material is covered in Appendix D (pgs 199-200). The results given here and in the body of the report do not incorporate the material in Appendix D.

A preliminary design was carried out for each of the advanced engines, and the performance, weight, and cost were estimated. These propulsion systems involve a combination of cycle and technology advances appropriate to the 1990 time period. The following is a comparison of the advanced engine characteristics with those of the CT7-5 with both engines scaled to the size required to power the aircraft designed to satisfy the specified mission.

	30-Passenger Aircraft		50-Passenger Aircraft	
	Scaled CT7-5	Advanced Engine	Scaled CT7-5	Advanced Engine
Takeoff Power - kW (hp) Std Day	1208 (1620)	1107 (1485)	2095 (2810)	1831 (2455)
Change in TSFC at Cruise	Base	-11%	Base	-16%
Change in Basic Engine Weight	Base	-15%	Base	-32%
Change in Propulsion System Weight*	Base	-23%	Base	-30%
Change in Basic Engine Cost	Base	-19%	Base	-23%
Change in Propulsion System Cost*	Base	-18%	Base	-23%
Change in Propulsion System Maintenance Cost*	Base	-26%	Base	-25%

*Includes advanced gearbox and propeller.

The above engines were then evaluated in the aircraft, the CT7-5 with a current technology propeller and gearbox and the advanced engine with an advanced propeller and gearbox, with the following results.

	30-Passenger Aircraft		50-Passenger Aircraft	
	Scaled CT7-5	Advanced Engine	Scaled CT7-5	Advanced Engine
Design Takeoff Gross Weight (TOGW) - kg (lbm)	10,840 (23,900)	10,475 (23,100)	17,820 (39,300)	16,820 (37,100)
Change in Fuel Burned*	Base	-12.6%	Base	-17.4%
Change in DOC* at $264/m^3$ ($1/gal)	Base	-7.8%	Base	-10.8%
Change in DOC* at $396/m^3$ ($1.50/gal)	Base	-8.4%	Base	-11.7%

*185.2 km (100 nmi) Average Trip and 1979 dollars.

A derivative version of the CT7 which could be available in the mid-80's was also defined for comparison with the advanced engine. This engine involved the addition of a compressor stage to the output shaft and an increase in turbine inlet temperature of 55.6°C (100°F) which resulted in a 2.7% reduction in cruise TSFC and lower weight and cost when scaled to the same power level. Following is a comparison of the mission merit factors associated with the basic engine changes only (prop, gearbox, and nacelle advances not included) using the scaled CT7-5 as a base.

Change In:	30 Passenger		50 Passenger	
	CT7 Derivative	Advanced Engine	CT7 Derivative	Advanced Engine
Fuel Burned*	-2.0%	-8.6%	-2.9%	-12.7%
DOC* at $264/m^3 ($1/gal)	-1.2%	-5.3%	-1.7%	-7.4%

*185.2 km (100 nmi) average trip and 1979 dollars.

The overall result of this study is that a substantial improvement in aircraft economics and fuel usage can be achieved by advanced engine, gearbox, and propeller technology integrated into an advanced turboprop propulsion system. And, this is using what is a rather challenging standard, the CT7-5 and growth thereof. Figure 1 illustrates the payoff graphically.

It is recommended that NASA pursue the technology for this category of engines by sponsoring appropriate R&D programs. The technology will be applicable to other small engine applications including other turboprop applications, turboshaft engines for civil and military rotorcraft, and turbofan derivatives for trainer and business aircraft. The basic core engine that might come out of a program directed toward the commuter turboprop application should be directly usable for many of these applications.

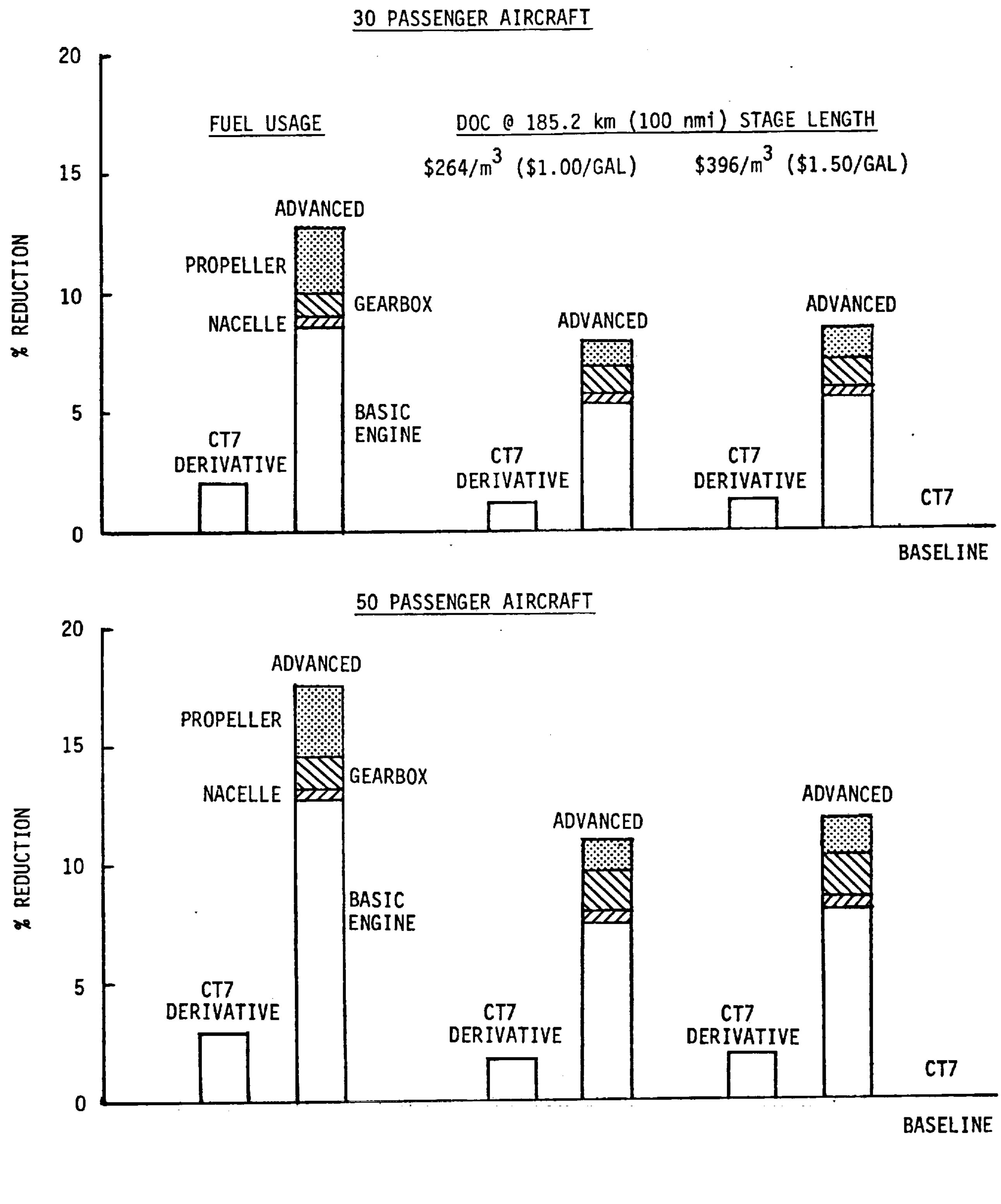


Figure 1. Propulsion System Mission Merit Factor Summary.

INTRODUCTION

Small (15-80 passengers), short-haul (75-1500 km) transport aircraft constitute a vital and growing element in the worldwide air transportation system. Although a portion of their operations is from the same airports as the medium and long range conventional takeoff and landing (CTOL) transports, the design and operational requirements for the small, short-haul transport aircraft differ considerably. Current operational experience and recent studies have indicated that turboprop propulsion is an attractive approach for both existing and future advanced, small, short-haul transport aircraft. This type of propulsion system may offer a good solution to the unique operational problems and requirements of these aircraft; that is, short runway and stage length capability, operation in adverse low altitude environment, low operating costs, and the more recent need for fuel conservation.

Aircraft and their engines currently used for this application were for the most part designed many years ago and in many cases not designed specifically for commuter airline service. Recently there has been considerable activity in this area and new airplane developments pointed directly at this application have been launched. The engines for these new aircraft incorporate modern technology. The CT7-5, which is a commercial turboprop derivative of the T700 turboshaft engine is one of these engines which will go into service in 1983.

NASA is considering Small Transport Aircraft Technology (STAT) pointed toward this application. The study reported herein is directed at propulsion technology for advanced commuter airline aircraft which might go into service in the 1990 time period. The objectives of this study including the following:

1. Identify aircraft for this application in 30-and 50-passenger sizes to provide a basis for evaluating and selecting engine technology.

2. Identify and evaluate propulsion system technology and design features for this application.

3. Select typical 1990 commuter turboprop propulsion systems and evaluate the payoff of these advanced engines relative to a current technology engine and a growth or derivative of the current technology engine.

4. Recommend programs to develop the propulsion technology identified in this study.

In conducting this study, General Electric selected the CT7-5 as the current technology engine. This selection provided a challenge in defining advanced engines with payoff since the performance and other characteristics of the CT7-5 already represent a major advance over any small turboprop or tuboshaft engine now in service.

General Electric performed the aircraft analysis for this study, coordinating with NASA. Hamilton Standard was engaged as a subcontractor to provide the input on gearbox technology. Propeller technology input was provided by Hamilton Standard under a direct contract to NASA.

DEFINITION OF BASELINE AIRCRAFT AND MISSIONS

CT7-5 BASELINE ENGINE

The General Electric CT7-5 1193 kW* (1600 hp) turboprop engine was selected as the baseline engine for both the 30-and 50-passenger aircraft. A challenging standard, the CT7-5 is a modern powerplant which will be in commuter aircraft service by early 1983. Figure 2 shows the CT7 power plant, offset gear, and propeller. This engine is a derivative of the military T700 engines powering the Army Black Hawk and Navy Seahawk helicopters. It is also available as the CT7-2 commercial turboshaft engine.

The engine design features are indicated in the cross-section, Figure 3. The engine consists of 4 major modules: cold section (inlet, compressor, and midframe); hot section (combustor and high pressure turbine); power turbine; and accessory module.

A low-loss, vaneless foreign object protector (FOP) prevents foreign object damage (FOD) by centrifuging runway debris outward. Approximately 15% of the air entering the engine inlet is used to eject the debris and is ducted and discharged overboard. The balance of the air plus the small amount of remaining sand and dust pass through the core. Experience with General Electric engines like the T58, T64, J85, and T700 indicates that erosion and damage to the leading edge of the compressor blades in these small engines is only a problem if the engines are completely unprotected, are exposed to severe environmental conditions, or are operated from unimproved runways. Under normal commercial operating conditions, the deterioration of performance caused by the loss of material on blades and vanes is insignificant and does not warrant the additional cost of an FOP. All of the mission analysis for this study was performed for engines without inlet protection. However, an integral or separate protective device may be required to pass the FAA certification for small aircraft engines. To pass this test, an engine must demonstrate the capability of ingesting birds, ice, sand, and gravel of specified quantities and size with less than 25% permanent power loss. This requirement applies equally to the baseline and advanced engines, and the inclusion of an FOP would not effect the overall results of the study.

The compressor has 5 axial stages and 1 centrifugal stage for high efficiency, producing a 17:1 pressure ratio. All stages are individual blisks, i.e., disk and blades are forged and machined in one piece, providing a rugged and low maintenance cost design. The inlet guide vanes and Stage 1 and 2 stators are variable. Attached to the rear flange of the axially split compressor casing is the diffuser and midframe casing assembly. The air leaving the last compressor stage is diffused in individual radial passages, turned axially by the casing and deswirled before entering the combustor.

The combustor is a through-flow annular type. The liner is machined and welded from forged rings providing both durability and even temperature profile. It can be removed as part of the hot section without removal of the fuel injectors. The fuel system is a low-pressure system using 12 nozzles and vortex air swirlers to create a very fine fuel dispersion without the use of fine nozzle orifices.

The high-pressure turbine rotor has two stages with air-cooled blades and cooling plates. High gas temperatures yield high cycle efficiency while the effective cooling system maintains low metal temperature for long component life.

* Flat-rated to 30°C (86°F).

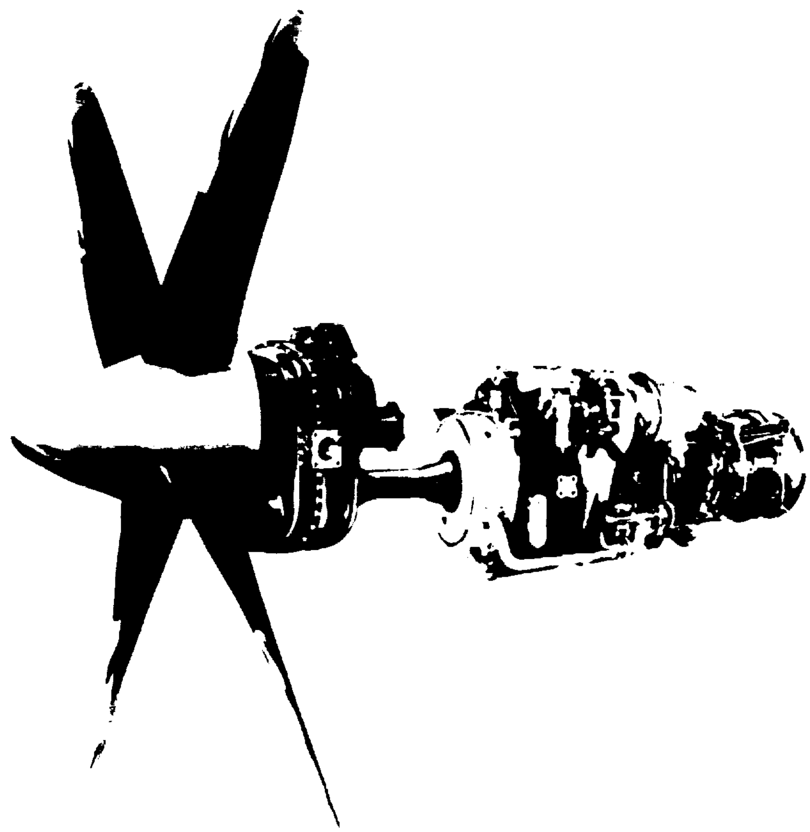


Figure 2. CT7 Turboprop.

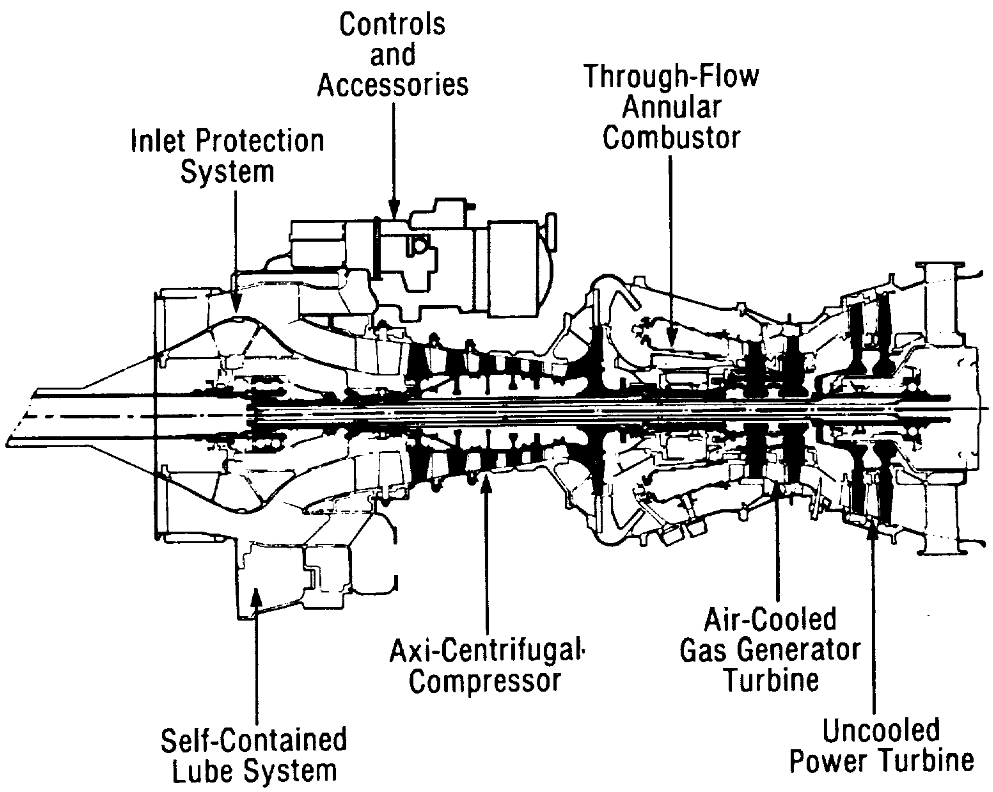


Figure 3. CT7 Turboprop Design.

CT7-5 BASELINE ENGINE - Continued

The power turbine also has two stages. The blades are tip shrouded and uncooled; they are attached to the disks by conventional dovetails. The power (or low-pressure) turbine section, output shaft, exhaust frame, and rear sump can be removed as a unit.

The accessories are grouped on a top-mounted gearbox and include the starter-generator pad for aircraft electrical power, fuel and lube pumps and filters, fuel control, and most aircraft system attachments.

Cycle and performance parameters of the CT7-5 at takeoff conditions are summarized in Table 3. Engine performance has been modified to reflect the removal of the foreign object protector. In performing the mission analysis, the CT7-5 was scaled as required to satisfy the design payload and range. Engine SFC, weight, and costs were adjusted to account for the effects of component physical size. The base cost of the CT7-5 was adjusted to exclude the cost of the FOP and related parts, and based on 1979 dollars, for an assumed total production quantity of 1000 engines.

The model used for estimating the maintenance cost is based on actual experience with commercial engines. First engine cost was broken down into major components and/or parts. The material cost over the life of the engine was determined by the expected replacement rate of each individual part. Labor cost was then calculated as a percentage of material cost, ranging in value from 20% to 85% depending on accessibility of each part. Finally, the total maintenance cost in dollars per engine flight hour was determined by dividing the total of material and labor cost by the projected number of flight hours (i.e., 2800 h/yr utilization x 12 yr = 33,600 h).

TABLE 3
BASELINE CT7-5 CYCLE - SEA LEVEL, STATIC
(No Inlet Protection)

Ambient Temperature	°C (°F)	15 (59)	32.2 (90)
Power Setting		Takeoff*	Takeoff
Turbine Inlet Temp	°C (°F)	1254 (2290)	1254 (2290)
Cycle Pressure Ratio		16.9	15.7
Output Power	kW (hp)	1365 (1830)	1212 (1625)
Specific Fuel Consumption	kg/kW·h(lbm/hp·h)	.283 (.465)	.295 (.485)
Inlet Corrected Flow	kg/s (lbm/sec)	4.63 (10.2)	4.44 (9.8)
Inlet Flow	kg/s (lbm/sec)	4.63 (10.2)	4.31 (9.5)

* Data in this column, at full rated turbine inlet temperature on a standard day, is provided for reference only. The CT7-5 engine is flat rated to 30°C (86°F).

BASELINE AIRCRAFT

30-and 50-passenger baseline commuter aircraft were designed to be representative of current technology and to satisfy the STAT requirements as defined in the Statement of Work[1] and detailed in Table 4. The baseline aircraft were used to determine the engine requirements of the short haul commuter mission, and as a framework to evaluate the proposed propulsion system advances.

1. See list of references, pg 207.

TABLE 4
MISSION AND AIRCRAFT REQUIREMENTS

1. Full payload range of 1111 km (600 nmi) plus reserves for 185.2 km (100 nmi) alternate and 45 minutes at maximum endurance power at 3048 m (10,000 ft) altitude.

2. Field length at sea level not to exceed 1219 m (4,000 ft) on a 32.2°C (90°F) day.

3. Maximum speed capability between 1829 m (6,000 ft) and 3048 m (10,000 ft) altitude shall be 128.6 m/s (250 knots), indicated.

4. The stall speed shall be less than 47.8 m/sec (93 knots) at the maximum landing weight, and in the landing configuration.

5. A terminal area speed capability of at least 92.6 m/sec (180 knots), indicated, with the gear and flaps extended.

6. Aircraft shall meet current FAR 36 Stage 3 noise limits minus 8 EPNdB at all measurement locations.

7. Maximum cabin interior noise level shall be less than 85 dB OASPL and a speech interference level of less than 65 dB.

8. 90.7 kg (200 lbm) per passenger.

* 9. Two-man crew at 90.7 kg (200 lbm) each plus one flight attendant at 59 kg (130 lbm).

*10. 1.8 m (6 ft) minimum interior aisle height.

*11. Minimum 0.81 m (32 in) seat pitch, 0.46 m (18 in) seat width between armrests and 0.46 m (18 in) aisle width.

*12. 0.14 m^3 (5 ft^3) per passenger for easily loaded preloaded baggage storage, plus carry-on baggage provision of 0.51 x 0.51 x 0.28 m (20 x 20 x 11 in) per passenger and garment storage area of 0.02 m (0.8 in) width per passenger.

*13. One lavatory.

*14. 34.5 kN/m^2 (5 lb/in^2) cabin pressurization, minimum.

*15. Airframe design life of at least 30,000 hours and 60,000 takeoff and landing cycles.

*Assumed met by use of airframer layouts and/or subweights.

BASELINE AIRCRAFT - Continued

The aircraft weight and drag levels were established using the baseline aircraft designs of two STAT airframe study contractors, Convair[2] and Lockheed[3], for guidance. General Electric's aircraft design computer program was modified such that, given the Convair or Lockheed geometries, a good match in weight and aerodynamics was achieved. The aircraft drag polars used are shown in Figure 4.

Based on a recent Lockheed study of interior noise control for turboprop aircraft[4], the acoustic treatment weight was fixed at 2.5% of design gross weight for both aircraft.

The aircraft fuselage dimensions and the wing and empennage characteristics (thickness/chord, aspect ratio, etc.) were taken from the Convair baseline aircraft, and were assumed to satisfy all the dimensional requirements in Table 4. Single slotted, 30% chord, 55% span flaps were selected for the baseline aircraft.

Both aircraft were twin turboprop powered, each powerplant a combination of a scaled General Electric CT7-5 engine as described above, a four bladed, 228.6 m/s (750 ft/sec) tip speed propeller, and an appropriate gearbox. Propeller and gearbox characteristics were defined by Hamilton Standard[5,6]. Propeller tip speed was selected to meet the aircraft far field noise requirements. With tip speed fixed, the other propeller characteristics were selected to give a near minimum DOC for the 185.2 km (100 nmi) mission. The resulting propeller had a static thrust to power ratio of 20.3 N/kW (3.4 lb/hp) and a cruise efficiency of 88 to 89%.

The aircraft wing loading (W/S) and thrust to weight ratio (T/W) were chosen to insure that all the performance requirements of Table 4 were met. In fact, only the 1219 m (4000 ft) takeoff field length* and 128.6 m/s (250 kt) indicated air speed cruise requirements were limiting. These limits were combined (with margin to account for approximations and uncertainties in the design procedure) as shown in Figure 5, and a wing loading of 2873 N/m^2 (60 lb/ft^2) selected, which resulted in an aircraft with near minimum design gross weight and operating cost.

Having completed the above design selections, the aircraft were sized for the design 1111 km (600 nmi) mission using fixed weight and drag correlations, fixed fuselage dimensions, and fixed wing, empennage, and powerplant characteristics while computing the required design gross weight, wing area, empennage area, and engine size. The resulting 10,840 kg (23,900 lbm) and 17,826 kg (39,300 lbm) aircraft, described in Tables 5-6, required engines providing, respectively, 1208 kW (1620 hp) and 2095 kW (2810 hp) takeoff power at full rated turbine inlet temperature, statically, at sea level on a standard day.

* A landing field length of less than 1219m (4000 ft) was assumed for any design which met the maximum stall speed requirement of Table 4.

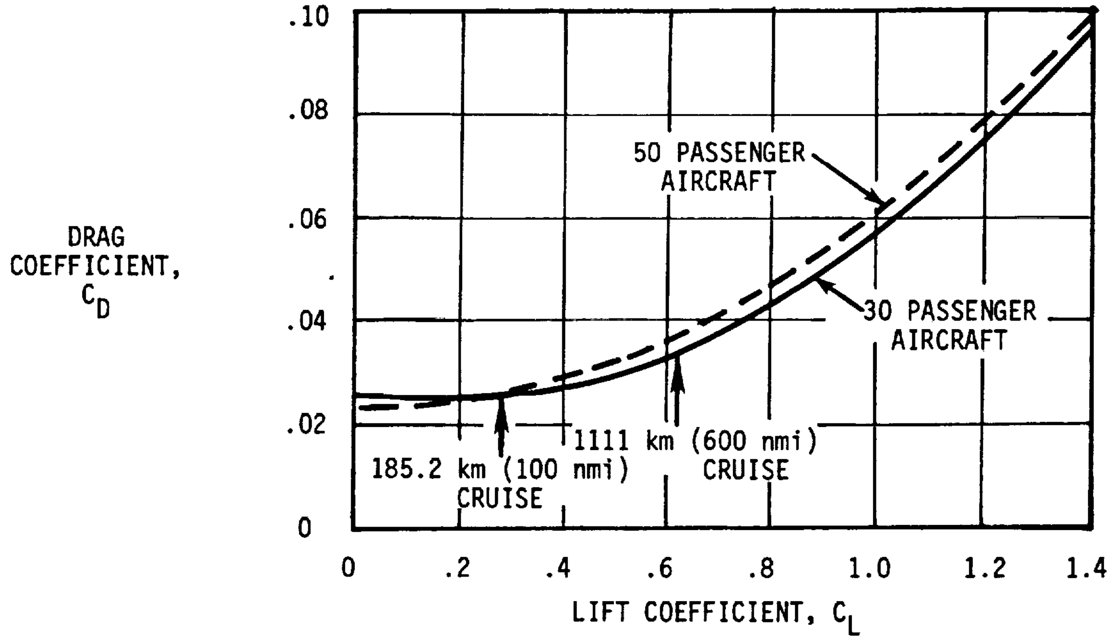


Figure 4. Baseline Aircraft Drag Polars.

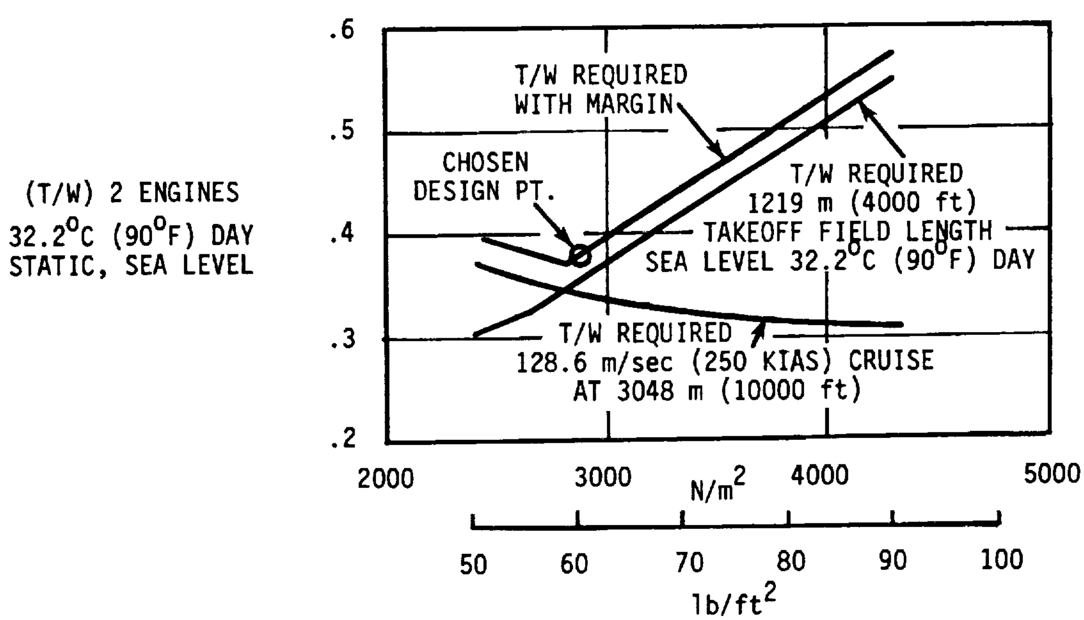


Figure 5. Selection of Wing Loading and Thrust-to-Weight Ratio for 30-Passenger Baseline Aircraft.

TABLE 5
BASELINE AIRCRAFT DESIGN SUMMARY

	30-Passenger Aircraft	50-Passenger Aircraft
Maximum Take-off Weight - kg (lbm)	10,840 (23,900)	17,830 (39,300)
Operating Weight Empty - kg (lbm)	7150 (15,760)	11,600 (25,580)
Payload - kg (lbm)	2720 (6000)	4540 (10,000)
Fuel for 1111 km (600 nmi) and Reserves - kg (lbm)	970 (2135)	1690 (3728)
Wing Loading - N/m^2 (lb/ft^2)	2873 (60)	2873 (60)
Wing Aspect Ratio	12	12
Wing Thickness - %	19	19
Wing Taper Ratio	.33	.33
Wing Span - m (ft)	21.2 (69.5)	27.2 (89.1)
Sea Level, Static Takeoff Performance		
Power, Std Day - kW (hp)	1208 (1620)	2095 (2810)
Power, 32.2°C (90°F) Day - kW (hp)	1059 (1420)	1834 (2460)
Power/Weight (2 engines), 32.2°C (90°F) Day - kW/kg (hp/lbm)	.20 (.12)	.21 (.13)
Thrust/Weight (2 engines), 32.2°C (90°F) Day - N/kg (lbf/lbm)	3.73 (.38)	3.92 (.40)
Propeller Diameter - m (ft)	3.65 (12.0)	4.81 (15.8)
Propeller Speed - rad/sec (rpm)	125 (1194)	95 (908)
Propeller Activity Factor/Blade	100	100
Propeller C_{Li}	.55	.55
Propeller Tip Speed - m/s (ft/sec)	229 (750)	229 (750)
Fuselage Length - m (ft)	20.1 (66)	22.9 (75)
Seating Abreast	3	4

TABLE 6
BASELINE AIRCRAFT WEIGHT SUMMARY

	30-Passenger Aircraft	50-Passenger Aircraft
Maximum Take-off Weight - kg (lbm)	10,840 (23,900)	17,830 (39,300)
Operating Weight Empty - kg (lbm)	7150 (15,760)	11,600 (25,580)
Payload - kg (lbm)	2720 (6000)	4540 (10,000)
Fuel for 1111 km (600 nmi) and Reserves - kg (lbm)	970 (2135)	1690 (3728)
Sub Weights, % of Max Takeoff Weight		
Fuselage	15.9	14.4
Wing and Controls	10.4	11.2
Tail	1.7	2.6
Landing Gear	3.8	3.8
Fuel System	0.7	0.7
Hydraulic, Electrical, and Pneumatic Systems	1.7	1.7
Air Conditioning and Anti-icing Systems	2.5	2.5
Acoustic Shielding	2.5	2.5
Furnishings	12.9	11.6
Operational Equipment	4.4	3.4
Engines	2.8	3.0
Gear Boxes	2.3	3.2
Propellers	2.9	3.1
Nacelles	1.2	1.2
Engine Accessories	0.3	0.2
Subtotal	66.0	65.1
Payload	25.1	25.4
Fuel	8.9	9.5
Total	100.0	100.0

The fuel burn breakdowns for both the 1111 km (600 nmi) design mission and the 185.2 km (100 nmi) off-design mission flown at the speeds for minimum DOC are given in Table 7. Note that 16% of the fuel is burned at low power during descent and taxi on the short mission. For the 185.2 km (100 nmi) mission cruise at 3048 m (10,000 ft), a cruise speed of Mach 0.45 is slightly slower than optimum if fuel is $264/m^3 ($1.00/gallon), and slightly faster than optimum if fuel is $396/m^3 ($1.50/gallon). However, the 185.2 km (100 nmi) mission cruise speed was fixed at Mach 0.45 for both aircraft and both fuel prices. The resultant direct operating costs were obtained using the method described in Table 8. Their breakdown is shown in Figures 6-7. Note the rapidly increasing significance of fuel costs as fuel goes above $264/m^3 ($1.00/gallon).

TABLE 7
BASELINE AIRCRAFT FUEL BURN SUMMARY

	Fuel Burn - kg (lbm) 30-Passenger Aircraft		Fuel Burn - kg (lbm) 50-Passenger Aircraft	
1111 km (600 nmi) Mission				
Takeoff	10	(23)	18	(40)
Climb	147	(324)	258	(567)
Cruise, Alt = 7620 m (25,000 ft)	465	(1024)(M=0.42)	820	(1807)(M=0.41)
Descent	21	(46)	35	(78)
Taxi	21	(46)	36	(80)
TOTAL	664	(1463)	1167	(2572)
Reserves				
Climb	44	(96)	74	(164)
Cruise, Alt = 3048 m (10,000 ft)	86	(191)(M=0.34)	152	(335)(M=0.35)
Loiter, Alt = 3048 m (10,000 ft)	165	(363)(M=0.23)	281	(620)(M=0.23)
Descent	10	(22)	17	(37)
TOTAL	305	(672)	524	(1156)
185.2 km (100 nmi) Mission				
Takeoff	10	(23)	18	(40)
Climb	56	(123)	95	(209)
Cruise, Alt = (3048 m (10,000 ft)	87	(192)(M=0.45)	148	(325)(M=0.45)
Descent	10	(21)	15	(34)
Taxi	21	(46)	36	(80)
TOTAL	184	(405)	312	(688)

TABLE 8
DIRECT OPERATING COST METHODOLOGY IN 1979 DOLLARS

Utilization	2800 Block Hours/Year
Crew	$75/Block Hour
Labor	$10/Man-Hour + 80% Burden
Fuel	$1.00/Gallon or $1.50/Gallon
Aircraft Price*	$175 x Weight + $500,000
Powerplant Price	As Computed Using Standard Preliminary Design Methods
Spares	6% Airframe + 30% Powerplant
Depreciation	12 Years Straight Line to 15% (Including Initial Spares)
Insurance	1.5%/Year of Flight Equipment (Excluding Initial Spares)
Airframe Maintenance*	
Material	$(.303 x Weight/1000)/Cycle + $(.243 x Weight/1000)/Flight Hour
Labor	$[.07345 \times (\text{Weight}/1000)^{.7908}]$ Man-Hour/Cycle + $[.2048 \times (\text{Weight}/1000)^{.595}]$ Man-Hour/Flight Hour
Powerplant Maintenance	As Computed Using Standard Preliminary Design Methods

*In these calculations, the airframe weight (in pounds) is taken as:

Weight = Operating Weight Empty - Operating Equipment - Powerplant - Powerplant Accessories

185.2 km (100 nmi) MISSION, 1979 DOLLARS

FUEL COST	$264/m^3$ ($1.00/GAL)	FUEL COST	$396/m^3$ ($1.50/GAL)
DOC	3.89¢/seat·km (7.20¢/seat·nmi)	DOC	4.43¢/seat·km (8.21¢/seat·nmi)

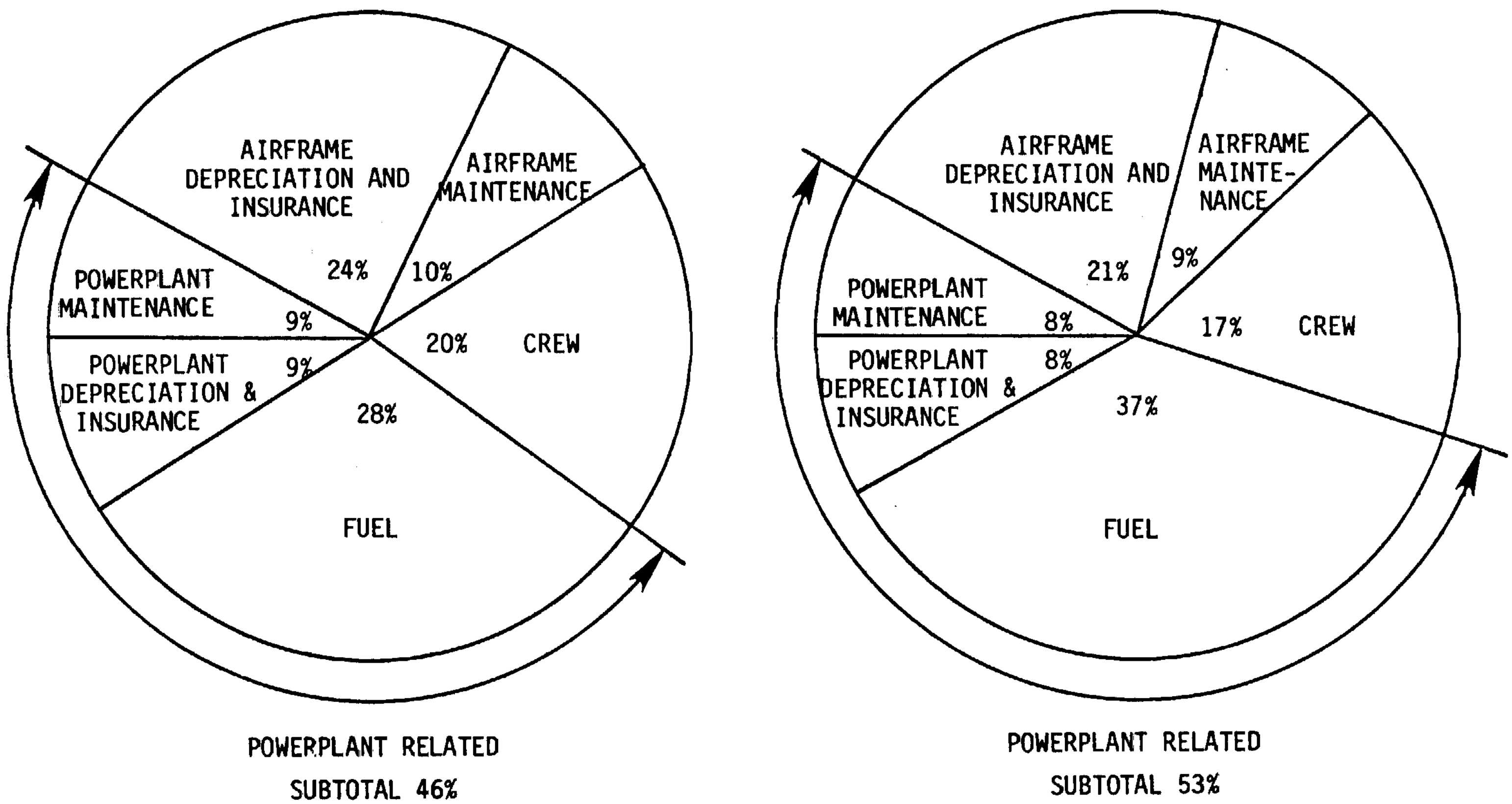


Figure 6. 30-Passenger Baseline Aircraft DOC Breakdown (Scaled CT7-5 Powered).

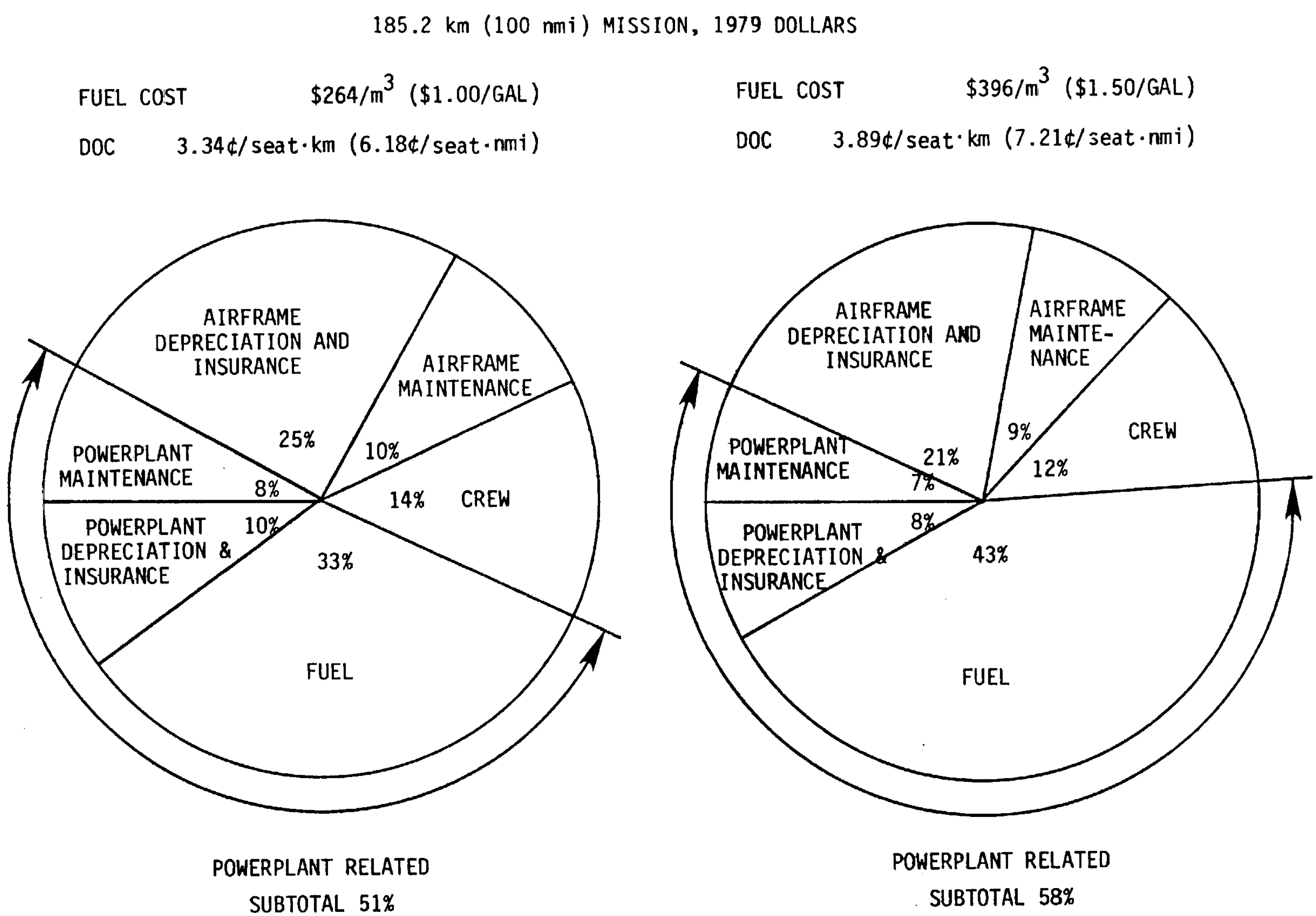


Figure 7. 50-Passenger Baseline Aircraft DOC Breakdown (Scaled CT7-5 Powered).

AIRCRAFT SENSITIVITY FACTORS

The effects of powerplant technology improvements were evaluated by adjusting the baseline engine and repeating the 185.2 km (100 nmi) mission and direct operating cost (DOC) calculations (see Tables 9-10). This procedure involved so-called rubber engine and rubber aircraft assumptions, which required scaling the aircraft and engine for constant payload and mission. The baseline aircraft was resized for each powerplant change so that it would still perform the design mission. Hence, the results include the compounding effects of improvements which result in a lighter aircraft and a smaller engine to meet the mission requirements. For example, a 1% SFC decrease would result in a 0.2% decrease in aircraft gross weight, and the engines required would be correspondingly smaller and less expensive. The combined effect of such changes was determined at the 185.2 km (100 nmi) range, using the economic model to determine the impact of the aircraft and engine cost and weight changes and the fuel burned changes on DOC.

TABLE 9
MISSION MERIT FACTOR SENSITIVITIES

30-Passenger Turboprop - 185.2 km (100 nmi) Mission
10,840 kg (23,900 lbm) Gross Weight - 1208 kW (1620 hp) Engine
1979 Dollars - 1000 Engines

Parameter	Change	Change in DOC (%) $264/m³ ($1.00/Gal)	Change in DOC (%) $396/m³ ($1.50/Gal)	Change in Fuel Flow (%)	Change in Takeoff Gross Weight (%)
Engine Weight*	+4.5 kg (+10 lbm)/engine	.063	.071	.11	.14
Engine Price*	+$1000/engine	.020	.017	-	-
Engine Maintenance*	+$1/h	.372	.321	-	-
SFC (Everywhere)	+1%	.385	.485	1.11	.16

* Also applies to gearbox, propeller or nacelle.

TABLE 10
MISSION MERIT FACTOR SENSITIVITIES

50-Passenger Turboprop - 185.2 km (100 nmi) Mission
17,826 kg (39,300 lbm) Gross Weight - 2095 kW (2810 hp) Engine
1979 Dollars - 1000 Engines

Parameter	Change	Change in DOC (%) $264/m³ ($1.00/Gal)	Change in DOC (%) $396/m³ ($1.50/Gal)	Change in Fuel Flow (%)	Change in Takeoff Gross Weight (%)
Engine Weight*	+4.5 kg (+10 lbm)/engine	.053	.058	.08	.09
Engine Price*	+$1000/engine	.014	.012	-	-
Engine Maintenance*	+$1/h	.264	.224	-	-
SFC (Everywhere)	+1%	.453	.558	1.13	.18

*Also applies to gearbox, propeller, or nacelle.

ADVANCED TECHNOLOGY IDENTIFICATION AND EVALUATION

EVALUATION PROCEDURE

The engine technology and cycle evaluation procedure was based on installing powerplants into the two baseline aircraft and tracing through the total impact on the aircraft design and mission. In practice this was done for the many cases which had to be exercised by using the generalized mission sensitivity factors described in the preceding section and summarized in Tables 9-10. Then the assumption of linearity was made and the sum of all the influences on each variable computed.

For the advanced technology evaluation procedure, a set of sensitivities of engine parameters to component changes was also developed. Table 11 provides the effects of an arbitrary change in the major component parameters on mission weighted SFC, compressor flow size, and output turbine flow size. The flow size changes were used to determine the impact on engine weight and price. (For example, low-pressure turbine weight and price correlate well with the average of turbine inlet and exit corrected flow).

In all cases, except for the rating studies and the combustor technology items, the design changes were applied holding engine life constant.

The base values of performance, weight, price, and maintenance were estimated for a nominal advanced engine typical of those under study by General Electric for the next generation of small turboshaft and turboprop engines. This nominal engine was scaled to the two sizes required by the baseline aircraft, with the following results. Note that these values do not apply to the final advanced engine designs, or the baseline CT7-5 engine. They are estimates made for use in this portion of the study only.

No. of Passengers	30	50
Engine Size, kW (hp)	1208 (1620)	2095 (2810)
Engine Weight, kg (lbm)	113 (250)	186 (410)
Engine Price, k$	285	354
Engine Maintenance, $/h	21.30	26.45

TABLE 11
ENGINE SENSITIVITIES

Constant Takeoff Power = 1208 kW (1620 hp)
Constant Takeoff T41 = 1260°C (2300°F)

Parameter	Change	Mission Weighted* %Change in SFC	% Change in Compressor Inlet Corrected Flow	% Change in Low-Pressure Turbine Corrected Flow	
				Inlet	Exit
Compressor Efficiency	+1 pt	-1.18	-1.70	-3.45	-1.70
High-Pressure Turbine Efficinecy	+1 pt	-1.25	-1.22	-3.05	-1.37
Low-Pressure Turbine Efficiency	+1 pt	-1.08	-1.08	-1.08	-1.23
Compressor Discharge Chargeable Cooling; Return Post High-Pressure Turbine	+1% W2	+.94	+2.03	+3.51	+1.81
Compressor Discharge Chargeable Cooling; Return Post Low-Pressure Turbine	+1% W2	+1.60	+2.70	+3.31	+2.63
Mid-Compressor Chargeable Cooling; Return Post Low-Pressure Turbine	+1% W2	+.68	+1.79	+1.46	+1.57
Power Extraction	+18.6 kW (+25 hp)	+.98	+.68	+1.42	+.76
Inlet Recovery	-1%	+.67	+1.68	+1.68	+.85
Combustor Δ P/P	+1%	+.70	+.70	+1.77	+1.77
Exhaust Δ P/P	+1%	+.69	+.68	+.68	+.68
Compressor P/P (Constant Polytropic Efficiency)	+5%	-.57	+.57	-.29	+.05

*Mission Weighting: 7% Takeoff, 37% Climb, 56% Cruise.

CYCLE AND ENGINE ARRANGEMENT PARAMETRIC ANALYSIS

Propulsion Alternatives

In selecting a propulsion system to meet the requirements of a commuter aircraft, the first choice to be made was between a turboprop and a turbofan engine. For the typical low altitude, low speed commuter mission, the turboprop has an undeniable advantage. For a given core engine size, the turboprop provides greater cruise thrust than the turbofan at a very much lower level of SFC. Table 12 provides a comparison of a turboprop engine and two turbofan engines based on the CT7-5 core.

The first turbofan cycle uses a 1.75 design pressure ratio fan stage based on the USAF Trainer Fan design (Contract F-33615-78-C-2060); the second incorporates a very high bypass ratio geared fan (based on the variable pitch QCSEE fan). Both fans were matched to the CT7-5 core at the STAT baseline cruise condition of 3048 m (10,000 feet), 0.45 Mach number. At this flight condition, the trainer fan operates at a pressure ratio of 1.58, and the geared fan at 1.34. The turboprop has a 30 to 40 point advantage in propulsive efficiency, with the result that the turbofan SFC's are 40 to 45% higher than the turboprop. The turbofans would also have to be scaled up by 8 to 20% to provide the same maximum cruise thrust.

In terms of DOC, a 1% decrease in SFC is equivalent to a 2 to 3% decrease each in propulsion system weight, price, and maintenance cost. While the mission merit factor sensitivities cannot be expected to be valid for such large changes in SFC, it is obvious that no weight and cost advantages that the turbofans might have can possibly outweigh the SFC differences.

TABLE 12
TURBOFAN VERSUS TURBOPROP CRUISE PERFORMANCE COMPARISON

3048 m (10,000 ft), 0.45 Mach No.

	Turboprop	Conventional Turbofan	Geared Fan
Turbine Rotor inlet Temp - °C (°F)	1252 (2285)	1252 (2285)	1252 (2285)
Core Corrected Flow - kg/s (lbm/sec)	4.67 (10.3)	4.67 (10.3)	4.67 (10.3
Core Pressure Ratio	17.2	17.2	17.2
Overall Pressure Ratio	17.2	27.5	20.9
Fan Pressure Ratio	-	1.58	1.34
Bypass Ratio	-	5.3	9.5
Thrust - Δ%	Base	-8.1	-19.6
SFC - Δ%	Base	+45	+40
Propulsive Efficiency*	0.98	0.61	0.70

*Propulsive Efficiency = (Useful Work)/(Useful Work + Kinetic Energy Loss)

$$= (F_N V_O)/[F_N V_O + 1/2\ m\ (V_J - V_O)^2]$$

where V_O = Flight Velocity
V_J = Average Velocity of Propeller or Fan and Core Engine Flow Leaving the System

This reduces to:

$$\text{Propulsive Efficiency} = 2(V_O/V_J)\ /(1 + V_O/V_J)$$

CYCLE AND ENGINE ARRANGEMENT PARAMETRIC ANALYSIS - Continued

In a prior study of turboprops for large transport aircraft, the turbofan propulsion system was about 30% lighter in weight than the engine-gearbox-propeller combination, but was within 5% of the cost and maintenance. Assuming that these trends hold, and that the STAT sensitivities can be applied for large changes, the turbofan cycles would have DOC's 15 to 25% higher than a turboprop. This result applies to the short haul, low speed mission used here. It is to be expected that the turboprop advantage would decrease with increasing cruise Mach number. Previous studies have indicated a potential DOC saving for a turboprop powered, 0.8 Mach number, medium haul transport on the order of 5% relative to a turbofan aircraft.

Based on the large estimated difference in DOC, the turbofan was not pursued as an alternative propulsion system.

Having eliminated the turbofans from consideration, there remains a choice to be made from among the three general classes of propellers for which Hamilton Standard has supplied data.

1. Propellers for low speed aircraft (Mach $\leq$ 0.5).
2. Propellers for higher speed aircraft (nominally Mach = 0.6).
3. Prop-Fans for Mach $\geq$ 0.6 aircraft.

General Electric has found the low speed (Mach approximately 0.45) aircraft best suited to the STAT mission, and the Hamilton Standard low speed propeller best suited to that aircraft.

Figure 8 compares the performance of representative propellers of the three types at the STAT 3048 m (10,000 ft), 0.45 Mach cruise condition. A common tip speed of 228.6 m/s (750 ft/sec) has been assumed. A qualitative comparison of the three follows:

	Low Speed Propeller	High Speed Propeller	Prop-Fan
Efficiency	Base	Slightly Lower	Lower
Weight	Base	Much Higher	Much Lower
Cost	Base	Higher	Much Higher
Maintenance	Base	Higher	Much Higher
DOC	Base	Higher	Higher

The high speed propeller is poorer in all respects than the selected propeller. The prop-fan offers a significant weight reduction (on the order of 50%) due to its higher loading and reduced diameter, but has a first cost several times that of a conventional prop, and correspondingly high maintenance costs. Both the high speed propeller and Prop-Fan would have DOC's on the order of 2-4% higher than the low speed prop.

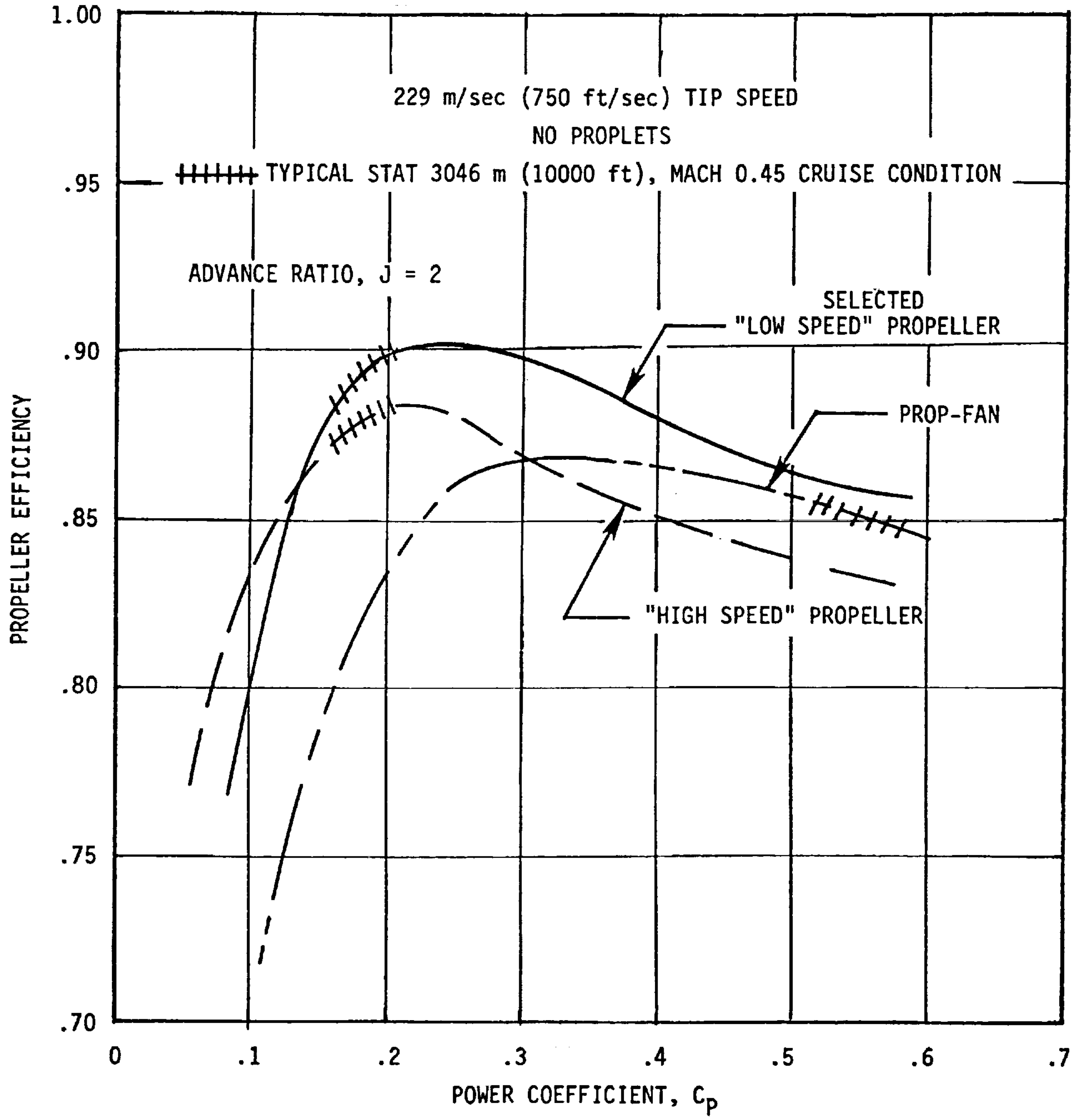


Figure 8. Propeller Cruise Efficiency Comparison.

CYCLE AND ENGINE ARRANGEMENT PARAMETRIC ANALYSIS - Continued

Exhaust Nozzle Pressure Ratio Selection

The selection of nozzle pressure ratio (P8/PAMB) for a turboprop engine has an impact on both propulsion system size and fuel consumption. The optimum value of pressure ratio is mission dependent; increasing nozzle pressure ratio tends to favor SFC at higher flight velocities, while increasing fuel consumption at takeoff and low flight speeds. Increasing nozzle pressure ratio also results in a larger engine for the same takeoff thrust, but a smaller propeller and gearbox. As the pressure ratio is increased, the engine exhaust provides a larger percentage of the total thrust, and the engine delivers less power to the propeller. This results in a smaller propeller and gearbox, but requires an increase in airflow size to maintain the same total thrust. Increasing P8/PAMB also tends to reduce the size of the low-pressure turbine and exhaust system, but this is a second order effect; the airflow increase dominates the engine weight.

Some of these trends are shown in Figure 9 for the STAT 30-passenger baseline aircraft. The results in terms of fuel burned and direct operating cost are shown in Figure 10 for the 185.2 km (100 nmi) mission. The optimum nozzle pressure ratio for cruise fuel consumption and propulsion weight is 1.10. The optimum for fuel burned and DOC is somewhat lower, at around 1.06 P8/PAMB. A value of 1.10 was selected for further use in the study because it is near the optimum, and tends to favor longer stage length missions where cruise SFC becomes more dominant.

Parametric Study Engines

A nominal advanced engine (typical of those under study by General Electric for the next generation of small engines) was selected as the point of departure for this portion of the study. This is the same engine used as the framework for evaluating the advanced technology features and design factors. Variations in cycle pressure ratio and turbine inlet temerature (T41) from the nominal cycle were considered, as were a variety of engine arrangements to achieve the desired cycles.

The nominal advanced engine comprises an advanced axi-centrifugal compressor with a 17:1 pressure ratio, a high through-flow annular combustor, a single stage, cooled high-pressure turbine with a 1260°C (2300°F) inlet temperature, and a two stage, uncooled, forward drive power turbine. The cycle parametric study encompasses pressure ratios from 11.5:1 to 30:1 and turbine inlet temperatures of 999° to 1371°C (1830° to 2500°F). Selected combinations of pressure ratio, temperature, and engine arrangement which seemed to have merit were investigated in some detail.

At the lowest pressure ratio, consideration was given to an uncooled turbine; at moderate pressure ratios a comparison was made between single and two stage compressor drive turbines; at moderate to high pressure ratios the addition of low-pressure compression stages (boosters) to the output shaft was studied; at the highest pressure ratio, a dual rotor core cycle was investigated. Altogether, 12 engine designs, summarized in Table 13, were analyzed. The base (nominal) cycle is Cycle 3.

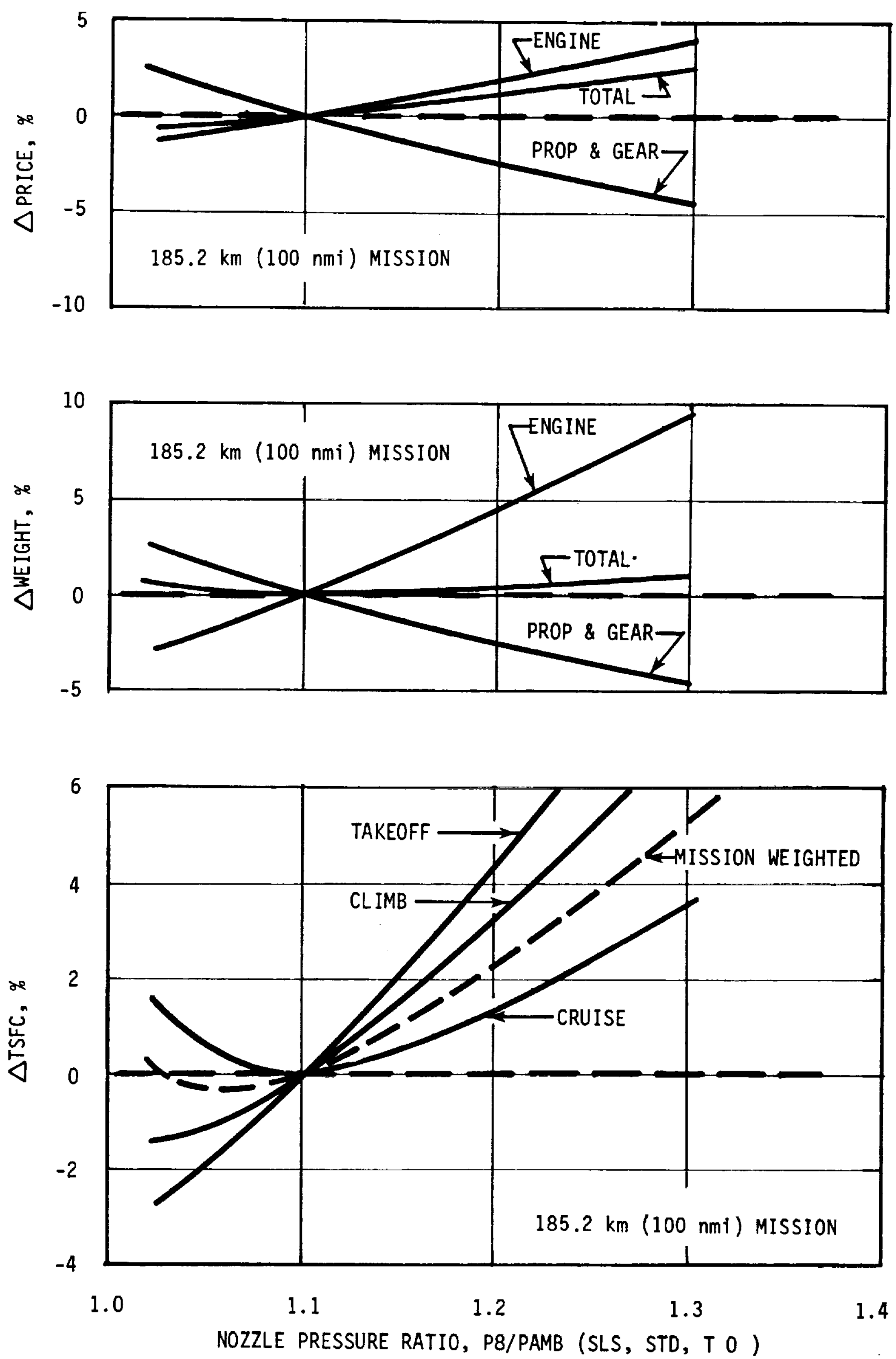


Figure 9. 30-Passenger Baseline Aircraft Trends with Nozzle Pressure Ratio.

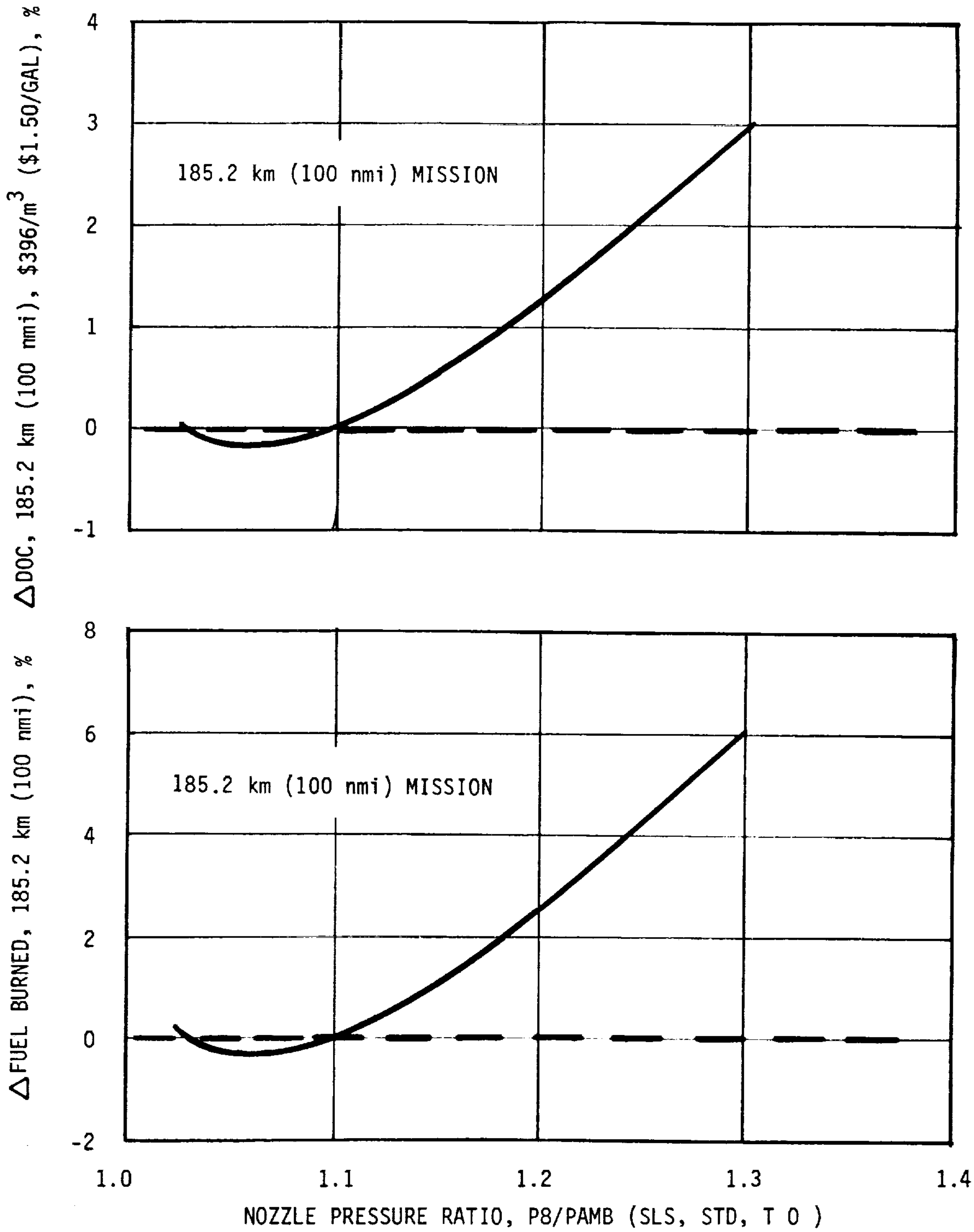


Figure 10. 30-Passenger Baseline Aircraft Merit Factor Trends with Nozzle Pressure Ratio.

TABLE 13
PARAMETRIC ENGINE STUDY
Engine Configurations

Cycle No.	Overall Pressure Ratio	Turbine Inlet Temp, T4 °C (°F)	Compressors* Staging	Compressors* Pressure Ratio	Turbines** Stages	Turbines** Drives	Special Features
1A	11.5	1082 (1980)	2 Ax + 1 Cent	11.5	HPT 1 LPT 2	Compressor Output Shaft	Uncooled HPT blades of advanced material.
1B	11.5	999 (1830)	2 Ax + 1 Cent	11.5	HPT 1 LPT 2	Compressor Output Shaft	Uncooled HPT blades of current material.
2	11.5	1260 (2300)	2 Ax + 1 Cent	11.5	HPT 1 LPT 2	Compressor Output Shaft	
3	17.0	1260 (2300)	3 Ax + 1 Cent	17.0	HPT 1 LPT 2	Compressor Output Shaft	Base
4	17.0	1371 (2500)	3 Ax + 1 Cent	17.0	HPT 1 LPT 2	Compressor Output Shaft	
5A	23.0	1260 (2300)	LPC 1 Ax HPC 3 Ax + 1 Cent	1.35 17.0	HPT 2 LPT 3	HP Compressor LP Compressor & Output Shaft	Booster on Output Shaft
5B	23.0	1260 (2300)	LPC 2 Ax HPC 3 Ax + 1 Cent	2.0 11.5	HPT 2 LPT 4	HP Compressor LP Compressor & Output Shaft	Booster on Output Shaft
6	30.0	1260 (2300)	LPC 2 Ax HPC 4 Ax + 1 Cent	1.79 17.0	HPT 2 LPT 4	HP Compressor LP Compressor & Output Shaft	Booster on Output Shaft
7	30.0	1371 (2500)	LPC 2 Ax HPC 4 Ax + 1 Cent	1.79 17.0	HPT 2 LPT 4	HP Compressor LP Compressor & Output Shaft	Booster on Output Shaft
8	17.0	1260 (2300)	3 Ax + 1 Cent	17.0	HPT 2 LPT 3	HP Compressor Output Shaft	
9	23.0	1260 (2300)	4 Ax + 1 Cent	23.0	HPT 2 LPT 3	HP Compressor Output Shaft	
10	30.0	1260 (2300)	LPC 1 Ax + 1 Cent HPC 1 Cent	7.5 4.0	HPT 1 IPT 1 LPT 2	HP Compressor LP Compressor Output Shaft	Dual Rotor Core, Three Turbine Arrangement

*LPC = low-pressure compressor; HPC = high-pressure compressor
**HPT = high-pressure turbine; LPT = low-pressure turbine; IPT = intermediate-pressure turbine

CYCLE AND ENGINE ARRANGEMENT PARAMETRIC ANALYSIS - Continued

Cycles 1A, 1B, 2, 3, and 4 combine to illustrate the trends with pressure ratio and temperature for conventional turboshaft engines with single stage high-pressure turbines. Cycles 1A and 1B have uncooled high-pressure turbine blades. Both are at a pressure ratio of 11.5:1, but differ in turbine temperature. Cycle 1B operates at the maximum temperature allowable for an uncooled turbine blade of current technology material, Cycle 1A operates 83.3°C (150°F) hotter, the estimated capability of an uncooled blade of an advanced, directionally solidified, eutectic material. Cycle 2 provides a comparable cycle with a cooled high-pressure turbine at 11.5:1, 1260°C (2300°F) T41. Cycle 3 is the nominal cycle, at 17:1, 1260°C (2300°F); Cycle 4 is the same configuration operating at 17:1 and 1371°C (2500°F).

Pressure ratios above 17:1 require other staging arrangements; either 2-stage turbines, or another compressor. Cycle 8, when compared to Cycle 3, yields the 2-stage versus 1-stage turbine comparison at the nominal cycle conditions [17:1, 1260°C (2300°F)]. Cycle 9, also with a 2-stage turbine, extends the pressure ratio trend to 23:1 at 1260°C (2300°F). This is considered to be the maximum pressure ratio obtainable with a single spool.

Cycle 5A has a single, 1.35:1 pressure ratio compression stage (booster) added to the low-pressure rotor, and runs to the same overall pressure ratio and T41 as Cycle 9. It also has a 2-stage high-pressure turbine. Thus Cycle 5A versus Cycle 9 provides a direct comparison of a boosted and conventional cycle. Cycle 5B differs from 5A in that it has a 2-stage, 2:1 booster, which allows a lower pressure ratio core and a single stage high-pressure turbine.

Cycles 6 and 7 both have 2-stage, 1.8:1 pressure ratio boosters, 2-stage turbines and 30:1 overall pressure ratios. Their turbine inlet temperatures are 1260° and 1371°C (2300° and 2500°F), respectively.

Cycle 10 is also 30:1, 1260°C (2300°F), but uses a dual rotor core, 3-turbine arrangement. The high-pressure compressor is a single centrifugal stage driven by a single, cooled turbine stage. The low-pressure compressor is an axi-centrifugal driven by another cooled, single stage turbine. The power turbine is an uncooled 2-stage design.

Component Cycle Trends

Each engine was modeled in sufficient detail to determine cooling flows, turbine loading, tip speeds, and other factors affecting engine performance and size. Performance was established in a common core airflow size, and costs and weights were estimated. The engines were then scaled to the mission thrust size required by the STAT baseline aircraft and performance adjusted for the resulting differences in component size, (e.g., clearance and Reynolds number effects).

Primary emphasis was given to selecting components and a cycle consistent with technology expected to be available in the early 1990's. The cycle trends are themselves dependent upon the component technology assumptions made. The cycle pressure ratio and SFC trend, for example is dependent upon the compressor arrangement and compressor efficiency trends with pressure ratio, as well as other pressure ratio related design factors such as turbine cooling flows. Turbine cooling flow dependence on turbine inlet temperature and compressor discharge (coolant) temperature is provided as an example in Figure 11 for single stage and 2-stage turbines at the temperature levels relevant to this study. Typical of the considerations involved in establishing component performance are the relations between single stage turbine efficiency and turbine loading, pressure ratio, and clearances. Care was exercised in modeling each component to assure that such effects were accounted for.

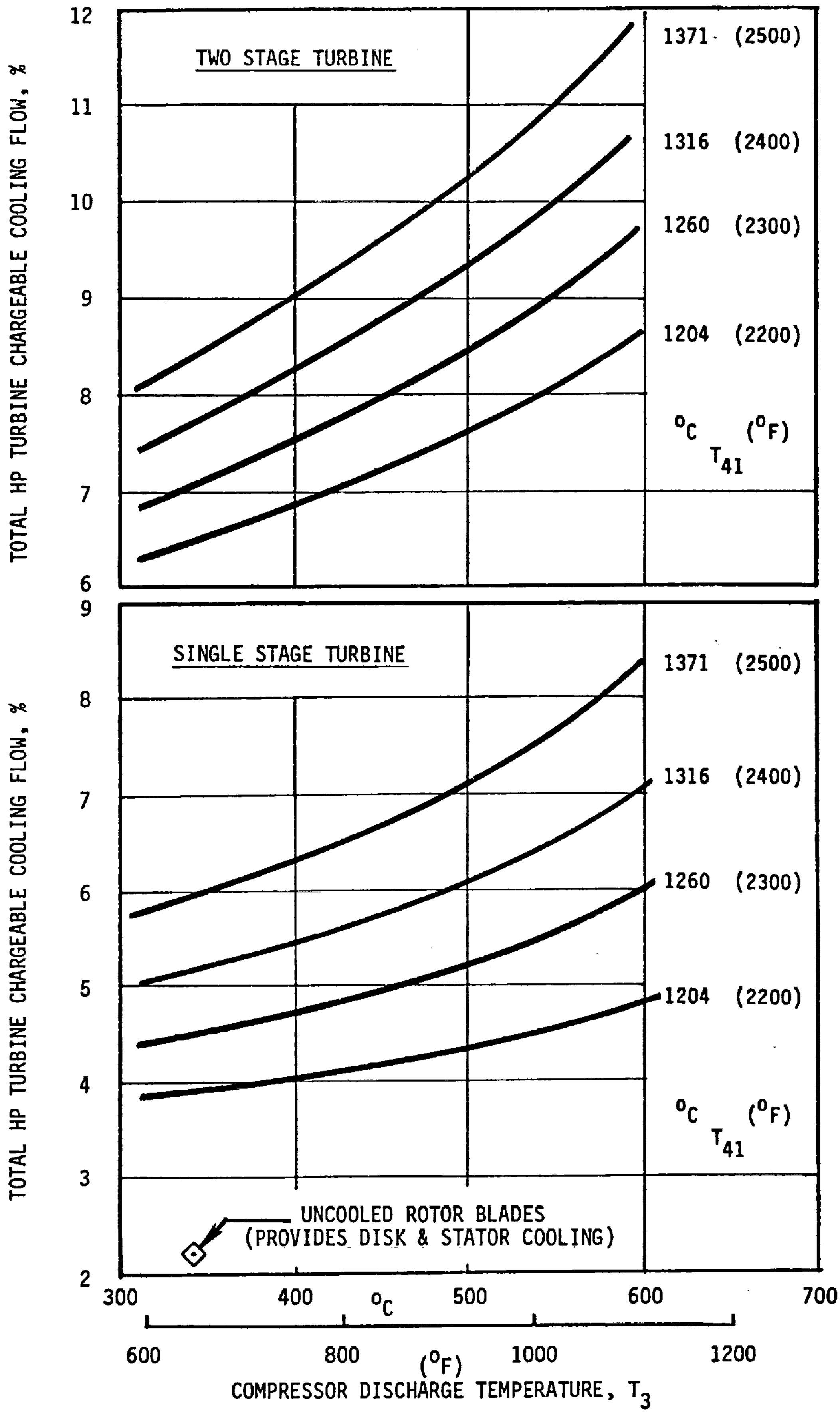


Figure 11. Estimated Turbine Cooling Flow Requirements.

CYCLE AND ENGINE ARRANGEMENT PARAMETRIC ANALYSIS - Continued

The engines with high pressure ratios and high turbine inlet temperatures, when scaled to the size required by the STAT baseline aircraft, result in turbomachinery components that are physically quite small. Since clearances, Reynolds number effects, etc. are more significant in small size, component performance must be adjusted to avoid biasing the study in favor of high pressure ratio and high temperature cycles. Figure 12 shows the trend in compressor adiabatic efficiency with size based on General Electric design experience, for example. The parameter used as an indicator of size is the average of the inlet and exit corrected flows at the compressor design point. This correlation applies to both large all-axial compressors and small axi-centrifugal machines.

Figure 13 presents the trend in SFC which results for the overall engine when size effects are accounted for in all components. Over the 30- to 50-passenger aircraft size range, the typical SFC variation due to size is of the order of 1%.

Results

The trends in engine parameters which result from the above considerations are summarized in Figures 14-15 for the 30-passenger mission size engines [1208 kW (1620 hp) at sea level, static, standard day rated takeoff temperature]. SFC shows the expected improvement with both increased temperature and pressure ratio. The improvement with pressure ratio is mitigated beyond about 20:1 however, by the component performance decrements associated with the small physical size of the rear compression stages and core drive turbines. Significant SFC improvements over the reference cycle are possible at a T41 of 1371°C (2500°F) and an overall pressure ratio of 25:1. However, all the effects on the engine must be considered in the cycle selection. Over the pressure ratio range considered, engine specific output (power/airflow) decreases with increasing pressure ratio, and increases with T41. Thus the engine weight trends, Figure 14, are favorable with increasing T41 at constant pressure ratio, but there is a weight penalty for high pressure ratio cycles due to the increased size required to offset the reduced specific output, as well as the addition of compressor stages.

The engine price and maintenance trends are shown in Figure 15. The effect on price of increasing turbine temperature is a result of the balance between savings due to a smaller core and increases due to a costlier hot section. Above 1082°C (1980°F), these trends tend to balance for the single stage turbine engines. For the 2-stage turbines, prices increase because of the costlier hot section. Price increases with pressure ratio for the same reasons weight does.

The hot section costs are weighted more strongly in the maintenance costs, and as a result the 1371°C (2500°F) T41 engines have a higher maintenance cost than the 1260°C (2300°F) T41 engines, although their prices are the same at the same cycle pressure ratio. The maintenance cost trend with pressure ratio balances two effects, resulting in a minimum in the trend [at about 17:1 pressure ratio for the 1260°C (2300°F) cycles]. The engine size increase with pressure ratio discussed above is partially offset because the increased density in the combustor and high-pressure tubine makes these high-maintenance components smaller relative to the rest of the engine.

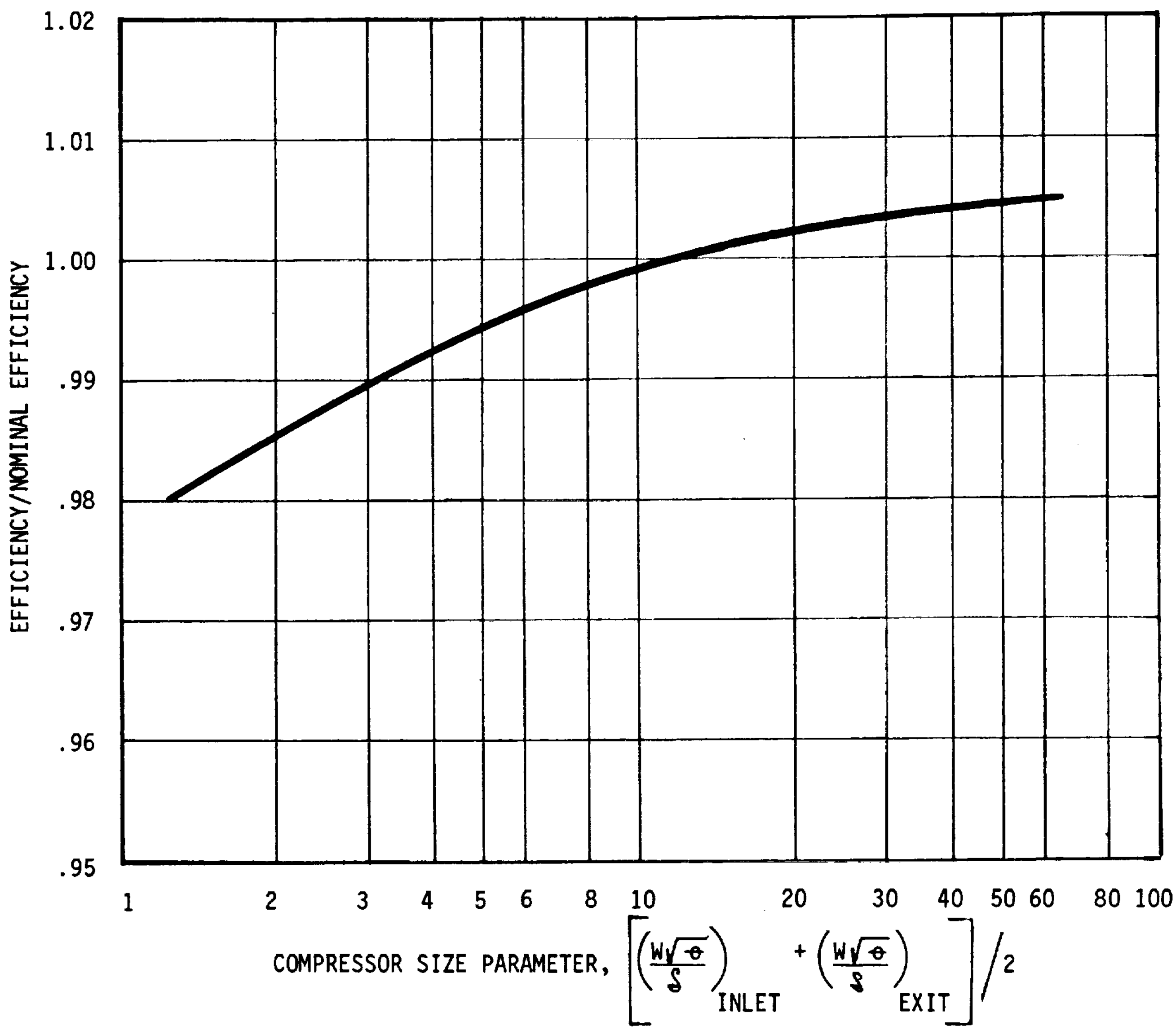


Figure 12. Compressor Efficiency Trend with Size.

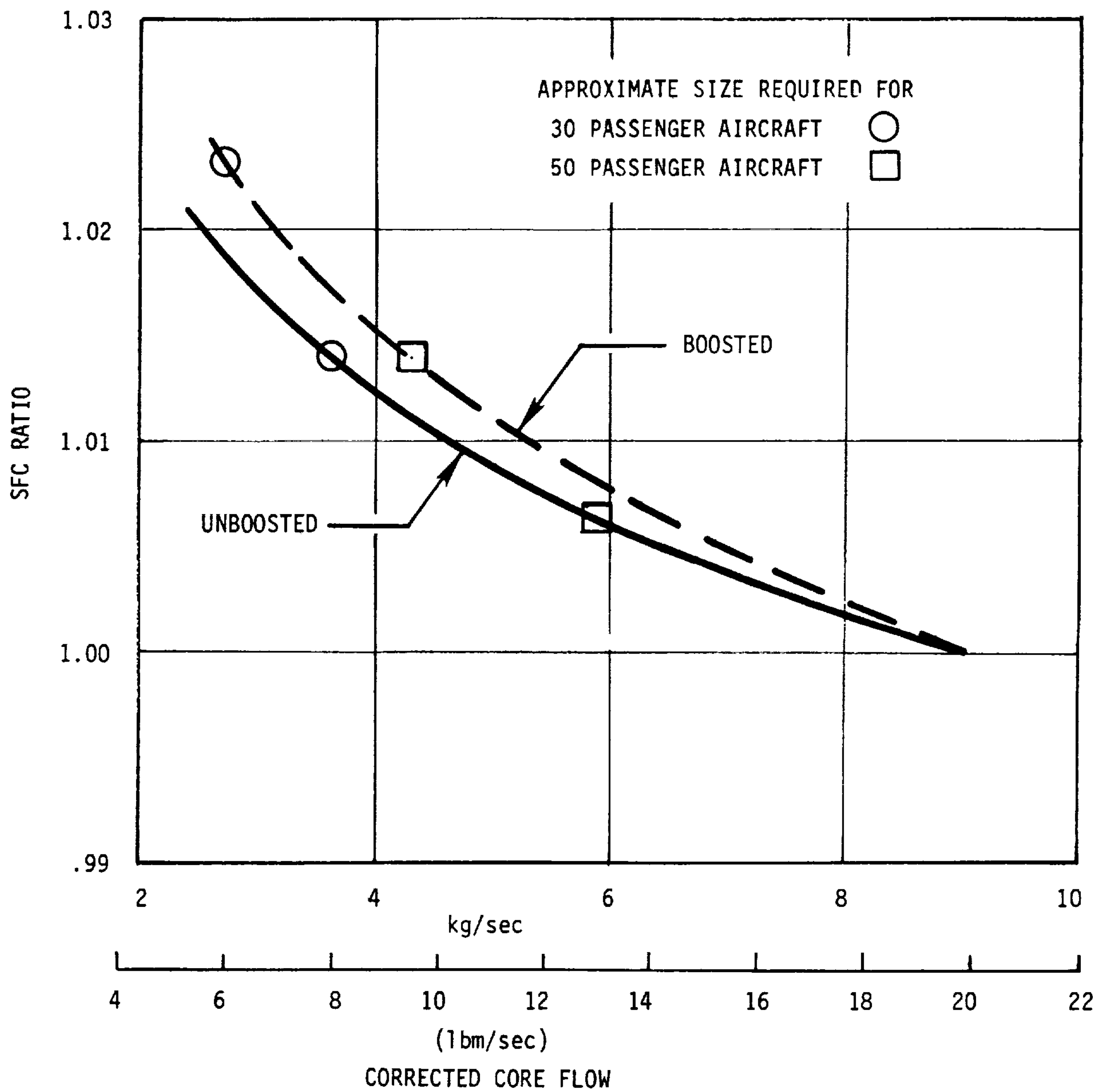


Figure 13. Engine SFC Trend with Size.

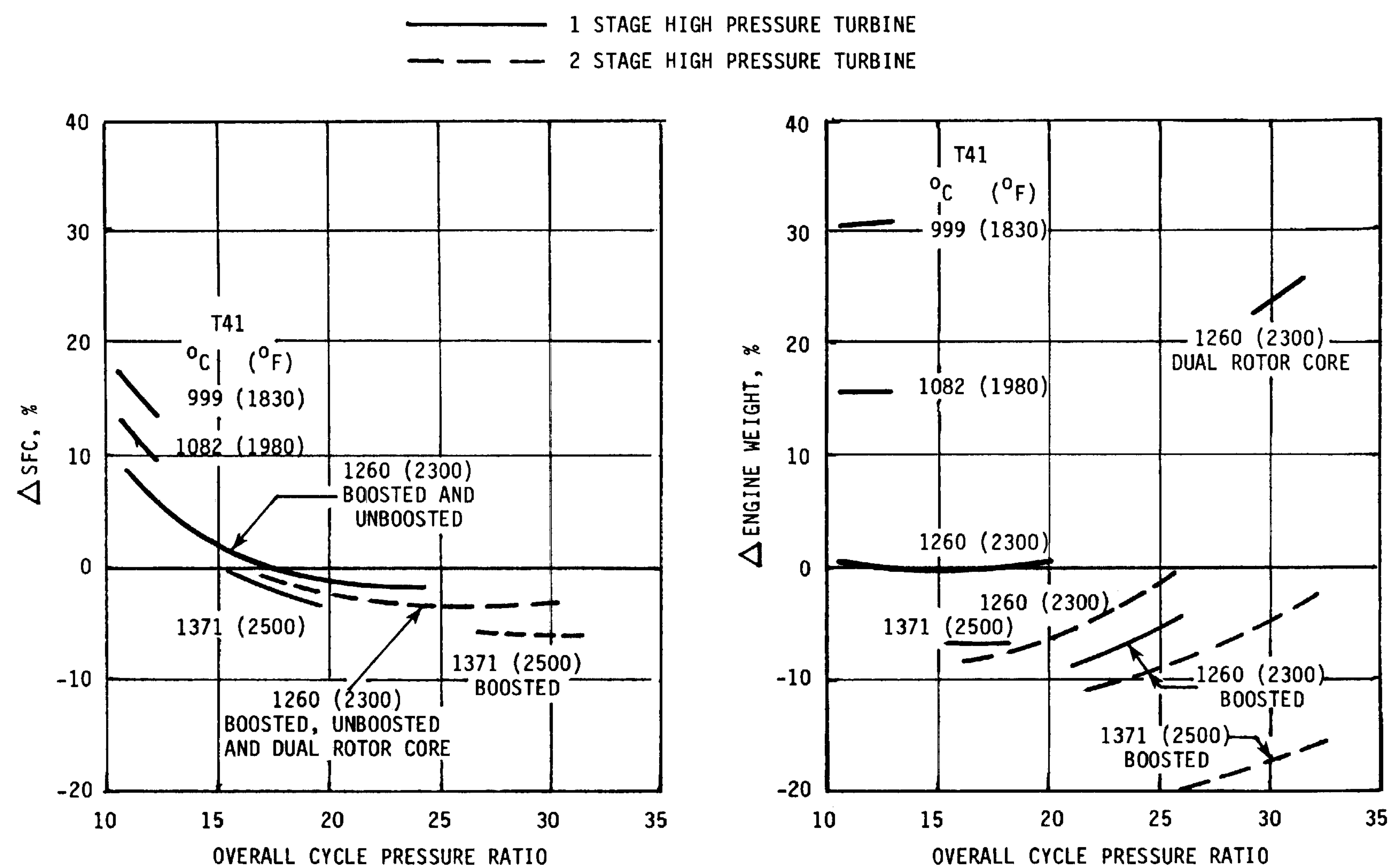


Figure 14. 30-Passenger Aircraft SFC and Engine Weight Trends.

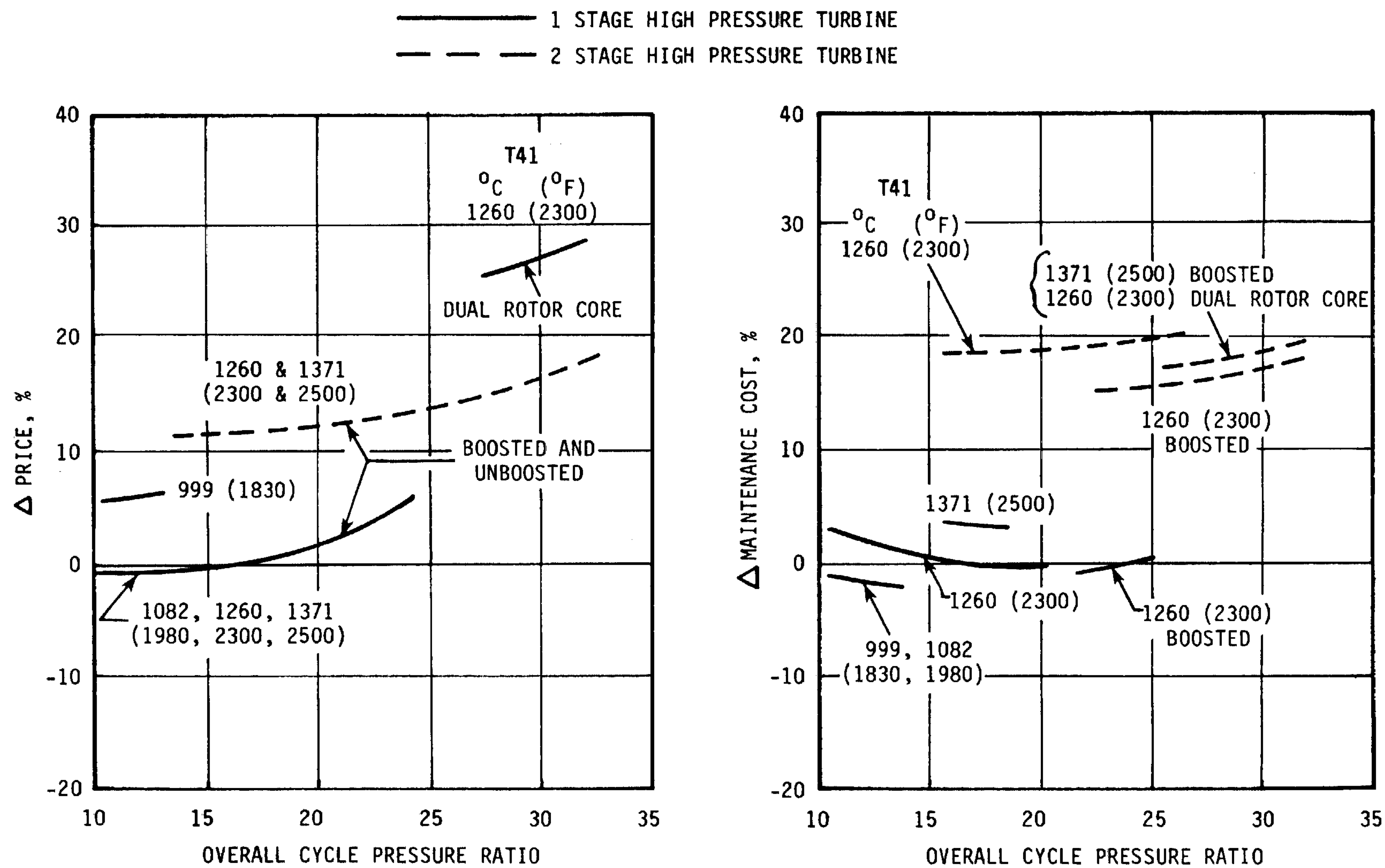


Figure 15. 30-Passenger Aircraft Price and Maintenance Cost Trends.

CYCLE AND ENGINE ARRANGEMENT PARAMETRIC ANALYSIS - Continued

The effects of SFC, weight, price and maintenance on the DOC of a 30-passenger commuter turboprop are combined in Figure 16. The minimum DOC at 1260°C (2300°F) T41 occurs at a pressure ratio of 20. The minimum DOC is, however, only a 1/2% less than the baseline. Clearly the payoff of very high pressure ratios is very small. The higher fuel cost of $\$396/m^3$ ($\$1.50$/gal) shows more justification for the selection of higher pressure ratios and T41. At $\$396/m^3$ ($\$1.50$/gal) for the 30-passenger aircraft on the 185.2 km (100 nmi) mission, fuel represents 41% of the total DOC.

Figure 17 shows the DOC results for the 50-passenger commuter aircraft. Cycle trends for the 50-passenger aircraft engine show a somewhat higher payoff for higher T41 and cycle pressure ratio. The absolute size penalties on cooling flows and component efficiencies show up less strongly in the larger engine size required for the 50-Passenger aircraft.

Results in terms of aircraft design takeoff gross weight and fuel burned on the 185.2 km (100 nmi) mission are provided on Figure 18-19.

The specific engine and mission characteristics for each of the study engines are provided in Tables 14-15 for reference.

Tables 16-18 are illustrative of the impact of configuration and staging variations. Each table compares two configurations at the same combination of pressure ratio and T41.

Table 16 compares two engines where the primary difference is a change from a single stage HP turbine to a 2-stage HP turbine. The 2-stage turbine is advantageous in terms of loading and efficiency. Being more lightly loaded, the rotor is of smaller diameter resulting in substantial weight savings when designed to the same stress levels and life as the single stage turbine. In the case shown here, it was also necessary to reduce the diameter of the low-pressure turbine by adding a stage to obtain a smooth flowpath transition between turbines. Although the net result of these changes is a reduction in engine weight, the added complexity increases engine price significantly. Because HP turbine parts are heavily weighted in the engine maintenance model, maintenance shows an even stronger adverse effect. Another disadvantage of the 2-stage turbine is that it requires more cooling air. The end result is a savings of 1.3% in fuel, but a 1.3% increase in DOC.

The tradeoff between a boosted and unboosted engine at 23:1 and 1260°C (2300°F) is neutral, as shown in Table 17. At a fixed power size, the supercharging effect of the booster results in small core components, which confer a weight and price advantage. The overall efficiency of the compression process is slightly higher for the conventional turboshaft engine, giving it 1.4% better SFC. The engine size effects on weight and cost just balance the performance effect, with the result that the boosted engine has the same DOC as the unboosted, but burns 1.5% more fuel.

A turboshaft engine with a dual rotor core is compared to a boosted engine at 30:1 and 1260°C (2300°F) in Table 18. The addition of an entire spool to the core results in a very large weight penalty for the dual rotor engine. Chief contributions to the weight increase are the additional frame and sump required to support the third rotor, and the large bore diameters required on the HP rotor (for the three concentric shafts) which result in heavy, inefficient disk designs.

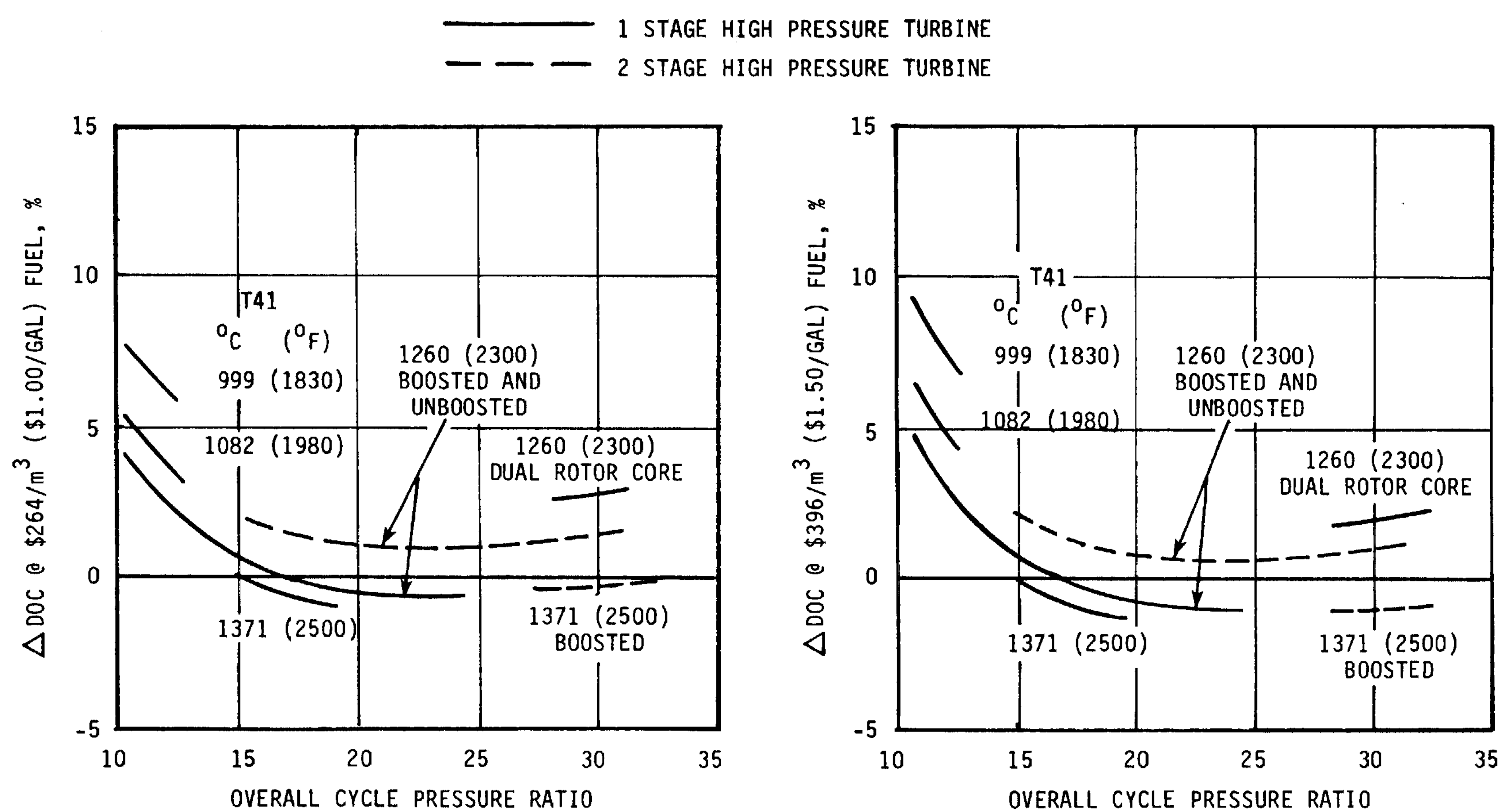


Figure 16. 30-Passenger Aircraft DOC Trends.

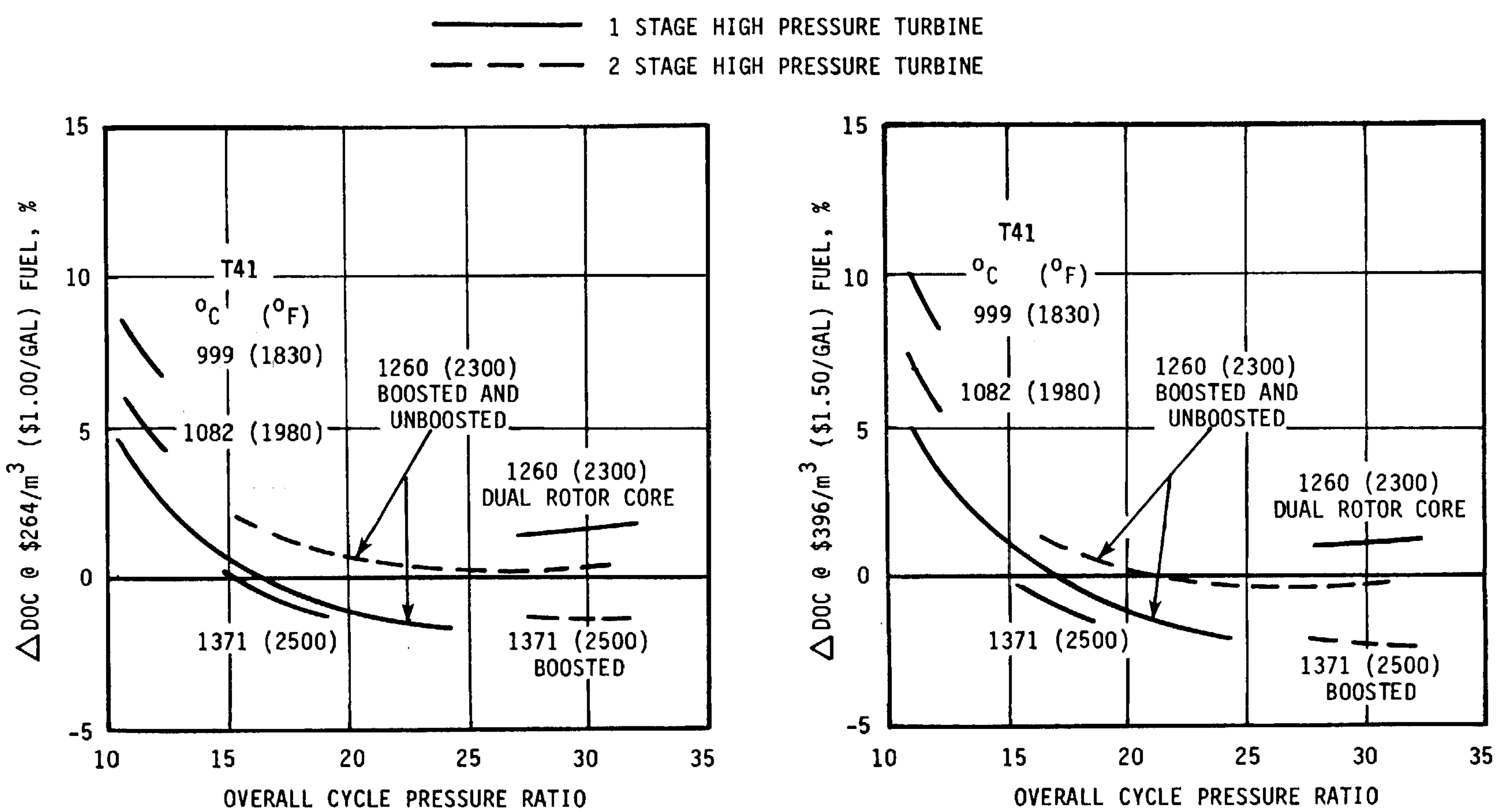


Figure 17. 50-Passenger Aircraft DOC Trends.

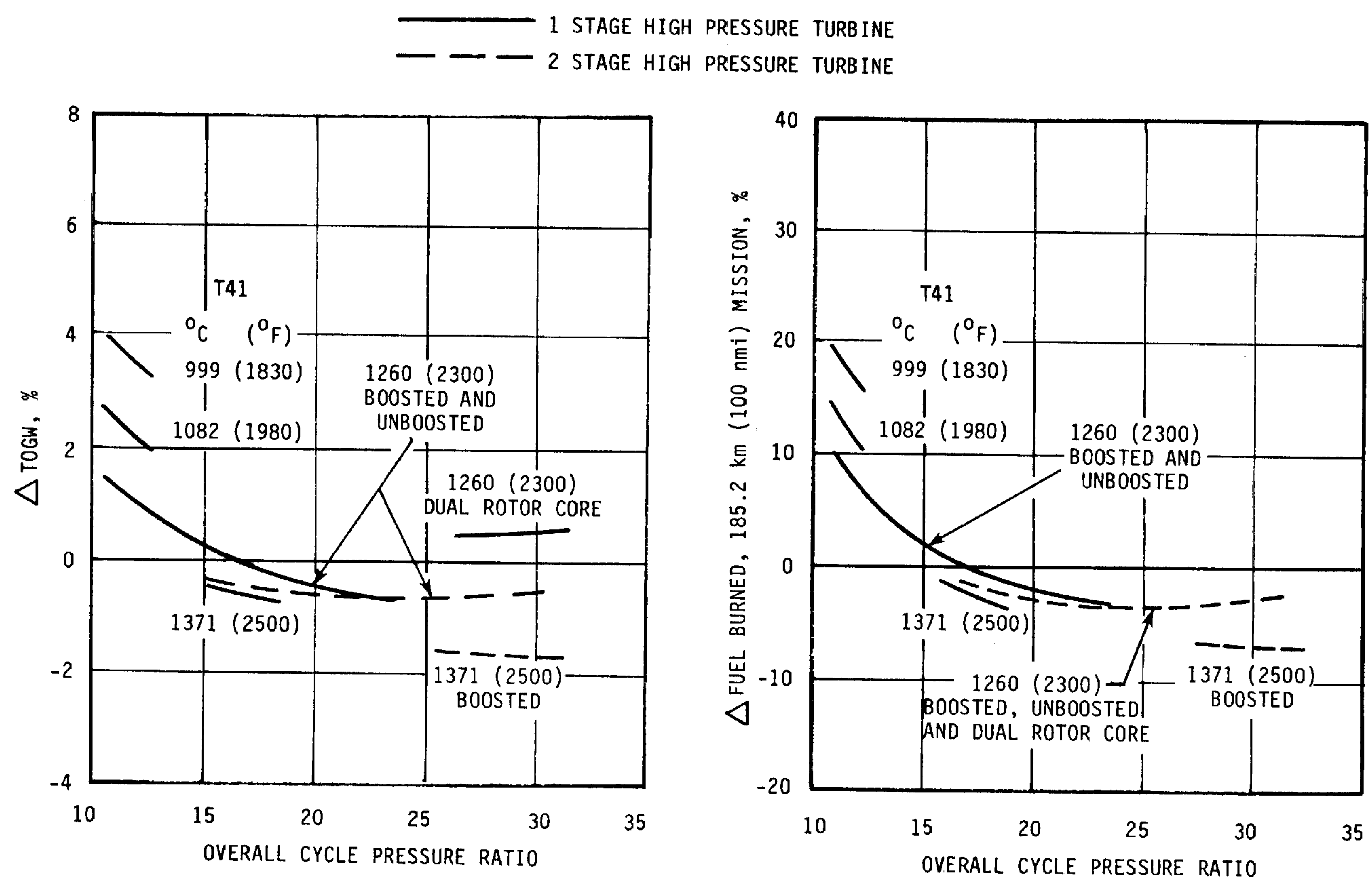


Figure 18. 30-Passenger Aircraft TOGW and Fuel Burned Trends.

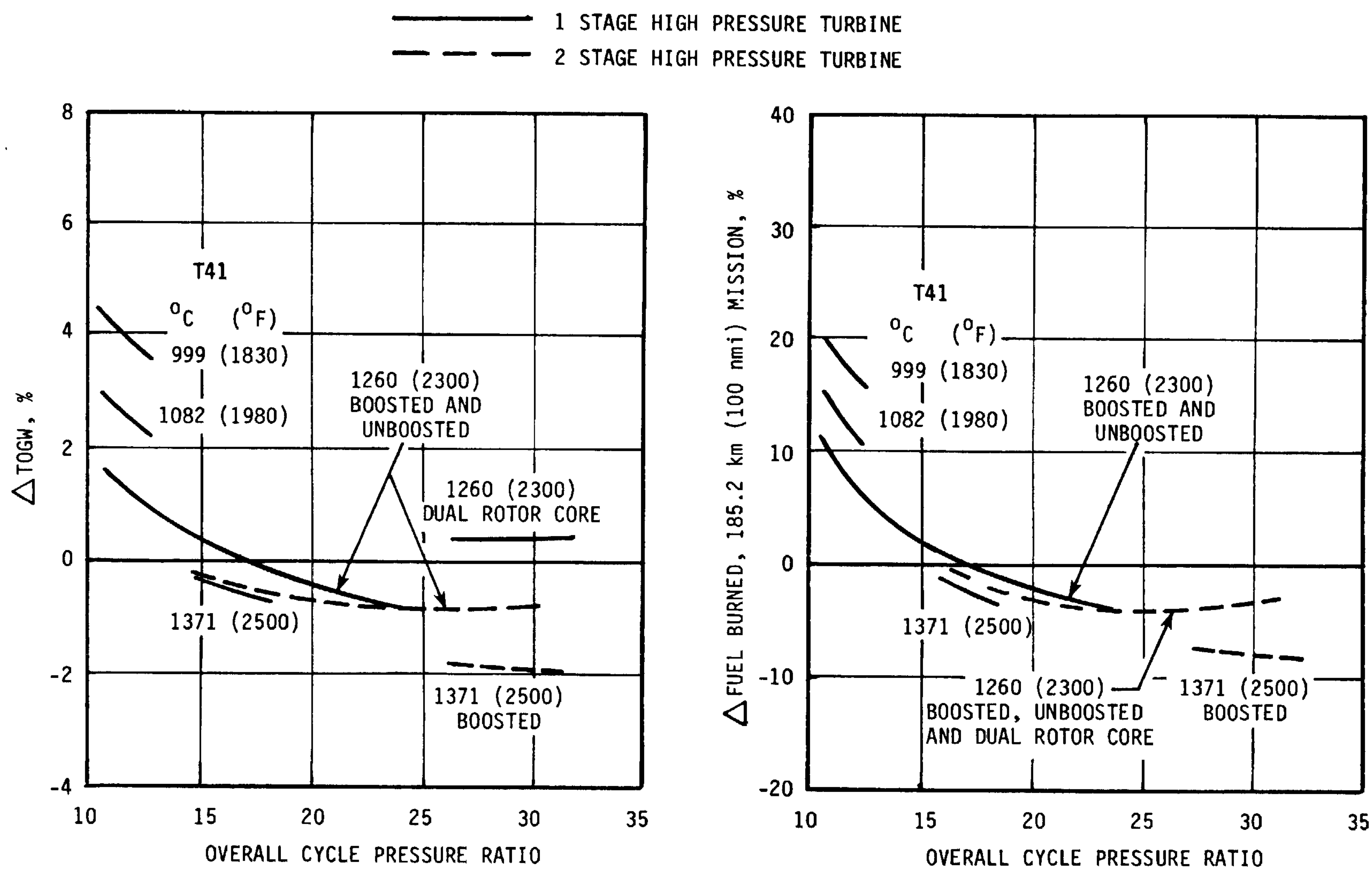


Figure 19. 50-Passenger Aircraft TOGW and Fuel Burned Trends.

CYCLE AND ENGINE ARRANGEMENT PARAMETRIC ANALYSIS - Continued

The performance of the two engines is similar, with the dual rotor core engine having a 0.5% advantage in SFC. The net difference between the engines is a 0.3% advantage in fuel burned for the dual rotor engine, and a 1.1% better DOC for the boosted engine.

TABLE 14
CYCLE AND ARRANGEMENT STUDY RESULTS

Engine Characteristics - 30-Passenger Mission Size

Cycle No.	Core Corrected Inlet Airflow kg/s (lbm/sec)	Change in SFC (%)	Change in Weight (%)	Change in Price (%)	Change in Maintenance (%)
1A	4.85 (10.7)	10.8	14.9	-.4	-2.0
1B	5.72 (12.6)	15.0	30.7	5.4	-1.1
2	3.76 (8.3)	7.5	0	-.5	2.3
3	3.81 (8.4)	BASE	BASE	BASE	BASE
4	3.27 (7.2)	-1.8	-7.1	.5	3.3
5A	3.31 (7.3)	-1.7	-10.5	11.6	15.1
5B	2.27 (5.0)	-2.6	-7.4	4.0	0
6	2.86 (6.3)	-2.2	-4.4	16.4	17.1
7	2.36 (5.2)	-5.8	-17.6	14.9	18.7
8	3.86 (8.5)	-.9	-8.8	11.5	18.7
9	4.13 (9.1)	-3.1	-3.4	14.2	19.3
10	4.54 (10.0)	-2.7	24.0	26.9	19.6

TABLE 15
CYCLE AND ARRANGEMENT STUDY RESULTS
Mission Merit Factors

Cycle No.	30-Passenger Mission Size: Change in DOC - (%) $264/m³ ($1.00/gal)	Change in DOC - (%) $396/m³ ($1.50/gal)	Change in Takeoff Gross Weight (%)	Change in Fuel Flow (%)	50-Passenger Mission Size: Change in DOC - (%) $264/m³ ($1.00/gal)	Change in DOC - (%) $396/m³ ($1.50/gal)	Change in Takeoff Gross Weight (%)	Change in Fuel Flow (%)
1A	4.2	5.4	2.4	12.5	5.2	6.4	2.6	12.9
1B	6.6	8.1	3.7	17.7	7.6	9.2	4.0	17.9
2	3.0	3.8	1.2	8.3	3.4	4.2	1.3	8.1
3	BASE	BASE	BASE	BASE	BASE	BASE	BASE	BASE
4	-.5	-.8	-.6	-2.2	-.7	-1.0	-.6	-2.3
5A	1.1	.6	-.7	-2.2	.3	-.2	-.9	-2.9
5B	-.9	-1.2	-.7	-3.1	-1.5	-1.9	-.9	-3.8
6	1.4	.9	-.5	-2.6	.3	-.3	-.8	-3.8
7	-.2	-1.1	-1.7	-7.0	-1.3	-2.3	-1.9	-7.7
8	1.5	1.3	-.5	-1.3	1.4	1.0	-.5	-1.2
9	1.2	.5	-.6	-3.6	.4	-.3	-.8	-4.1
10	2.6	1.9	.6	-2.2	1.6	.9	.4	-2.9

TABLE 16
ENGINE ARRANGEMENT COMPARISON

30-Passenger Size - $396/m³ ($1.50/gal) - 185.2 km (100 nmi)

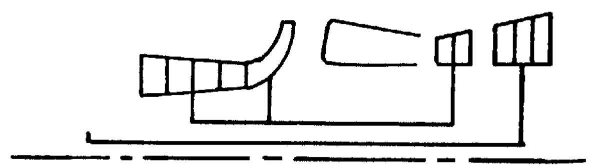
	Conventional Turboshaft: 1-Stage HP Turbine	2-Stage HP Turbine
Turbine Inlet Temp - °C (°F)	1260 (2300)	1260 (2300)
Pressure Ratio	17	17
No. of Rotors	2	2
No. of HP Turbine Stages	1	2
No. of LP Turbine Stages	2	3
Change in SFC	Base	-.9
Change in Power/Airflow	Base	-2.3
Change in Weight	Base	-8.8
Change in Price	Base	+11.5
Change in Maintenance	Base	+18.7
Change in Fuel Burned	Base	-1.3
Change in DOC	Base	+1.3

TABLE 17

ENGINE ARRANGEMENT COMPARISON

30-Passenger Size - \$396/m^3 (\$1.50/gal) - 185.2 km (100 nmi)

	Conventional Turboshaft	Boosted Turboshaft
Turbine Inlet Temp - °C (°F)	1260 (2300)	1260 (2300)
Pressure Ratio	23	23
No. of Rotors	2	2
No. of HP Turbine Stages	2	2
No. of LP Turbine Stages	3	3
Change in SFC (%)	Base	+1.4
Change in Power/Airflow (%)	Base	-1.7
Change in Weight (%)	Base	-7.3
Change in Price (%)	Base	-2.3
Change in Maintenance(%)	Base	-3.5
Change in Fuel Burned (%)	Base	+1.5
Change in DOC (%)	Base	0



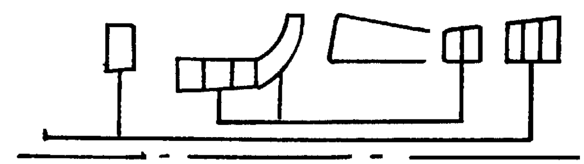
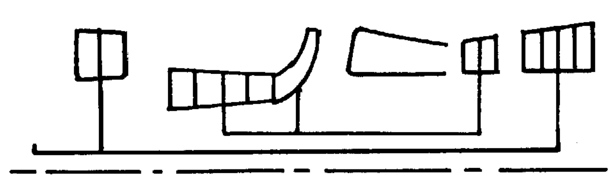


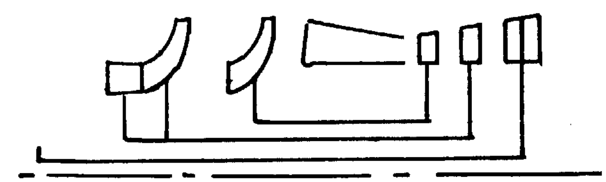
TABLE 18

ENGINE ARRANGEMENT COMPARISON

30-Passenger Size - \$396/m^3 (\$1.50/gal) - 185.2 km (100 nmi)

	Boosted Turboshaft	Dual Rotor Core Turboshaft
Turbine Inlet Temp - °C (°F)	1260 (2300)	1260 (2300)
Pressure Ratio	30	30
No. of Rotors	2	3
No. of HP Turbine Stages	2	1
No. of IP Turbine Stages	0	1
No. of LP Turbine Stages	4	2
Change in SFC (%)	Base	-.5
Change in Power/Airflow (%)	Base	+1.2
Change in Weight (%)	Base	+34
Change in Price (%)	Base	+9
Change in Maintenance (%)	Base	+2.2
Change in Fuel Burned (%)	Base	-.3
Change in DOC (%)	Base	+1.1





ADVANCED ENGINE TECHNOLOGY SUMMARY

A list of advanced technology features and design factor options were identified at the start of the study and of these, thirteen advanced technology features and four design factors were selected for detailed evaluation. Table 19 shows the items initially considered, and those in the detailed evaluation are indicated by an asterisk. The remaining six items were dropped because they did not show enough promise.

The following paragraphs present the primarily aerodynamic and performance related advanced technology features first, which are followed by the primarily mechanical technology features and the design factors.

The technology features considered were advanced aerodynamics and performance, advanced materials, processes and configurations which, when incorporated in the engine designs, were expected to show a payoff in DOC.

The design factor options considered were features which could be selected for incorporation in the engine, but which do not require development to prove their value.

The evaluation of each of these advanced technology options consisted of comparing the advanced feature with the current technology base CT7 engine feature. Characteristics which were compared included weight, cost (or price) differences, effect on engine maintenance, and effect on engine performance. For each of these, the percentage differences in direct operating cost were estimated for both he 30- and 50-passenger aircraft at $264/m^3 ($1.00/gal) and $396/m^3 ($1.50/gal) fuel cost. The separate DOC increments were summed to give the total (or net) effect on DOC. Total mission fuel burned changes were evaluated in a similar manner.

Tables 20-21 provide quantitative DOC and fuel burn results of the evaluation of all the technology items, design factors, and also for the advanced technology propeller and gearbox discussed separately in the following paragraphs.

TABLE 19

ADVANCED TECHNOLOGY FEATURES AND DESIGN FACTORS CONSIDERED

TOTAL LIST CONSIDERED
ITEMS MARKED (*) EVALUATED IN DETAIL

ADVANCED TECHNOLOGY FEATURES

*Highly Loaded Axial Compressor
*Multi-Blade Centrifugal Impeller
*Advanced Centrifugal Diffuser
*Active HP Turbine Clearance Control
*Closed Loop Accel Schedule and Reduced Stall Margin
Cast Compressor Blisks
*Two Material Impeller
Shingle Combustion Liner
*Thermal Barrier Coating on Combustor
*Advanced Combustor Material
*Advanced Material HP Turbine Blade
*Advanced Cooling Technique HP Turbine Blade
*Cast Blisks for LP Turbine
*Metal Matrix LP Shaft
Ceramic Blades for HP Turbine
Variable Area LP Turbine Nozzle
Titanium Aluminide Materials for Structures
Composite Materials for Structures
*Composite Materials for Nacelle

DESIGN FACTORS

*Modular Construction
*Inlet Protection Systems
*Diagnostic Data Recording
*Alternate Ratings

TABLE 20
MERIT FACTOR SUMMARY - ADVANCED TECHNOLOGY FEATURES

	30-Passenger Aircraft			50-Passenger Aircraft		
	Change in DOC (%)		Change in Fuel Flow (%)	Change in DOC (%)		Change in Fuel Flow (%)
	$264/m³ ($1.00/gal)	$396/m³ ($1.50/gal)		$264/m³ ($1.00/gal)	$396/m³ ($1.50/gal)	
Highly Loaded Axial Compressor	-.89	-.96	-1.42	-.95	-1.03	-1.46
Multi-Blade Centrifugal Impeller	-.50	-.60	-1.23	-.58	-.68	-1.26
Two Material Centrifugal Impeller	+.19	+.15	-.06	+.15	+.12	-.07
Advanced Centrifugal Diffuser	-.63	-.74	-1.38	-.71	-.82	-1.41
Advanced Combustor						
Advanced Material	-.27	-.23	-.01	-.23	-.19	-.01
Thermal Barrier Coating	-.30	-.25	+.01	-.26	-.23	+.01
Active Clearance Control for HP Turbine	-.01	-.08	-.50	-.05	-.12	-.50
Advanced HP Turbine Blade						
Advanced Material 1260°C (2300°F) T41	+.47	+.30	-.80	+.16	-.07	-1.46
Advanced Cooling Technique 1371°C (2500°F) T41	0	-.26	-1.85	-.20	-.46	-1.90
Cast Blisks for LP Turbine	-.08	-.07	-.03	-.08	-.07	-.04
Metal Matrix LP Shaft	-.03	-.04	-.06	-.04	-.05	-.08
Closed Loop Accel Schedule and Reduced Stall Margin	-.13	-.20	-.68	-.19	-.26	-.69
Composite Materials for Nacelle	-.31 to -.38	-.32 to -.39	-.32 to -.39	-.4 to -.48	-.42 to -.5	-.4 to -.48
Advanced Gearbox	-1.2	-1.2	-1.0	-1.7	-1.7	-1.3
Advanced Propeller	-1.0	-1.3	-2.7	-1.3	-1.6	-3.0

TABLE 21
MERIT FACTOR SUMMARY - DESIGN FACTORS

	30-Passenger Aircraft			50-Passenger Aircraft		
	Change in DOC (%)		Change in Fuel Flow (%)	Change in DOC (%)		Change in Fuel Flow (%)
	$264/m³ ($1.00/gal)	$396/m³ ($1.50/gal)		$264/m³ ($1.00/gal)	$396/m³ ($1.50/gal)	
Modular Construction	+.41	+.46	+.78	+.45	+.50	+.81
Inlet Particle Separator-Vaned	+1.98	+2.15	+3.25	+2.15	+2.34	+3.39
Foreign Object Protector-Vaneless	+.39	+.44	+.79	+.46	+.52	+.84
Diagnostic Data Recording	-.89	-.77	+.07	-1.01	-.85	+.05
10% Derate When Allowed	-1.58	-1.41	0	-1.37	-1.22	0
APR with 5% Reduction in Engine Size	-.06 to +.28	-.24 to -.03	-1.35			

ADVANCED AERODYNAMIC DESIGN AND PERFORMANCE FEATURES

Highly Loaded Axial Compressor

The advanced technology to be applied to the design of a high stage loading compressor utilizes high speed airfoils uniquely designed for each stage. Current technology usually consists of the use of modified standard airfoils. Advanced technology in the field of three dimensional, high speed blade design is expected to provide capability of positively generating airfoil sections which fit the three dimensional transonic flow field and are designed with predictable pressure distributions for high efficiency. The base level of technology for this item is that of the T700 axi-centrifugal compressor; 5 axial stages with an average work coefficient of 0.82 plus 1 centrifugal stage (5 + 1). The pressure ratio split between the axial and centrifugal portions for an overall pressure ratio of 17 is approximately 5.5 to 3.1. The advanced design has an average axial stage work coefficient of 0.92 (+12%), 3 axial stages and 1 centrifugal stage (3 + 1), and a pressure ratio split of 4.25 to 4.0. The centrifugal stages in the two designs are of the same technology. A gain of 1 point in overall efficiency is predicted for the 3 + 1 compressor versus the 5 + 1 baseline.

The merit factor results are summarized in Tables 22-23 for the 30- and 50-passenger turboprops respectively, for nominal estimates of the compressor efficiency, weight, cost and maintenance differences between the designs. The same tabular form will be used to summarize each of the technology items and design factors. It shows the fuel burned and DOC results due to each element of change, i.e., SFC, costs, and weight. The effect of performance on engine size and therefore weight, price, and maintenance is included under SFC.

The weight, price, and maintenance effects reported are those resulting from the design changes prior to resizing the aircraft. Note that the results are very similar for the 30- and 50-passenger aircraft. In the following sections, results will generally be given only in the 30-passenger size. Results for both sizes have already been summarized in Tables 20-21.

The performance effects for the nominal improvement of 1 point in overall compressor efficiency represent 3/4 of the DOC improvement potential. Figure 20 shows the sensitivity of this nominal result to the compressor efficiency improvement prediction at the two levels of fuel cost. Curves such as this are provided for many of the items which follow because of the uncertainties inherent in the prediction of the benefits and costs of new and untried designs.

TABLE 22

HIGHLY LOADED AXIAL COMPRESSOR - MISSION MERIT FACTOR RESULTS

30-Passenger Aircraft - 185.2 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact: Change in DOC (%) $264/m^3 ($1.00/gal)	Merit Factor Impact: Change in DOC (%) $396/m^3 ($1.50/gal)	Merit Factor Impact: Change in Fuel Burned (%)
Engine Weight - kg (lbm)	-1.8 (-4.0)	-.03	-.03	-.05
Engine Price - $1000	-5.3	-.11	-.09	-
Engine Maintenance - $/h	-.39	-.14	-.12	-
Engine SFC* - %	-1.2	-.61	-.72	-1.37
TOTAL		-.89	-.96	-1.42

*Includes performance and scaling effects.

TABLE 23

HIGHLY LOADED AXIAL COMPRESSOR - MISSION MERIT FACTOR RESULTS

50-Passenger Aircraft - 185.2 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact: Change in DOC (%) $264/m^3 ($1.00/gal)	Merit Factor Impact: Change in DOC (%) $396/m^3 ($1.50/gal)	Merit Factor Impact: Change in Fuel Burned (%)
Engine Weight - kg (lbm)	-2.9 (-6.5)	-.03	-.04	-.06
Engine Price - $1000	-6.6	-.10	-.08	-
Engine Maintenance - $/h	-.49	-.13	-.11	-
Engine SFC* - %	-1.2	-.69	-.80	-1.40
TOTAL		-.95	-1.03	-1.46

*Includes performance and scaling effects.

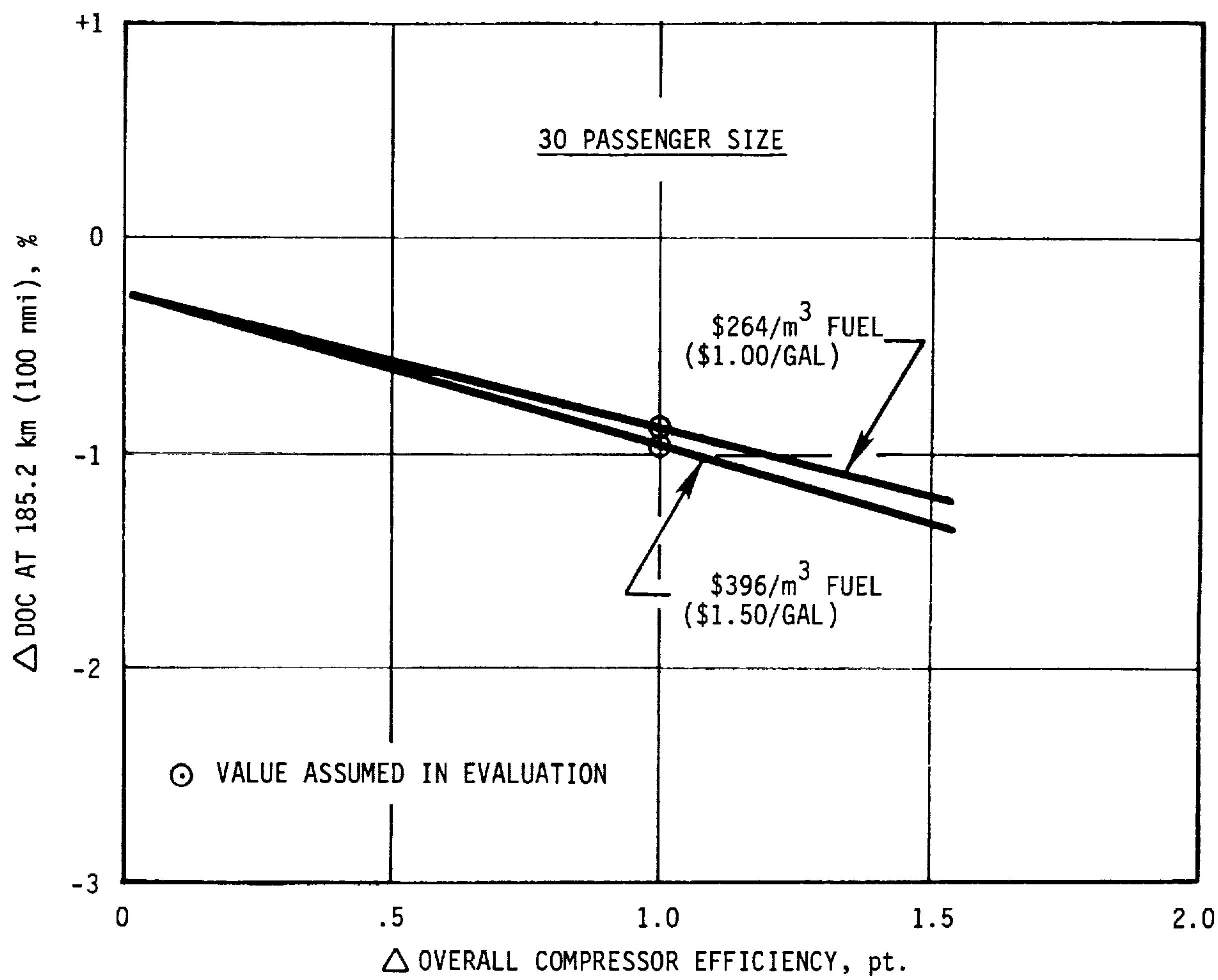


Figure 20. Highly-Loaded Axial Compressor - Sensitivity of DOC Payoff to Compressor Efficiency.

ADVANCED AERODYNAMIC DESIGN AND PERFORMANCE FEATURES - Continued

Multiblade Centrifugal Compressor Impeller

The concept of a multiblade centrifugal compressor impeller consists of splitting the energy input into two regions (inducer and impeller), which permits greater flexibility in aerodynamic blade design. The inducer section, which is fashioned after axial compressor design technology, can more efficiently handle the transonic flow than conventional continuous impeller blades. When the inducer blade is separate, the design can accommodate higher spanwise twist gradients to better control blade loading and the passage throat contour to avoid choking. This design concept permits the use of higher inlet Mach numbers with satisfactory control of the flows along the suction side of the blades to avoid separation. The successful execution of the concept depends upon the development of three-dimensional, viscous flow analysis computational methods which are not yet available. An illustration of the design concept is shown in Figure 21 with a 34 bladed-design, the same number being used in each blade row. The blades would probably be displaced circumferentially for maximum advantage. A 1 to 2 point centrifugal stage efficiency improvement has been estimated for the multiblade impeller approach. The improved design estimate was made with a 4:1 pressure ratio centrifugal stage. The 1 to 2 point centrifugal stage efficiency improvement results in a 0.6 to 1.2 point improvement in the overall, axi-centrifugal compressor efficiency. A nominal improvement of 0.9 point was assumed.

The DOC and fuel burned benefits of the multiblade impeller are summarized in Table 24 for the 30-passenger commuter turboprop. Owing to small weight and price increases, the only benefits due to the multiblade impeller are derived from the centrifugal impeller efficiency improvement. The sensitivity of the result to variations in the compressor efficiency improvement is shown on Figure 22.

TABLE 24
MULTIBLADE CENTRIFUGAL COMPRESSOR IMPELLER - MISSION MERIT FACTOR RESULTS

30-Passenger Aircraft - 185.2 km (100 nmi) Mission

		Merit Factor Impact		
		Change in DOC (%)		Change in Fuel Burned (%)
Parameter	Change	$264/m³ ($1.00/gal)	$396/m³ ($1.50/gal)	
Engine Weight - kg (lbm)	+.2 (+.4)	0	0	0
Engine Price - $1000	+.8	+.02	+.01	-
Engine Maintenance - $/h	+.08	+.03	+.03	-
Engine SFC* - %	-1.1	-.55	-.64	-1.23
TOTAL		-.50	-.60	-1.23

*Includes performance and scaling effects.

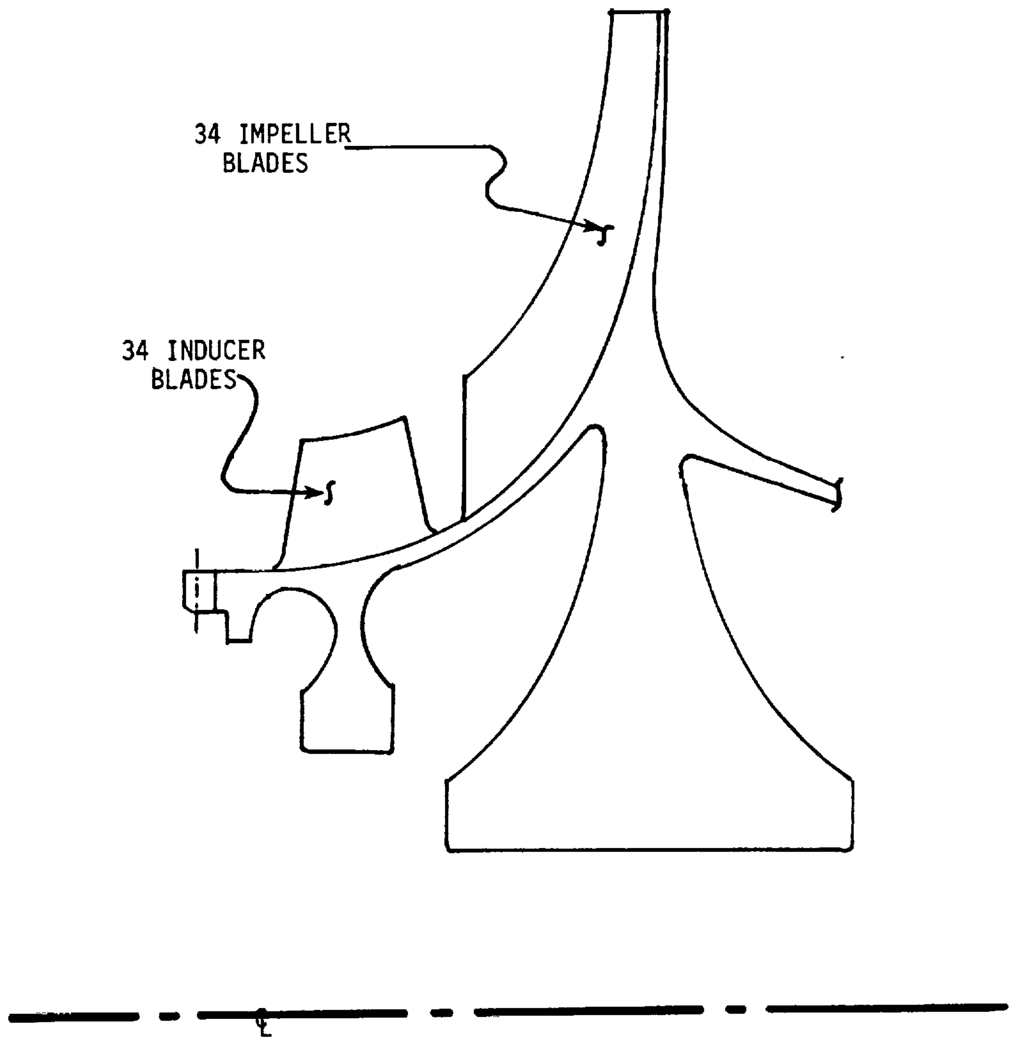


Figure 21. Multiblade Centrifugal Compressor Impeller Concept.

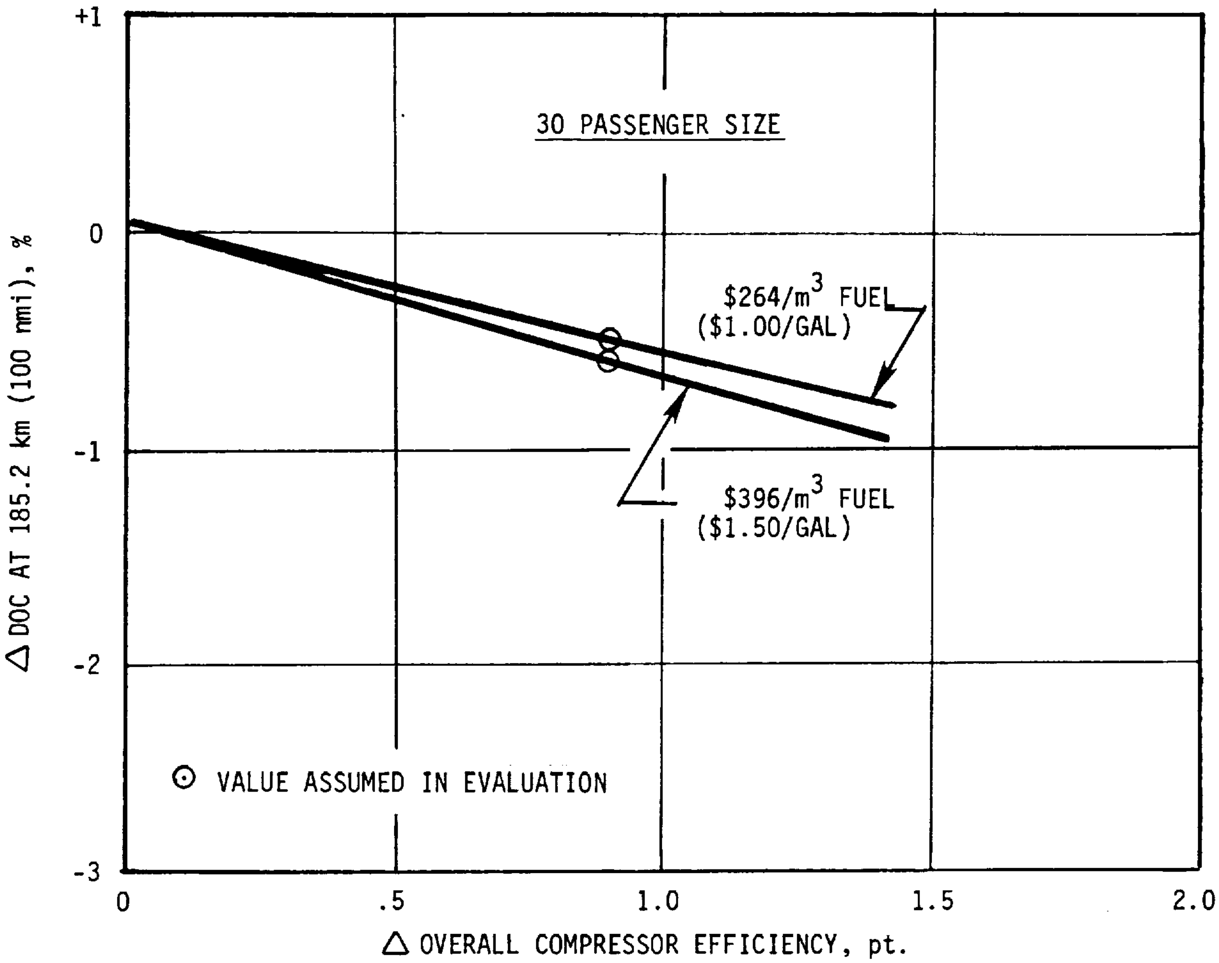


Figure 22. Multiblade Centrifugal Compressor Impeller-Sensitivity of DOC Payoff to Compressor Efficiency.

ADVANCED AERODYNAMIC DESIGN AND PERFORMANCE FEATURES - Continued

Advanced Centrifugal Compressor Diffuser

The production CT7-5 engine utilizes a centrifugal compressor diffuser system which discharges low Mach number (approximately 0.2) swirling flow into a plenum and then deswirls this flow before discharge into the combustor. Advanced axial-centrifugal compressors avoid this initial dump loss by use of controlled-contour passages which both deswirl the flow and form the radial-to-axial turn. A potential stage efficiency gain of about 1 point is achievable with this more efficient diffuser system.

Diffuser throat blockage has a major influence on the resulting losses in the downstream diffusing passages. This blockage can be reduced using wall bleed to improve the pressure recovery. An additional 1 point in centrifugal stage efficiency is obtainable with the bleed feature. A nominal improvement in overall axi-centrifugal efficiency of 1 point was assumed for the combination of these two improvements in diffuser design.

The use of throat bleed to improve centrifugal diffuser efficiency is illustrated by Figure 23. When the bleed was increased beyond 1% for this model test, the incremental improvement was small.

The DOC and fuel burned benefits are summarized in Table 25. They again illustrate the dominance of the compressor efficiency improvement. Figure 24 illustrates the sensitivity of the payoff to short falls or excess over the nominal level.

The potential eficiency gains of the advanced centrifugal diffuser and the multiblade impeller are independent and would both be introduced into an advanced compressor design.

TABLE 25
ADVANCED CENTRIFUGAL COMPRESSOR DIFFUSER - MISSION MERIT FACTOR RESULTS

30-Passenger Aircraft - 185.2 km (100 nmi) Mission

		Merit Factor Impact		
		Change in DOC (%)		Change in Fuel Burned (%)
Parameter	Change	$264/m^3 ($1.00/gal)	$396/m^3 ($1.50/gal)	
Engine Weight - kg (lbm)	-.4 (-.8)	-.01	-.01	-.01
Engine Price - $1000	-.6	-.01	-.01	-
Engine Maintenance - $/h	-.01	-.01	0	-
Engine SFC* - %	-1.2	-.60	-.72	-1.37
TOTAL		-.63	-.74	-1.38

*Includes performance and scaling effects.

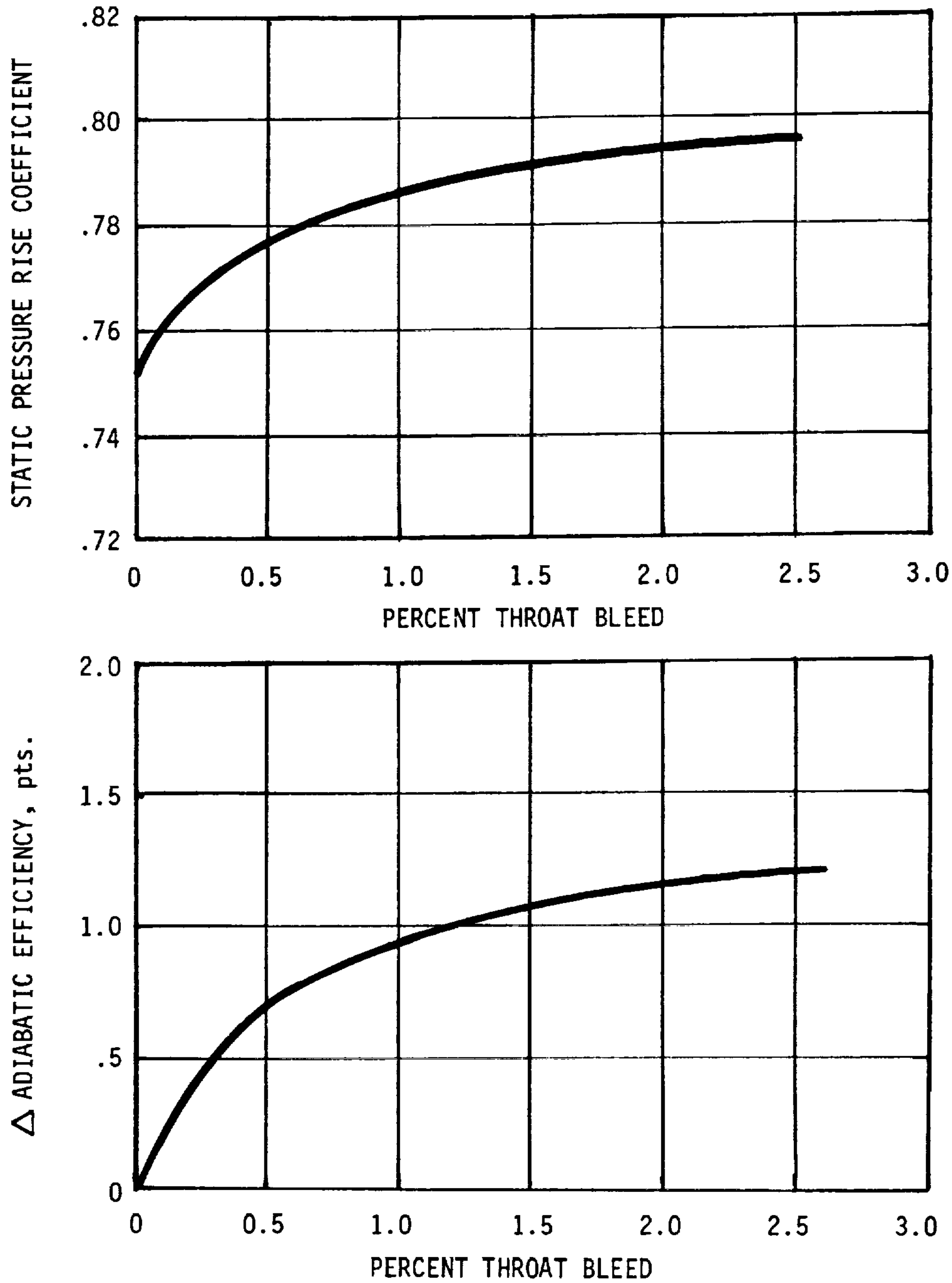


Figure 23. Diffuser Blow Test Results.

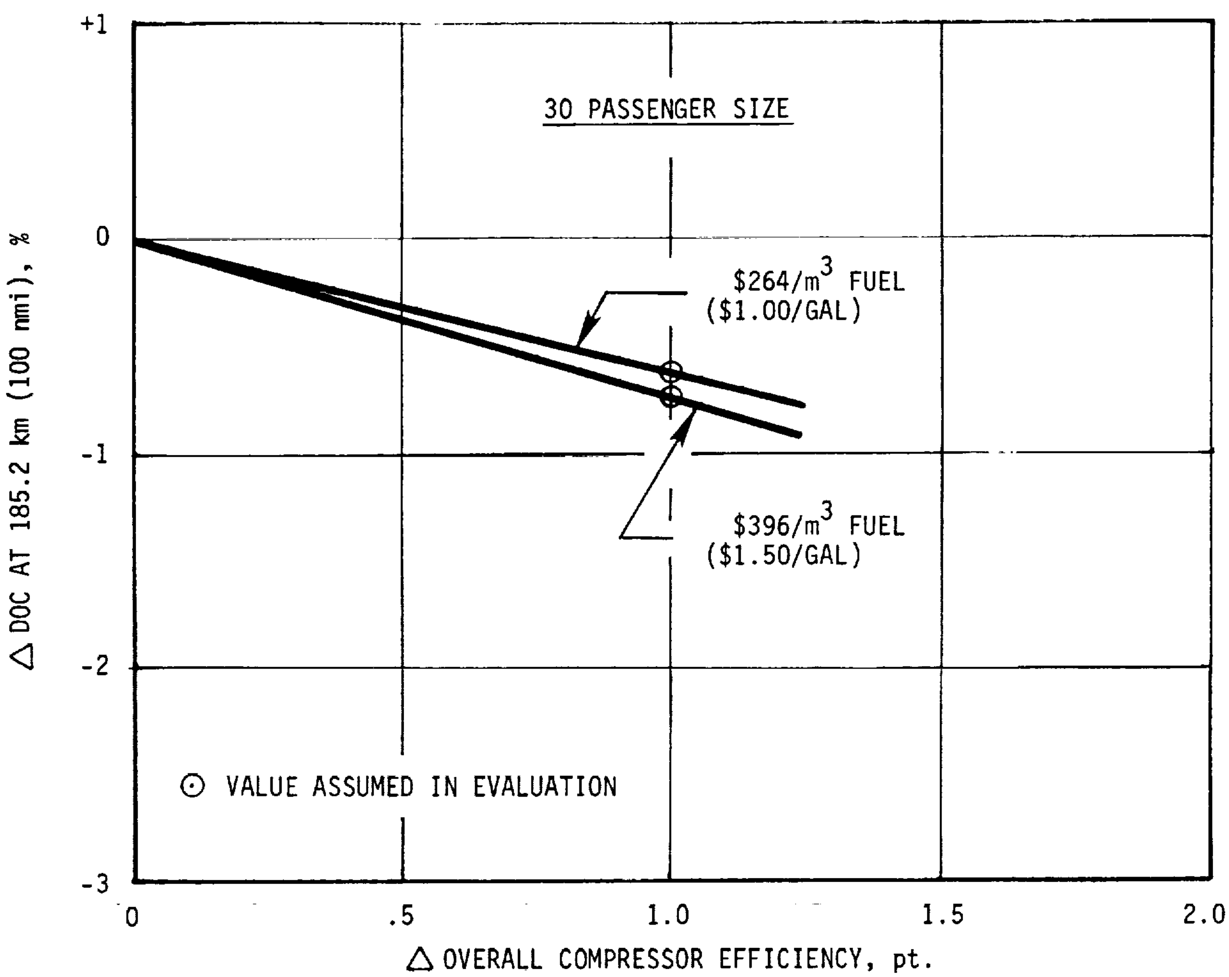


Figure 24. Advanced Centrifugal Compressor Diffuser - Sensitivity of DOC Payoff to Compressor Efficiency.

ADVANCED AERODYNAMIC DESIGN AND PERFORMANCE FEATURES - Continued

Active Clearance Control - High-Pressure Turbine (HPT)

The HPT shroud ring is cooled at cruise to reduce steady state clearances and SFC. Cooling air is diverted from strut and service tube cooling, which is not required at cruise temperatures. Figure 25 shows how the cooling air is directed at the extended metal surface of the shroud ring support to control the temperature and diameter of this clearance controlling structure. Full Authority Digital Electronic Control (FADEC) control logic will allow cooling air to be turned on only after an interval of steady state operation in a specified rotor speed range.

At the STAT cruise condition, the potential exists for a 0.7 pt improvement in turbine efficiency (1% SFC). The power settings at cruise are fairly high, and the clearance reductions obtainable are not as large as they would be at a loiter, low rotor speed condition. The payoff is small because only 47% of the mission fuel burned is at cruise in the 185.2 km (100 nmi) mission. The mission weighted effect on SFC is approximately 0.5% when the cruise turbine efficiency improvement is the expected 0.7 pt.

Table 26 shows that the price, maintenance, and weight increases required to add the HPT active clearance control feature nearly offset the fuel saving at $\$264/m^3$ (\$1.00/gal). Clearance control begins to show a small payoff at $\$396/m^3$ (\$1.50/gal).

The effect of more time at cruise for longer range missions increases the overall DOC advantage as shown on Figure 26.

TABLE 26
ACTIVE CLEARANCE CONTROL - HPT - MISSION MERIT FACTOR RESULTS

30-Passenger Aircraft - 185.1 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact: Change in DOC (%) $\$264/m^3$ (\$1.00/gal)	Change in DOC (%) $\$396/m^3$ (\$1.50/gal)	Change in Fuel Burned (%)
Engine Weight - kg (lbm)	+1.9 (+4.2)	+.03	+.03	+.05
Engine Price - \$1000	+4.1	+.08	+.07	-
Engine Maintenance - \$/h	+.19	+.07	+.06	-
Engine SFC* - %	-.5	-.19	-.24	-.55
TOTAL		-.01	-.08	-.50

*Includes performance and scaling effects.

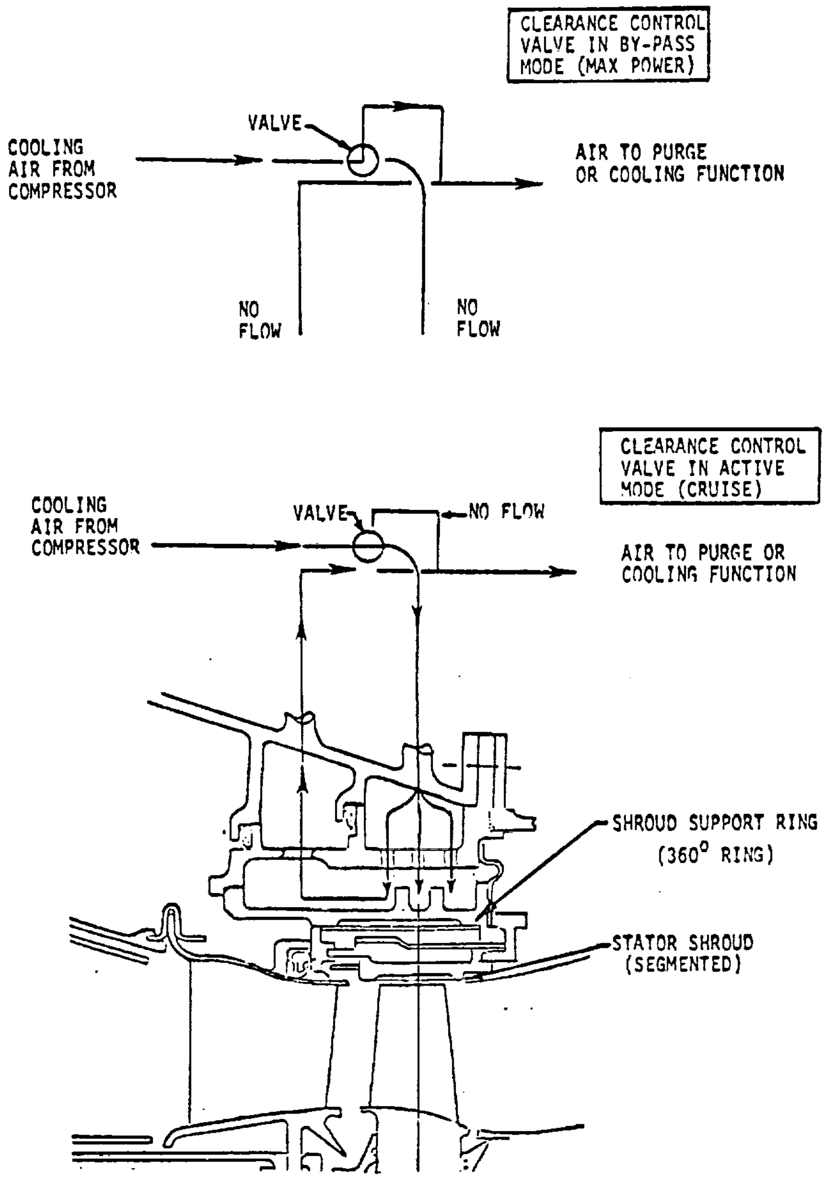


Figure 25. High-Pressure Turbine Active Clearance Control.

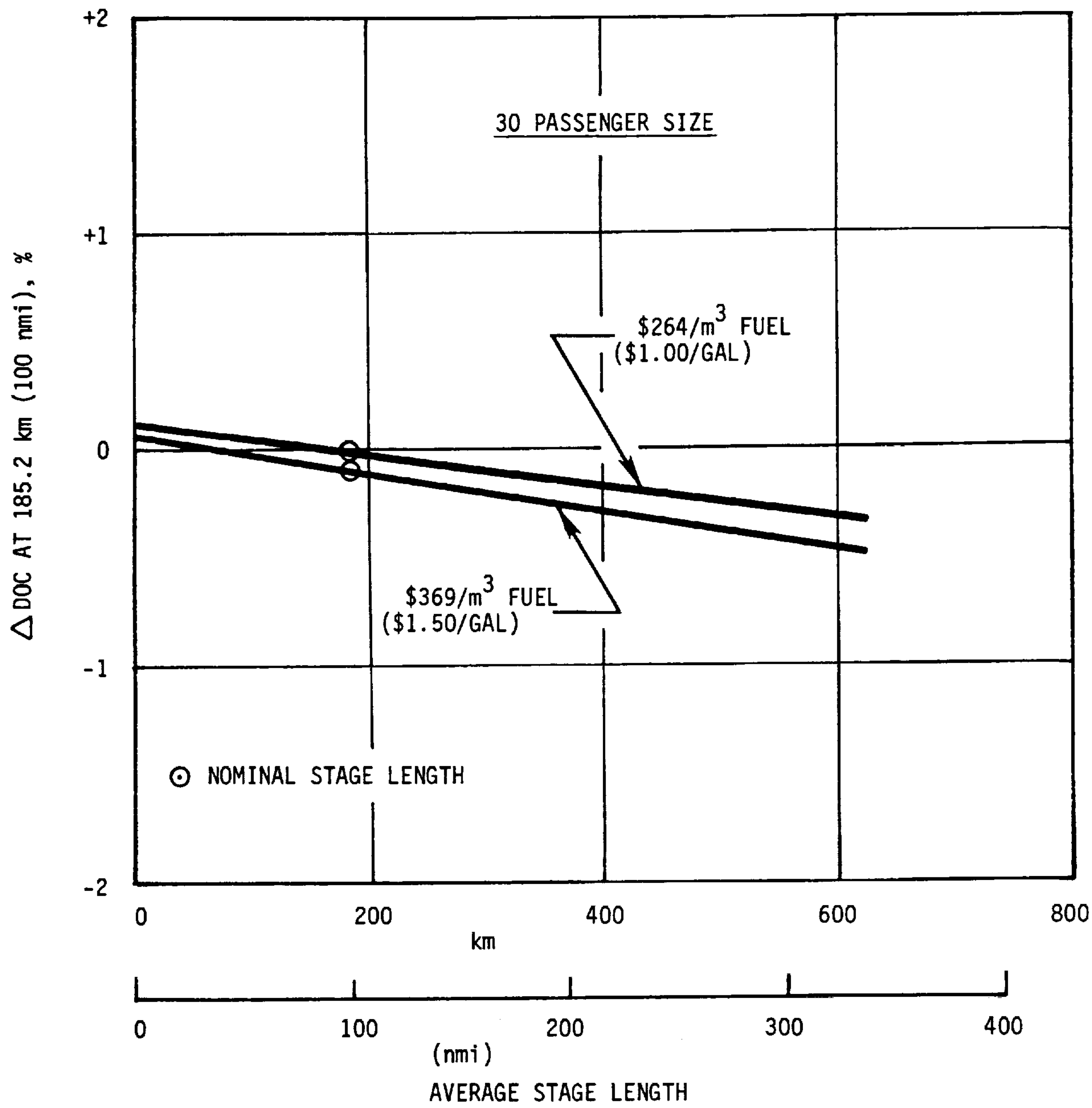


Figure 26. High-Pressure Turbine Active Clearance Control - DOC Payoff Sensitivity to Average Stage Length.

ADVANCED AERODYNAMIC DESIGN AND PERFORMANCE FEATURES - Continued

Compressor Stall Margin Reduction via Closed-Loop Acceleration Control

The use of a Full Authority Digital Electronic Control (FADEC) is assumed highly probable for an advanced turboprop engine in the late 1980's. This technology item explores one of the systems utilization modes of the FADEC. Specifically, it is proposed, by the addition of a sensing system to measure compressor discharge Mach number (M3), to schedule acceleration fuel as a function of M3 on a closed loop basis. The details of the design require extensive system analysis and engine test data before the anticipated payoff can be established. However, it is expected that this acceleration fuel scheduling logic will have the potential of a 5% part speed stall margin reduction by reducing allowances for some of the variables which enter into the stall margin stack-up calculation. It is proposed to trade off this part speed stall margin requirement reduction into an improvement in compressor efficiency within a range of speeds corresponding to significant power usage (at the design conditions and generally in the high power range). Figure 27 illustrates the trade off on a schematic compressor map. The compressor efficiency contours for the compressor designed for reduced stall margin requirements would be improved in level at high speed. This effect is not shown in Figure 27. Only the downward shift in part speed stall margin is shown. The operating lines for the base compressor and the compressor designed for lower stall margin would be identical.

The benefit analysis results are based on adding the cost of the additional sensor only. The basic FADEC is assumed to be part of the advanced engine. Table 27 illustrates some net DOC and fuel-burned advantage to this system. If there is any substantial shortfall in the nominal 0.5 pt compressor efficiency gain, the net DOC benefit would be cancelled out as evident from Figure 28.

TABLE 27
CLOSED-LOOP ACCELERATION CONTROL - MISSION MERIT FACTOR RESULTS

30-Passenger Aircraft - 185.1 km (100 nmi) Mission

		Merit Factor Impact		
		Change in DOC (%)		Change in Fuel Burned (%)
Parameter	Change	$264/m³ ($1.00/gal)	$396/m³ ($1.50/gal)	
Engine Weight - kg (lbm)	+.3 (+.6)	0	0	+.01
Engine Price - $1000	+4.6	+.09	+.08	-
Engine Maintenance - $/h	+.22	+.08	+.07	-
Engine SFC* - %	-.6	-.30	-.35	-.69
TOTAL		-.13	-.20	-.68

*Includes performance and scaling effects.

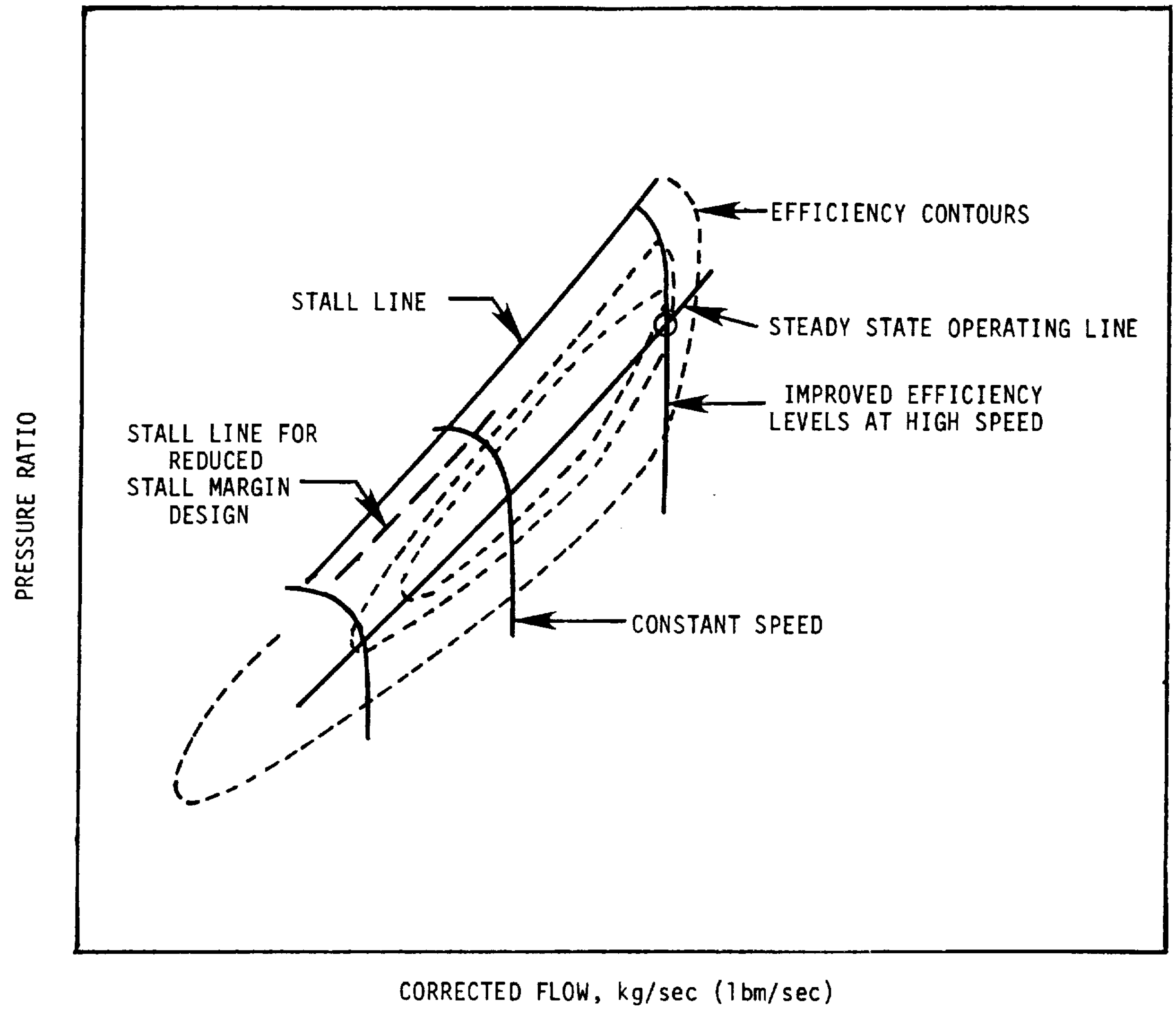


Figure 27. Normal Stall Line vs Stall Line for Closed Loop Accel Schedule Integrated with Compressor Discharge Mach Sensor.

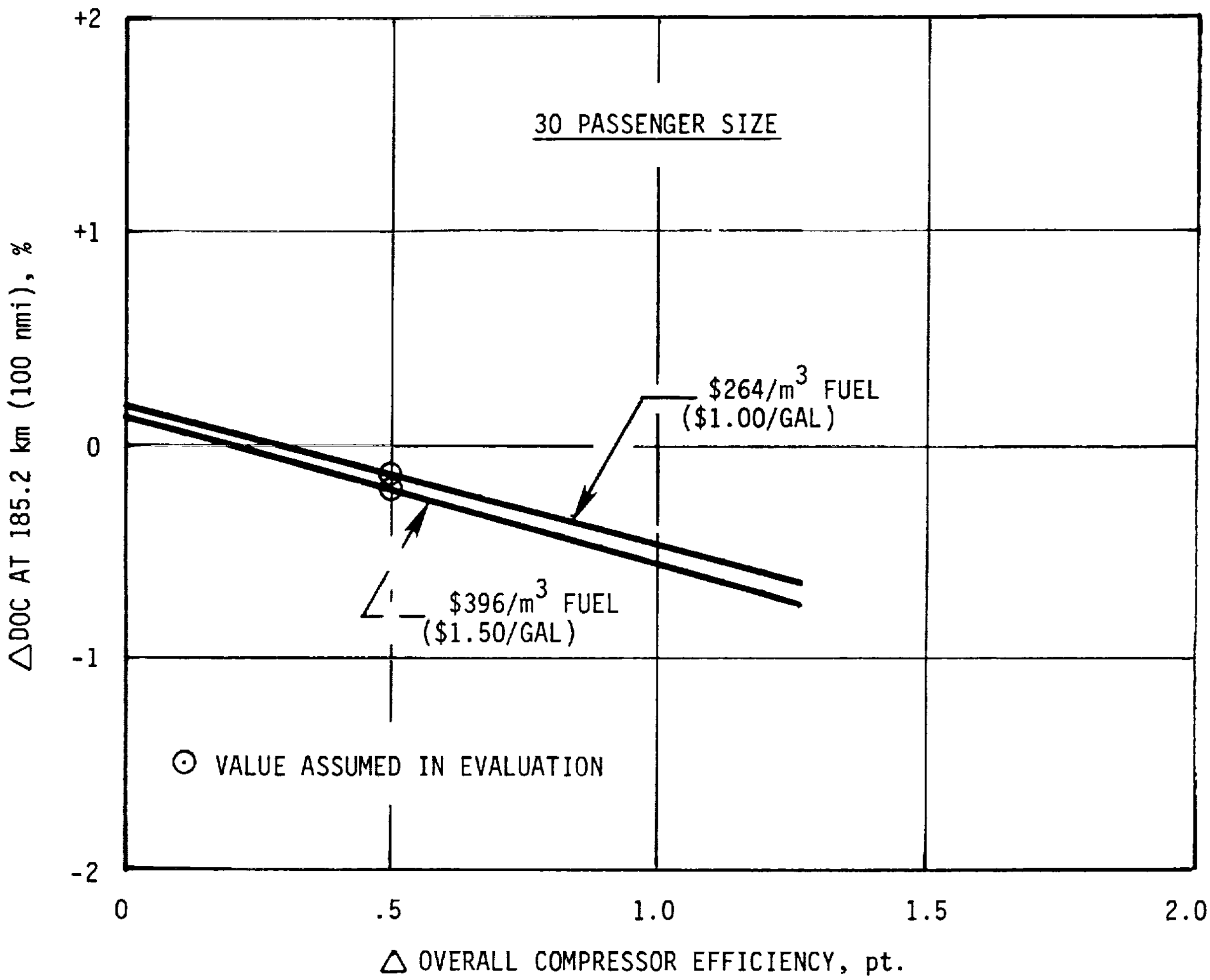


Figure 28. Closed Loop Acceleration Control - Sensitivity of DOC Payoff to Compressor Efficiency.

ADVANCED MECHANICAL DESIGN FEATURES

Two-Material Centrifugal Impeller

This impeller utilizes a low cost flow path and blade unit, which is inertia welded to a high strength hub. Figure 29 shows the concept. The blades and rim are cast or machined from Inconel 718 alloy, and the hub is made from a high strength, turbine disk alloy such as direct aged, wrought Inconel 718 or powdered metal Rene' 95.

Advanced technology centrifugal impeller tip speeds are higher than those of current technology designs, to achieve increased pressure ratio with high efficiency. Centrifugal compressor impeller weight increases rapidly with increasing tip speed until the strength limits of the disk material are exceeded, thus limiting the operating speed. Figure 30 shows this limit for the 30-passenger aircraft engine size, for a conventional disk of Inconel 718 material with an operating bore stress of 0.96 GN/m^2 (140,000 lb/in^2). It also shows that an impeller using a higher strength material, (powdered metal Rene' 95) in the bore, joined by inertia welding to the Inconel 718 rim, is lighter in weight for a given tip speed or for a given weight has a higher tip speed capability.

The lower weight option was exploited here, with the results shown in Table 28. The weight reduction is more than offset by the price and maintenance increases, resulting in an increase in DOC. Higher impeller speed capability could alternately be utilized by changing the work split between the axial and centrifugal compressors; doing more compression in the centrifugal, less in the axial while staying within the capability of the single stage drive turbine. However, it is believed that this approach will not result in higher overall efficiency.

TABLE 28
ADVANCED IMPELLER MECHANICAL DESIGN - MISSION MERIT FACTOR RESULTS

30-Passenger Aircraft - 185.2 km (100 nmi) Mission

		Merit Factor Impact		
		Change in DOC (%)		Change in Fuel Burned (%)
Parameter	Change	$264/$m^3$ ($1.00/gal)	$396/$m^3$ ($1.50/gal)	
Engine Weight - kg (lbm)	-2.4 (-5.2)	-.03	-.04	-.06
Engine Price - $1000	+4.0	+.08	+.07	-
Engine Maintenance - $/h	+.38	+.14	+.12	-
Engine SFC* - %	0	0	0	0
TOTAL		+.19	+.15	-.06

*Includes performance and scaling effects.

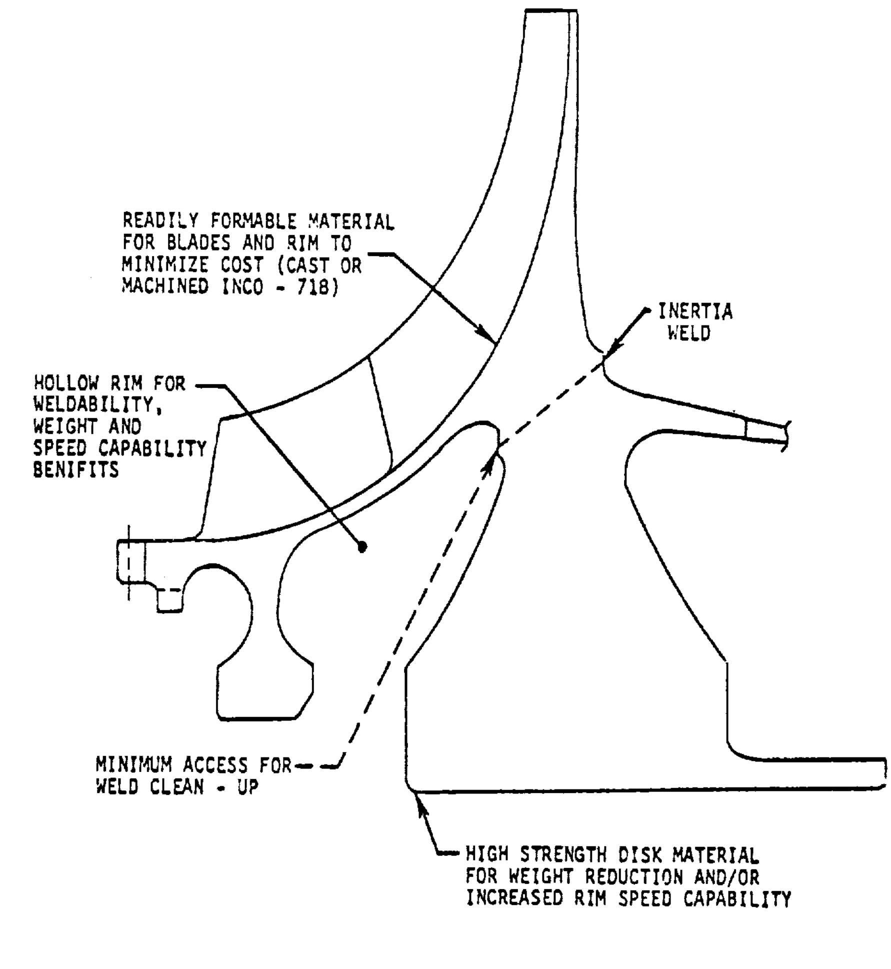


Figure 29. Two-Material Centrifugal Impeller Configuration.

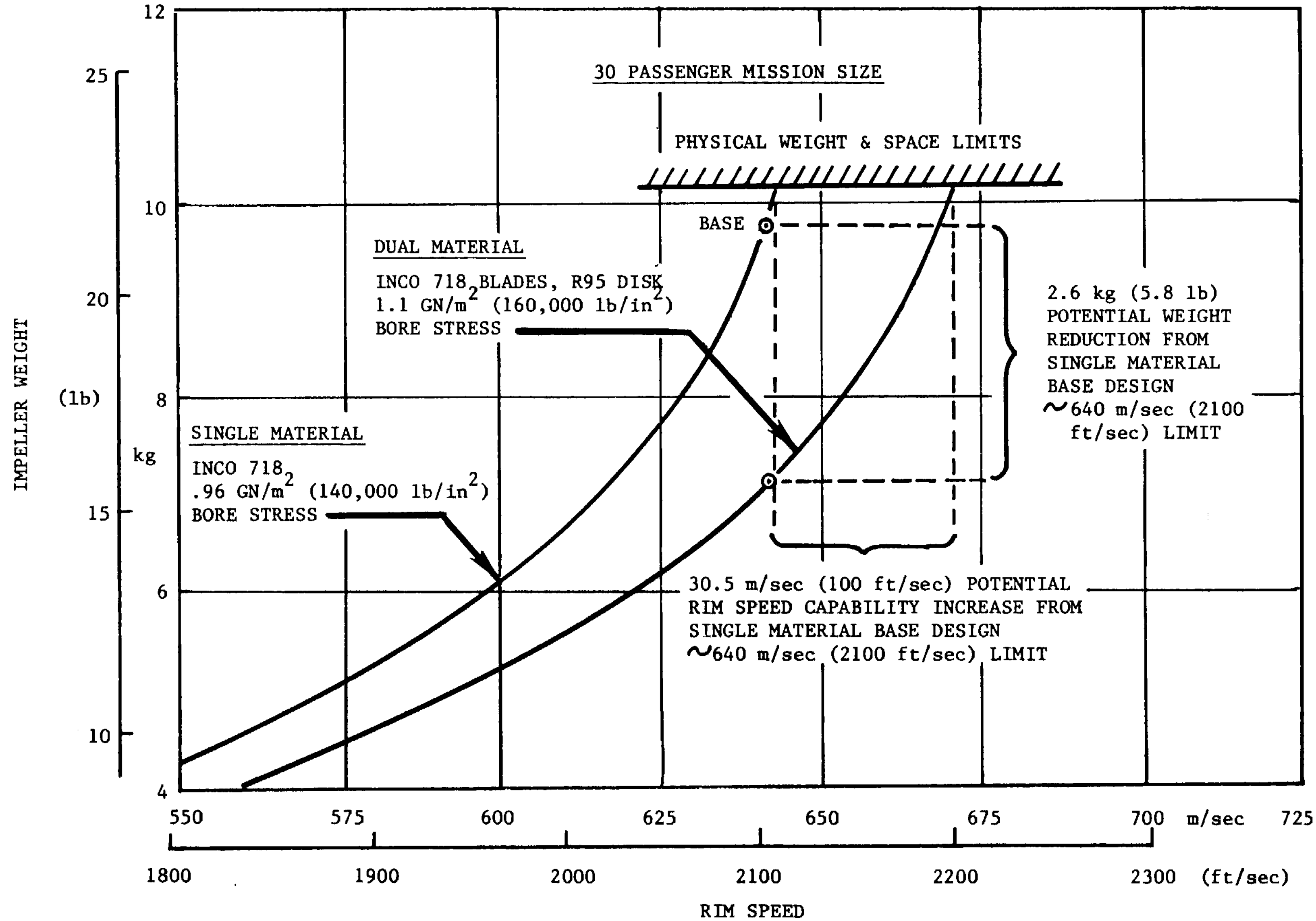


Figure 30. Two-Material Centrifugal Impeller Advantages.

ADVANCED MECHANICAL DESIGN FEATURES - Continued

Advanced Combustor Material

An oxide dispersion strengthened (ODS) allow (MA956) was evaluated as an advanced technology combustor liner because it offers 4 times the life and +333°C (+600°F) operating temperature capability over the Hastelloy X material used in the base engine combustor. Table 29 lists the advantages and concerns associated with MA956 relative to Hastelloy X. The chief concerns are weldability and material cost. Although the alloy promises better machinability, this does not offset the material cost, and the net estimated price increase for a finished liner is $14,000 (more than double).

The increased temperature capability allows a reduction in liner cooling air and a corresponding increase in the dilution air used to control the combustor discharge temperature pattern, while achieving the above liner life increase. The improved pattern results in a less difficult cooling requirement for the HP turbine vanes, bands, and shrouds and an estimated life increase for these parts of 15%.

For this evaluation, the cost and performance tradeoff was made assuming that the liner life and turbine nozzle and shroud life would increase when using the same amount of total liner cooling and dilution air as the base engine. Because combustor cooling air has no direct cycle impact, and the effects of turbine temperature were evaluated independently in the parametric study, this is the best way to establish a payoff for this item. The benefits for 30-passenger aircraft engine are summarized in Table 30 for the estimated increased part price and life expectancy. However, since both of these characteristics may vary from expectations, a sensitivity plot has been made to show how net change in DOC for the 30-passenger, 185.2 km (100 nmi) mission is affected by price increase, over a range of combustor life (Figure 31).

TABLE 29
ADVANCED COMBUSTOR ODS (MA956) MATERIAL DATA

ADVANTAGES

- Oxidation and Hot Corrosion Resistance
- High Temperature Strength and Creep Resistance
- Melting Point 1482°C (2700°F) versus 1302°C (2375°F) for Hastelloy X and 1329°C (2425°F) for HS-188
- Machinability Index Estimate = 24 versus 9 of Hastelloy X, 12 of L605, and 10 of HS-188
- Formability Shows Potential for a Controlled Hot Ring Rolling Process
- Low Density of 7200 kg/m^3 (.26 lb/in^3) versus 8200 (.297) of Hastelloy X, 9100 (.33) of L605 and 9100 (.33) of HS-188
- No Cobalt versus 1.5% of Hastelloy X, 49.4% of L605 and 35.25% of HS-188

CONCERNS

- Fatigue Resistance Unknown
- Nonrecoverable Property Loss in Welds
- Cost approximately $220/kg ($100/lb) versus approximately $22/kg ($10/lb) for Hastelloy X

TABLE 30

ADVANCED COMBUSTOR MATERIAL - MISSION MERIT FACTOR RESULTS

30-Passenger Aircraft - 185.2 km (100 nmi) Mission

		Merit Factor Impact		
		Change in DOC (%)		Change in Fuel Burned (%)
Parameter	Change	$264/m³ ($1.00/gal)	$396/m³ ($1.50/gal)	
Engine Weight - kg (lbm)	-.18 (-.4)	0	0	-.01
Engine Price - $1000	+ 14	+.29	+.25	-
Engine Maintenance - $/h	-1.49	-.56	-.48	-
Engine SFC* - %	0	0	0	0
TOTAL		-.27	-.23	-.01

*Includes performance and scaling effects.

Advanced Combustor Cooling - Thermal Barrier Coating and Impingement Cooling Shields

The combination of applying an insulation coating to the hot side surfaces of the combustor liner and using impingement cooling on the aft end combustor panels increases the effectiveness of the liner cooling air. This results in the need for less cooling air for a given combustor discharge temperature. This can be translated into an increase in liner life, or, as with the advaned liner material above, into an improvement in combustor exit pattern factor and nozzle and shroud life, or some combination of the two.

The insulation is called thermal barrier coating (TBC) and consists of a multi-layer magnesium zirconate application to the "hot" surface. Table 31 describes the coating, its cost and weight when applied to the STAT engines, and the life extension expected.

The impingement cooling shields are used with the aft combustor panels. Figure 32 shows the impingement shields on the outer shell. A grid of holes in the shield passes the jets of cooling air, which then exhaust into the combustor flowpath through the film cooling holes. Table 31 also shows cost, weight and life extension expected due to the impingement shields.

The net effects on the 30-passenger aircraft mission are summarized in Table 32 for the estimated increases in price, weight and life. The actual life increase could vary, so the sensitivity of net change in DOC for the 30-passenger, 185.2 km (100 nmi) mission to liner life achievement is shown in Figure 33. The evaluation was done assuming a combined improvement for coating and shields of 50% liner life and 15% nozzle and shroud life.

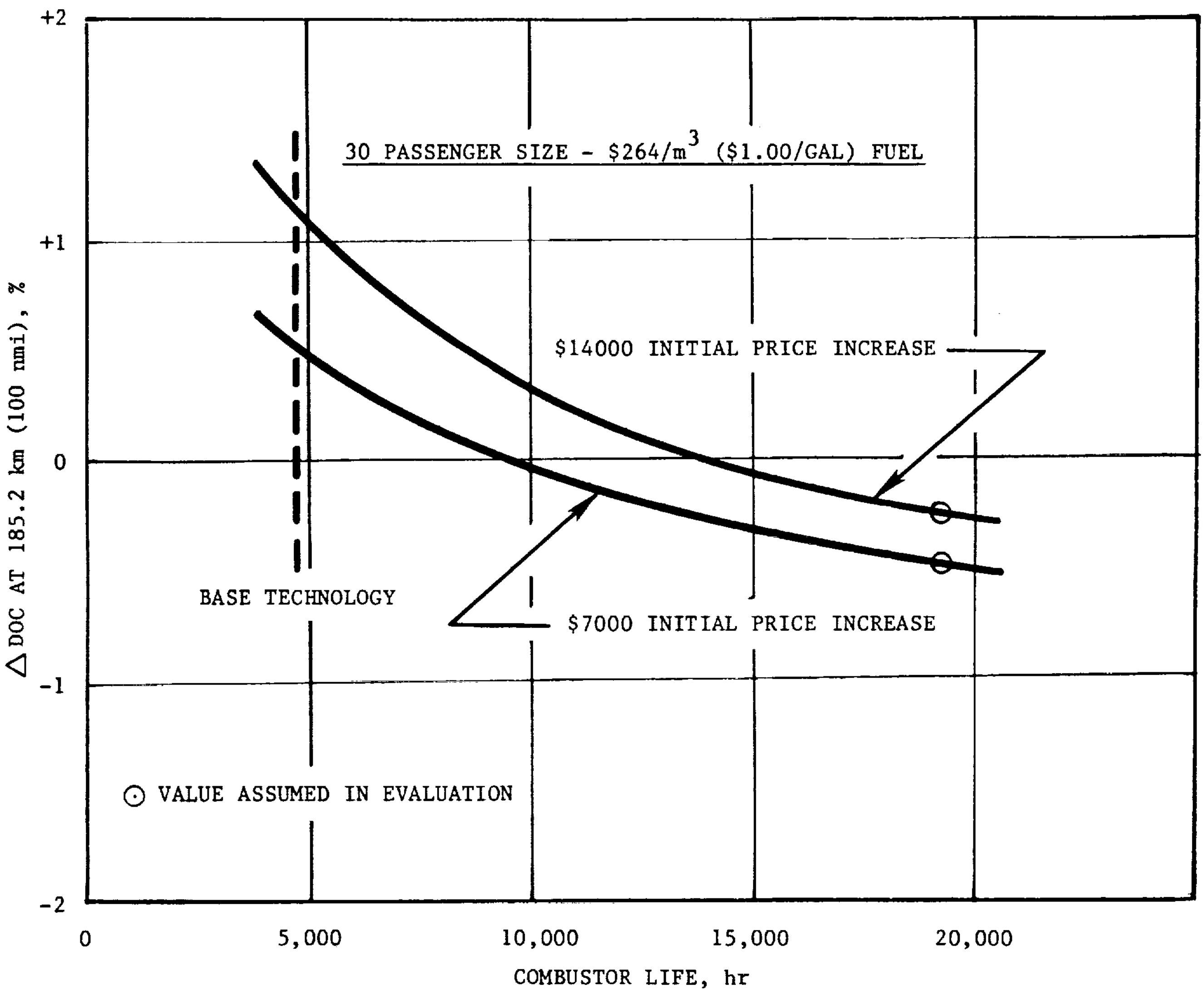


Figure 31. Advanced Combustor Material - DOC Payoff Sensitivity to Combustor Life and Price Increase.

TABLE 31
ADVANCED COMBUSTOR COOLING
THERMAL BARRIER COATING AND IMPINGEMENT COOLING SHIELDS

THERMAL BARRIER COATING

- 3-Ply Magnesium Zirconate (Mg Zr) Process

Material	Thickness - cm (in.)	Total Thickness
1. METCO 450 Base	.008-.013 (.003-.005)	
2. METCO 450 Plus Mg Zr Blend	.008-.013 (.003-.005)	.028-.043 cm (.011-.017 in.)
3. Mg Zr	.013-.018 (.005-.007)	

- Cost: +$300 per unit
- Weight: +.73 kg (+1.6 lbm)
- Life: 1.5X for liner or 1.15X for nozzle and shrouds via reduced liner metal temps or improved dilution (reduced pattern factor).

IMPINGEMENT COOLING SHIELDS

- Ref: F404 Aft Outer Panels
- Cost: +500 per Unit
- Weight: +.23 kg (+.5 lbm)
- Life: 1.25X for liner and 1.05 to 1.10 for nozzles and shrouds.

TABLE 32
ADVANCED COMBUSTOR COOLING - MISSION MERIT FACTOR RESULTS

30-Passenger Aircraft - 185.2 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact: Change in DOC (%) $264/m³ ($1.00/gal)	Merit Factor Impact: Change in DOC (%) $396/m³ ($1.50/gal)	Merit Factor Impact: Change in Fuel Burned (%)
Engine Weight - kg (lbm)	+.4 (+.8)	+.01	+.01	+.01
Engine Price - $1000	+1.0	+.02	+.02	-
Engine Maintenance - $/h	-.88	-.33	-.28	-
Engine SFC* - %	0	0	0	0
TOTAL		-.30	-.25	+.01

*Includes performance and scaling effects.

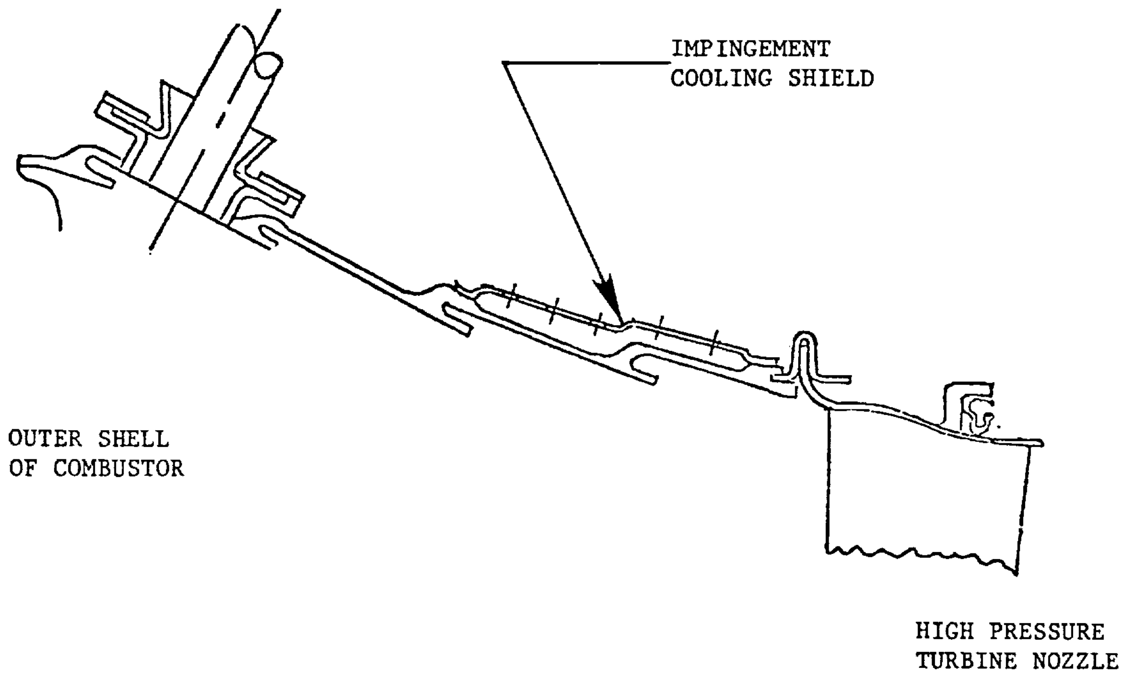


Figure 32. Advanced Combustor Impingement Cooling Shield.

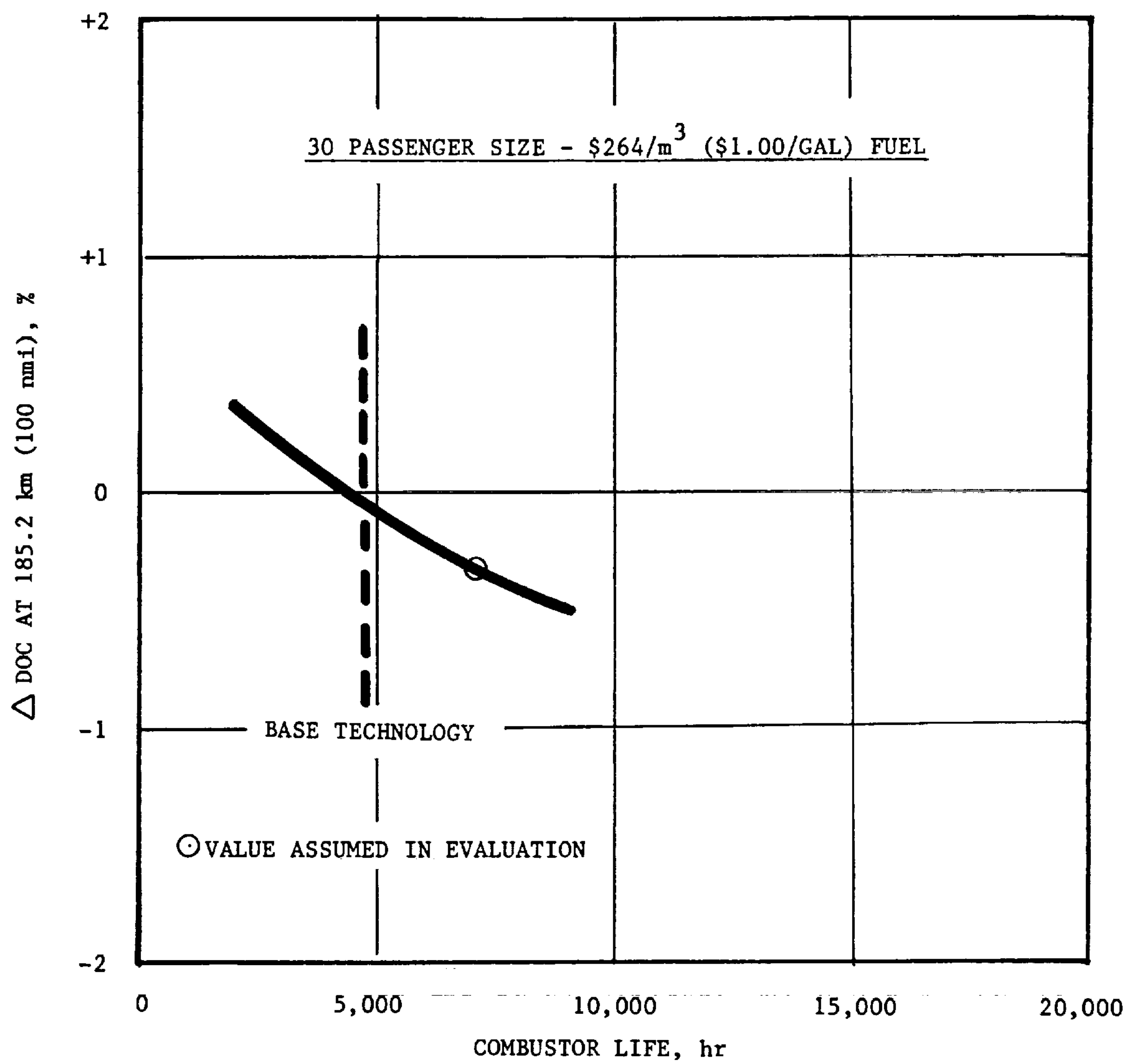


Figure 33. Advanced Combustor Cooling - DOC Payoff Sensitivity to Combustor Life.

ADVANCED MECHANICAL DESIGN FEATURES - Continued

Advanced Material High-Pressure Turbine Blade

Metal turbine blades in engines where turbine rotor inlet temperature (T41) exceeds 1093°C (2000°F) require air cooling which penalizes the cycle, reducing power available and increasing SFC. As T41 increases, more cooling air is required. This technology evaluation is for materials which operate at higher temperatures than in the base engine, and thus require less cooling air. The materials considered were:

Materials	Bulk Temperature Capability	Change in Cooling Flow (% W2)* T41 1260°C (2300°F)	T41 1371°C (2500°F)
Rene' 125	Base	0	+1.9
Rene' 150	+36°C (+65°F)	-.6	+.8
Mono-Crystal	+47°C (+85°F)	-.7	+.6
Directionally Solidifed Eutectic Alloy	+92°C (+165°F)	-1.2	-.1

*Baseline cooling configuration.

The evaluation of the effect on DOC for the mono-crystal material relative to the base is presented in Tables 33-34. Results for Rene' 125 and mono-crystal blades of the baseline, radial hole, convection cooling configuration are shown at two levels of T41 for the 30-passenger engine size. The benefits in reduced cooling flow and improved SFC increase with temperature, but are outweighed by the higher cost and maintenance of the advanced material. (The trade between performance and costs was even more unfavorable for the other two materials.)

Advanced Cooling Technology High-Pressure Turbine Blade

An additional HP turbine blade evaluation using the base material, but with a more effective cooling configuration, was made. In this case, the blade is cooled by a combination of convection, impingement and film techniques. This "cold bridge" cooling configuration has a series of passages which impinge flow on the leading edge. This flow then exits the blade through film cooling holes into the hot gas flowpath. The rest of the blade is cooled by convection through radial holes. Tables 35-36 show the effect on DOC for engines operating at 1371°C (2500°F) T41. The advanced cooling system shows an increasing reduction in DOC for the larger engine and with higher price fuel. Figure 34 shows the sensitivity of the effect on DOC to blade cost.

After the 50-passenger advanced engine cycle was selected at 1316°C (2400°F) T41, the evaluation was repeated for this item at 1316°C (2400°F) resulting in changes in DOC of +0.2% and 0% at $264/m^3$ ($1.00/gal) and $396/m^3$ ($1.50/gal) fuel costs, respectively, and a fuel burn saving of 1%.

TABLE 33
ADVANCED HIGH-PRESSURE TURBINE BLADE - MISSION MERIT FACTOR RESULTS

Mono-Crystal vs Rene' 125 Material at 1260°C (2300°F) T41

30-Passenger Aircraft - 185.2 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact: Change in DOC (%) $264/m³ ($1.00/gal)	Merit Factor Impact: Change in DOC (%) $396/m³ ($1.50/gal)	Merit Factor Impact: Change in Fuel Burned (%)
Engine Weight - kg (lbm)	0	0	0	0
Engine Price - $1000	+6.9	+.14	+.12	-
Engine Maintenance - $/h	+1.94	+.73	+.63	-
Engine SFC* - %	-.68	-.40	-.45	-.80
TOTAL		+.47	+.30	-.80

*Includes performance and scaling effects.

TABLE 34
ADVANCED HIGH-PRESSURE TURBINE BLADE - MISSION MERIT FACTOR RESULTS

Mono-Crystal vs Rene' 125 Material at 1371°C (2500°F) T41

30-Passenger Aircraft - 185.2 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact: Change in DOC (%) $264/m³ ($1.00/gal)	Merit Factor Impact: Change in DOC (%) $396/m³ ($1.50/gal)	Merit Factor Impact: Change in Fuel Burned (%)
Engine Weight - kg (lbm)	0	0	0	0
Engine Price - $1000	+6.9	+.14	+.12	-
Engine Maintenance - $/h	+1.94	+.73	+.63	-
Engine SFC* - %	-1.23	-.71	-.82	-1.46
TOTAL		+.16	-.07	-1.46

*Includes performance and scaling effects.

TABLE 35

ADVANCED HIGH-PRESSURE TURBINE BLADE - MISSION MERIT FACTOR RESULTS

Cold Bridge vs Radial Hole Cooling at 1371°C (2500°F) T41

30-Passenger Aircraft - 185.2 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact: Change in DOC (%) $264/m³ ($1.00/gal)	Change in DOC (%) $396/m³ ($1.50/gal)	Change in Fuel Burned (%)
Engine Weight - kg (lbm)	-.05 (-.1)	0	0	0
Engine Price - $1000	+7.1	+.14	+.12	-
Engine Maintenance - $/h	+2.00	+.75	+.65	-
Engine SFC* - %	-1.6	-.89	-1.03	-1.85
TOTAL		0	-.26	-1.85

*Includes performance and scaling effects.

TABLE 36

ADVANCED HIGH-PRESSURE TURBINE BLADE - MISSION MERIT FACTOR RESULTS

Cold Bridge vs Radial Hole Cooling at 1371°C (2500°F) T41

50-Passenger Aircraft - 185.2 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact: Change in DOC (%) $264/m³ ($1.00/gal)	Change in DOC (%) $396/m³ ($1.50/gal)	Change in Fuel Burned (%)
Engine Weight - kg (lbm)	-.05 (-.1)	0	0	0
Engine Price - $1000	+8.8	+.13	+.11	-
Engine Maintenance - $/h	+2.58	+.68	+.57	-
Engine SFC* - %	-1.6	1.01	-1.14	-1.90
TOTAL		-.20	-.46	-1.90

*Includes performance and scaling effects.

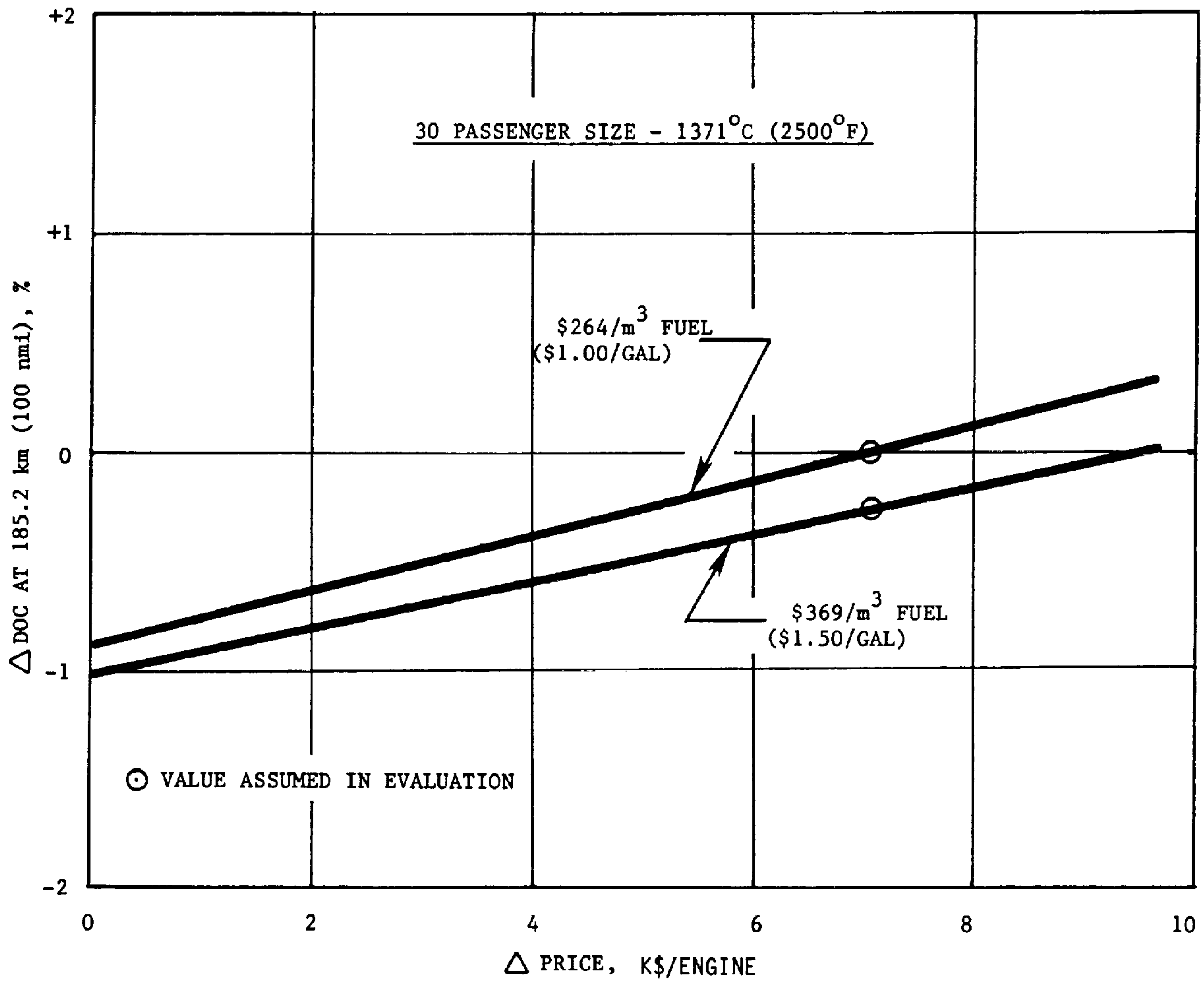


Figure 34. Advanced HPT Blade - DOC Payoff Sensitivity to Blade Price.

ADVANCED MECHANICAL DESIGN FEATURES - Continued

Low-Pressure Turbine Disk with Integral Cast Blades

The base engine uses forged low-pressure turbine disks with individual cast solid airfoil blades with dovetails and integral tip shrouds. Low maintenance costs are achieved with the ability to replace or repair individual blades. This study compared a one piece cast disk and blades (a blisk) to determine whether lower initial cost and weight would offset the more difficult maintenance. Figure 35 shows the blisk compared to the base design.

Table 37 shows that there is a small reduction in DOC, regardless of fuel cost, since no advantage in SFC was assumed. The elimination of hot gas leakage paths between separate blades and the disk might even improve turbine efficiency, but this has not been included because it is difficult to measure. The cost and weight reductions more than balance the increase in maintenance costs.

Since the maintenance cost of the blisks is a variable, and may depend on type of flight service as well as maintenance practices, a sensitivity plot in Figure 36 shows how DOC is affected by a range in maintenance cost.

TABLE 37
LOW-PRESSURE TURBINE DISK WITH CAST BLADES - MISSION MERIT FACTOR RESULTS

30-Passenger Aircraft - 185.2 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact: Change in DOC (%) $264/m^3 ($1.00/gal)	Merit Factor Impact: Change in DOC (%) $396/m^3 ($1.50/gal)	Merit Factor Impact: Change in Fuel Burned (%)
Engine Weight - kg (lbm)	-1.3 (-2.9)	-.02	-.02	-.03
Engine Price - $1000	-5.6	-.11	-.10	-
Engine Maintenance - $/h	+.15	+.05	+.05	-
Engine SFC* - %	0	0	0	0
TOTAL		-.08	-.07	-.03

*Includes performance and scaling effects.

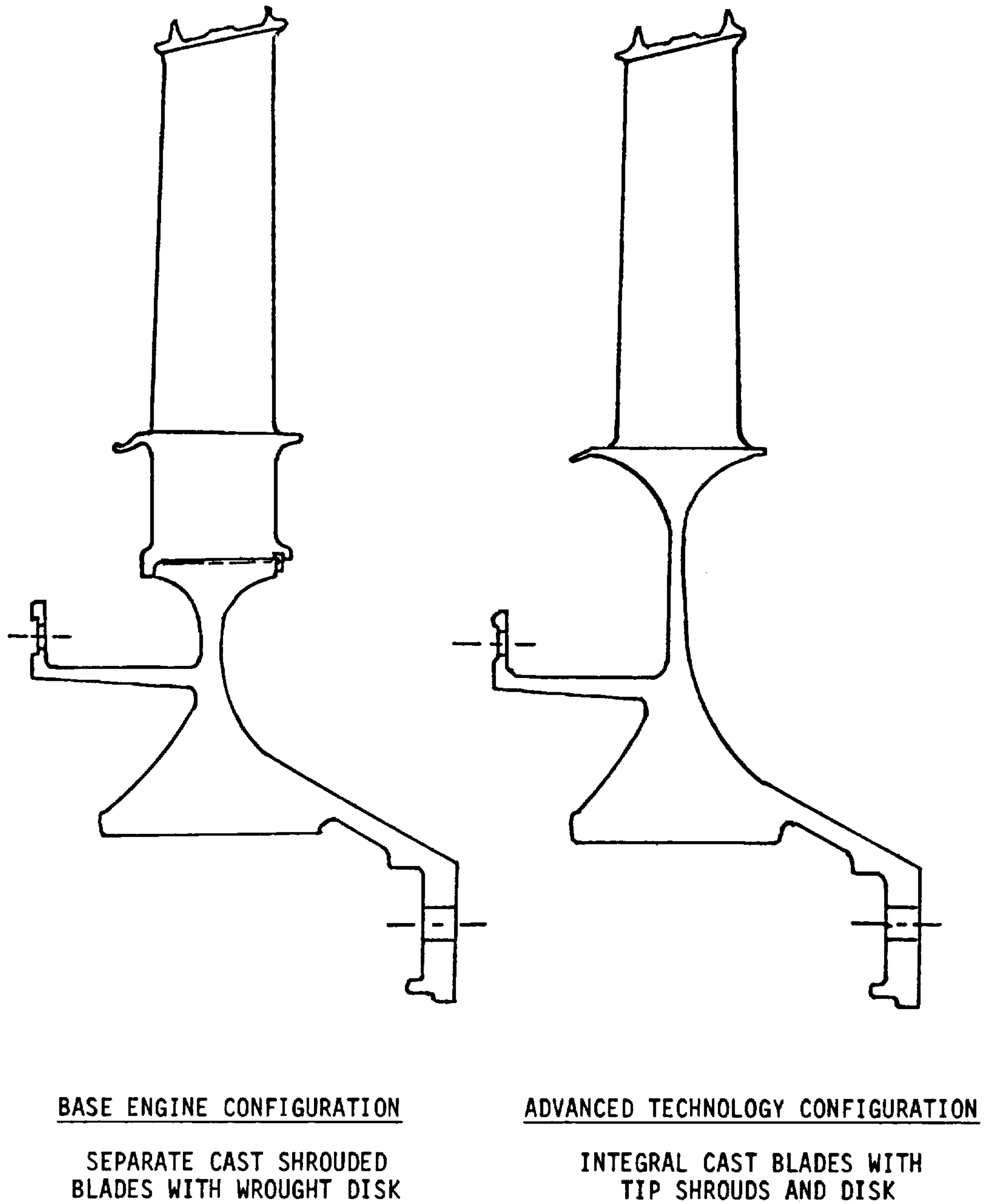


Figure 35. LP Turbine Disc with Integral Blades.

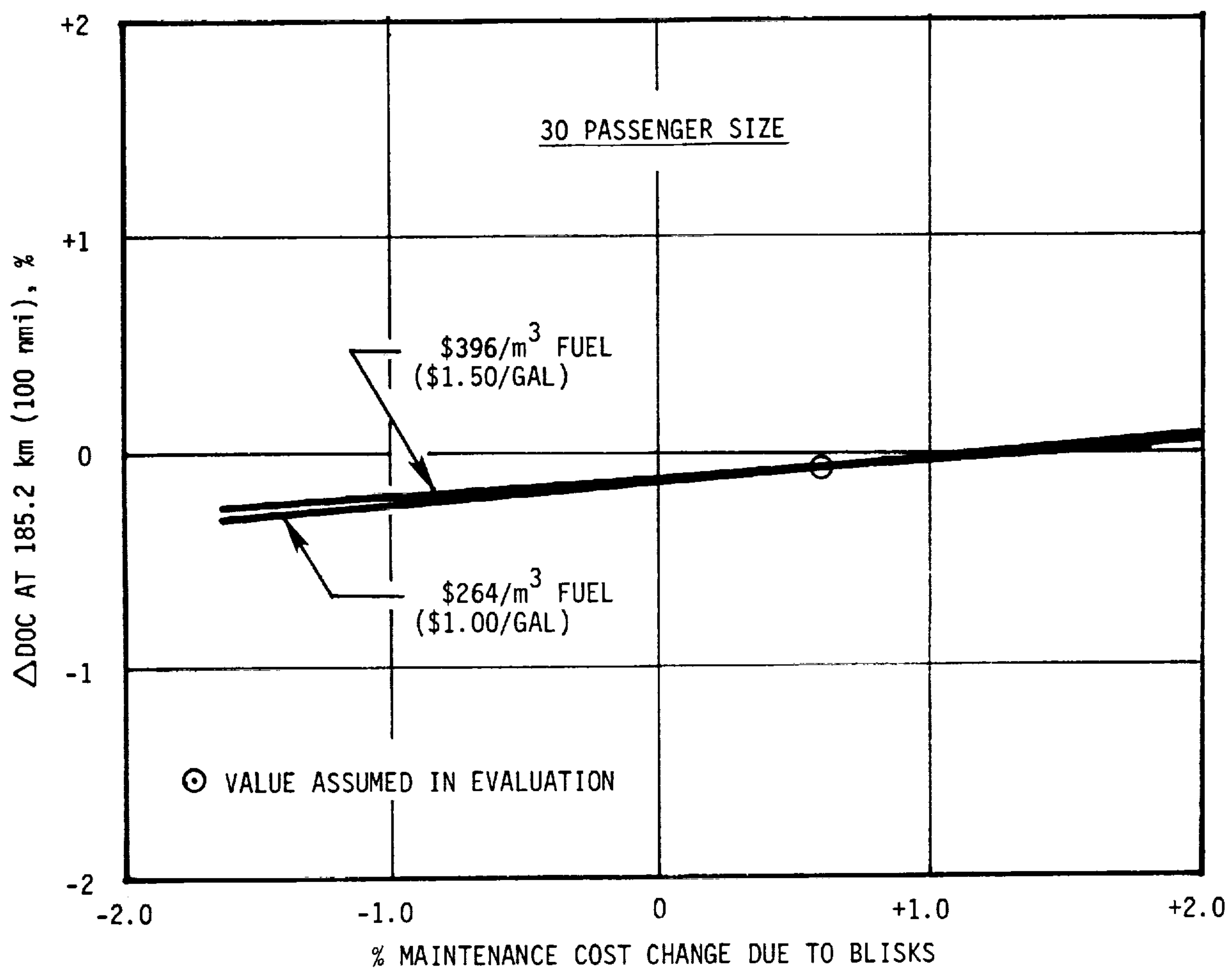


Figure 36. LP Turbine Blisk - Sensitivity of DOC Payoff to Blisk Maintenance Cost.

ADVANCED MECHANICAL DESIGN FEATURES - Continued

Metal Matrix Low-Pressure Rotor Shaft

Small, advanced technology engines tend to use higher tip speeds than current technology engines. These high tip speeds result in high centrifugal blade loads that require massive compressor and turbine disks to support them when using currently available disk materials. The disk weight can be reduced, however, if bore diameters can be reduced.

Smaller bores in turn require low-pressure turbine front drive shafts to be long and thin, creating a problem in achieving satisfactory low-pressure shaft critical speeds. The use of a material for the LP shaft with a higher modulus of elasticity to density ratio (E/ρ) than steel can increase critical speeds for a given geometry, or allow a reduction in shaft (and therefore disk bore) diameter with no adverse impact on rotor dynamics. This study compares shafts of composite metal matrix materials (such as titanium matrix and boron fibers) with conventional steel shafts. The low density of these materials more than offsets their effective modulus (which is lower than steel's), resulting in a high value of E/ρ and up to a 40% increase in shaft critical speed for a given geometry.

Figure 37 compares composite shafts with all steel and beryllium shafts, showing the critical speed variations with length and diameter.

To estimate the impact on DOC, weight savings were estimated for the high pressure rotor disks when sized with reduced bore diameters allowed by the use of a composite LP shaft. Table 38 presents the results; a very small improvement in DOC and fuel burned.

TABLE 38
METAL MATRIX LP SHAFT - MISSION MERIT FACTOR RESULTS

30-Passenger Aircraft - 185.2 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact: Change in DOC (%) $264/m³ ($1.00/gal)	Merit Factor Impact: Change in DOC (%) $396/m³ ($1.50/gal)	Change in Fuel Burned (%)
Engine Weight - kg (lbm)	-2.5 (-5.6)	-.03	-.04	-.06
Engine Price - $1000	+.1	0	0	-
Engine Maintenance - $/h	+.01	0	0	-
Engine SFC* - %	0	0	0	0
TOTAL		-.03	-.04	-.06

*Includes performance and scaling effects.

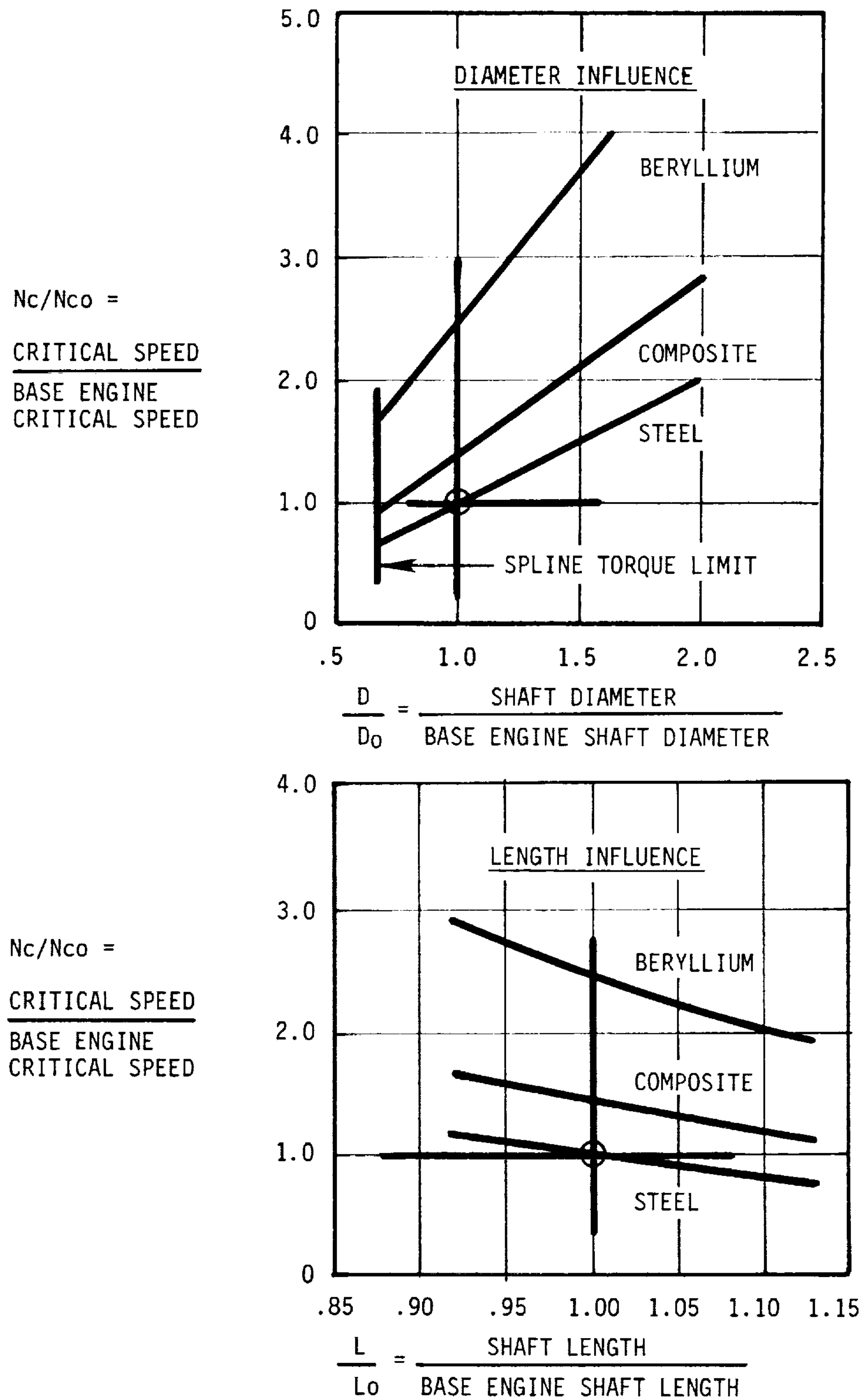


Figure 37. Shaft-Bending Mode Critical Speeds.

ADVANCED MECHANICAL DESIGN FEATURES - Continued

Composite Materials for Nacelle

A cost and weight comparison was made to determine the effect of substituting composite materials such as glass and epoxy or graphite and epoxy for aluminum in the nacelles. These materials draw their high strength-to-weight ratio from a combination of high tensile strength fibers with an epoxy filler material. The development and tooling cost required to set up new manufacturing facilities have delayed their extensive use in aircraft applications. However, several airframe manufacturers have flight-tested a limited number of nonstructural parts - so far with good results.

Production of these parts is still very labor intensive and new, automated production methods are needed to make them cost effective. To estimate the effect of cost and weight savings on DOC, the results of a prior study[7] for NASA have been used.

This analysis showed that the achievable savings vary greatly with size and location of components but that for the overall nacelle structure a weight reduction of 20 to 25% and a cost reduction fo 25 to 30% are obtainable.

Using the above values, the savings for the 30-passenger installation would calculate to be 14 to 16 kg (30 to 36 lbm) and $6000 to $7400, while values for the 50-passenger installation would be 23 to 27 kg (50 to 60 lbm) and $10,000 to $12,500. The resulting benefits in terms of DOC and fuel burned are shown in Table 39. Because the ultimate cost of producing composite structures is a matter of great uncertainty throughout the aircraft industry, sensitivity to material cost is shown in Figure 38.

TABLE 39
COMPOSITE MATERIALS FOR NACELLE - MISSION MERIT FACTOR RESULTS

30-Passenger Aircraft - 185.2 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact: Change in DOC (%) $264/m^3 ($1.00/gal)	Merit Factor Impact: Change in DOC (%) $396/m^3 ($1.50/gal)	Merit Factor Impact: Change in Fuel Burned (%)
Engine Weight - kg	-14 to -16	-.19 to -.23	-.21 to -.26	-.32 to -.39
- (lbm)	(-30 to -36)			
Engine Price - $1000	-6 to -7.4	-.12 to -.15	-.11 to -.13	-
Engine Maintenance - $/h	0	0	0	-
Engine SFC* - %	0	0	0	0
TOTAL		-.31 to -.38	-.32 to -.39	-.32 to -.39

*Includes performance and scaling effects.

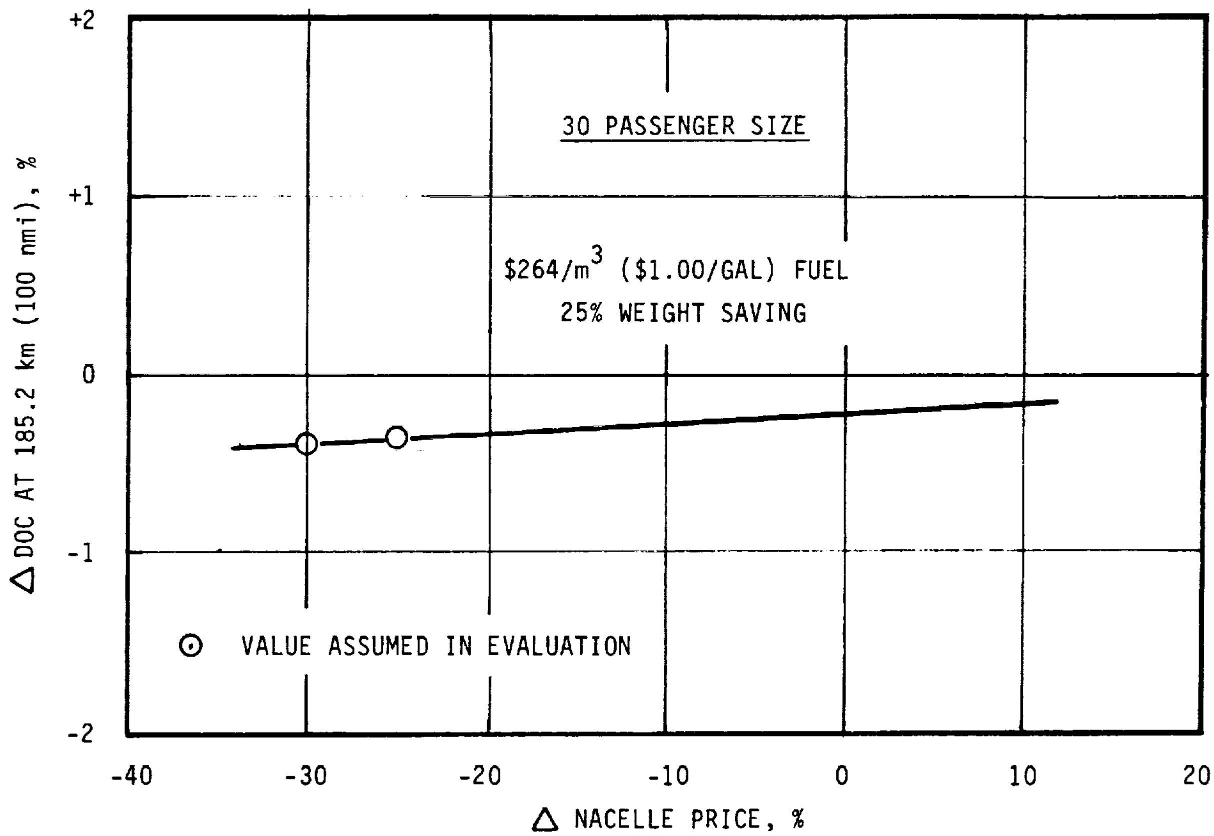


Figure 38. Composite Materials for Nacelle - Sensitivity of DOC Payoff to Composite Material Price.

DESIGN FACTORS

Modular Construction

Aircraft engines which need major maintenance, including replacement of components and parts, in poor working environments benefit from totally modular construction. The T700 engine was designed for such an environment as a military helicopter engine. Modules in this case permit replacement of units with simple tools without opening bearing cavities or realigning rotors. Usually, however, this type of modular construction requires extra joints, flanges, and bolts to accomplish these replacements.

In the case of engines for commuter airlines, maintenance will normally be done in well equipped shops on an overnight schedule. The criterion used in this study for an acceptable maintenance procedure is whether it can be done in an approximately 8-hour overnight period between scheduled flights.

For this design factor, two basic engine structural arrangements were compared. Figure 39 shows a totally modular, 3-sump configuration which permits both low-pressure and high-pressure turbine replacement as components without exposing bearing cavities, and a more compact, lower cost, lower weight configuration with only two sumps. The same maintenance and replacement can be performed in the required time but the rear bearings and sumps are opened up in the process. The increased complexity of the 3-sump design results in higher weight and cost and a greater number of parts. The increase in part replacement cost offsets the labor saving, resulting in a small net increase in engine maintenance cost.

When compared on a DOC basis, the 2-sump design has the advantage. All merit factors are favorable, including SFC, since the overhung high-pressure turbine of the 3-sump design requires larger tip clearances to prevent rubs during maneuver load deflections. A decision to incorporate totally modular construction in an all new engine of this type would have to be made based on factors other than DOC.

Table 40 shows the evaluation results.

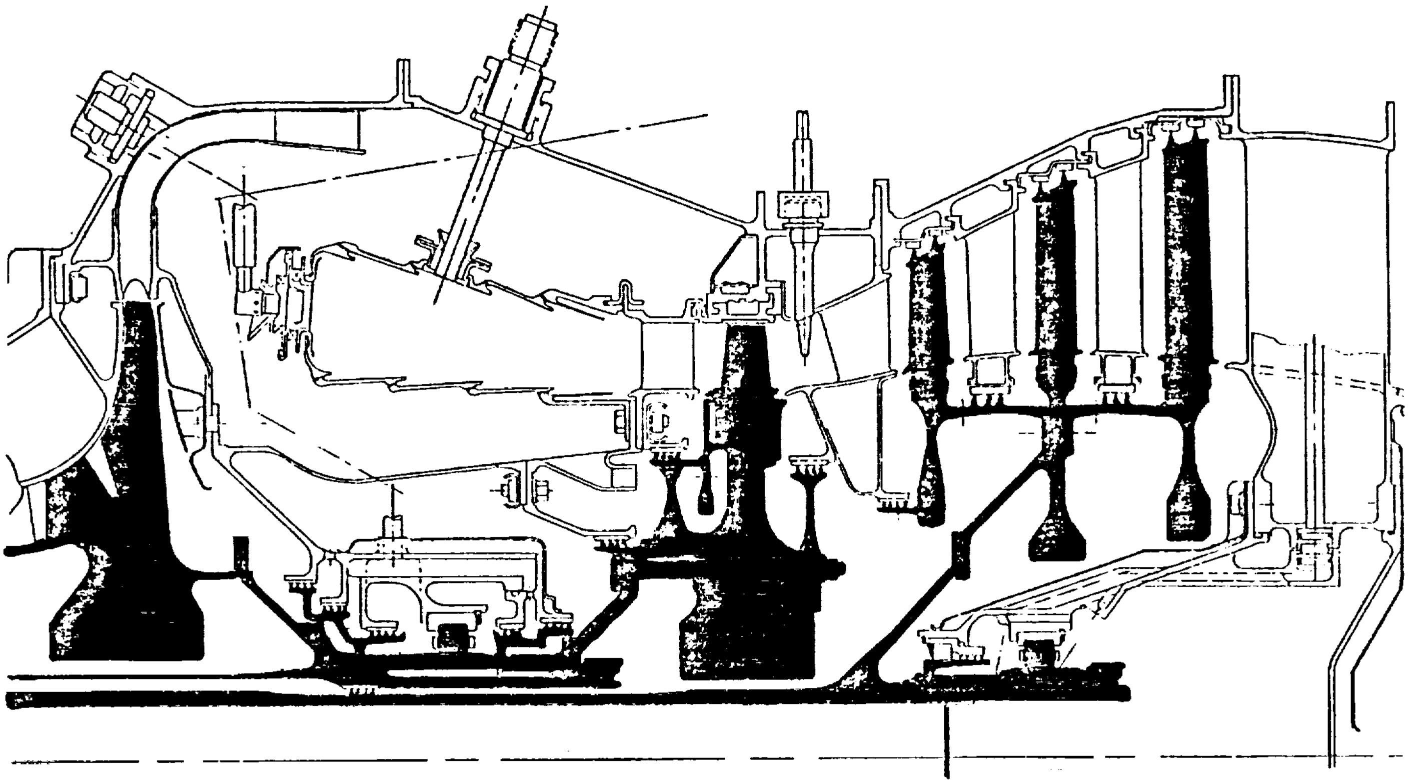
TABLE 40
MODULAR CONSTRUCTION - MISSION MERIT FACTOR RESULTS

3-Sump Versus 2-Sump Design

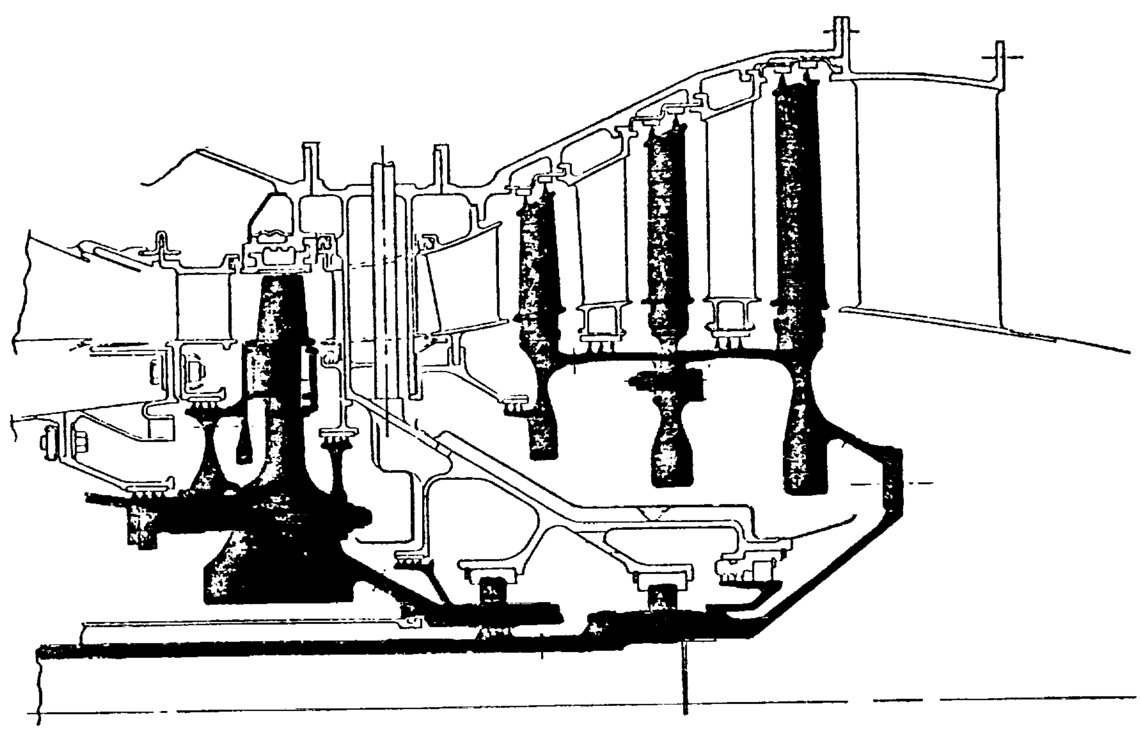
30-Passenger Aircraft - 185.2 km (100 nmi) Mission

		Merit Factor Impact		
		Change in DOC (%)		Change in Fuel Burned (%)
Parameter	Change	$264/m^3 ($1.00/gal)	$396/m^3 ($1.50/gal)	
Engine Weight - kg (lbm)	+2.2 (+4.8)	+.03	+.03	+.05
Engine Price - $1000	2.4	+.05	+.04	-
Engine Maintenance - $/h	+.11	+.04	+.04	-
Engine SFC* - %	+.6	+.29	+.35	+.73
TOTAL		+.41	+.46	+.78

*Includes performance and scaling effects.



THREE-SUMP MODULAR CONFIGURATION



TWO-SUMP CONFIGURATION

Figure 39. Bearing and Sump Arrangement Comparison.

ADVANCED MECHANICAL DESIGN FACTORS - Continued

Inlet Particle Separator (IPS) and Foreign Object Protector (FOP)

It is widely known that an IPS or FOP at the inlet of an aircraft gas turbine engine will reduce the frequency of blade damage and erosion, and thereby reduce maintenance. There is, however, an increase in acquisition cost of the separator, increased weight, and a performance loss. For aircraft operating from hard runways which are kept clean, as was assumed for this study, the separator may not pay off as it would for an aircraft operating from unimproved fields.

For this design factor, two types of separators were evaluated. The first one (shown in Figure 40) - called an IPS - has fixed inlet swirl vanes and a scavenge system powered by a continuously operating blower. It has a very high separator efficiency for fine sand, coarse sand, and gravel and is currently used on the T700 Black Hawk engine and the CT7-2 turboshaft engine. The second type of separator - an FOP - has no vanes, is powered by a bleed driven ejector and is operated only during takeoff to minimize the performance loss. Separation of foreign objects from the air stream is achieved through special shape of the flowpath walls. It has the same separator efficiency for gravel as an IPS, but is not as effective on sand. Currently, it has been proposed for the CT7-5 turboprop engine.

Tables 41-42 show the effects on DOC. FOD incident rates without a separator were assumed to be 5 times the rates with a separator (based on General Electric Co. small engine experience) and it was assumed that compressor blisks would be repaired and replaced on a 50/50 basis. The sensitivity to these assumptions is shown in Figure 41 and indicates that even if all blisks could be repaired, a separator would not reduce DOC. The net effect on maintenance cost balances the reduction due to reduced FOD and the increase due to the fact that the separator and associated parts require maintenance themselves. However, it may be necessary to add an FOP regardless of cost in order to pass FAA requirements on bird, ice, sand and gravel ingestion.

TABLE 41
INLET PARTICLE SEPARATOR (IPS) - MISSION MERIT FACTOR RESULTS

30-Passenger Aircraft - 185.2 km (100 nmi) Mission

		Merit Factor Impact		
		Change in DOC (%)		Change in Fuel Burned (%)
Parameter	Change	$264/m^3 ($1.00/gal)	$396/m^3 ($1.50/gal)	
Engine Weight - kg (lbm)	+12.7 (+28)	+.18	+.20	+.32
Engine Price - $1000	+18.3	+.37	+.31	-
Engine Maintenance - $/h	+.46	+.17	+.15	-
Engine SFC* - %	+2.6	+1.26	+1.49	+2.93
TOTAL		+1.98	+2.15	+3.25

*Includes performance and scaling effects.

TABLE 42

FOREIGN OBJECT PROTECTOR (FOP) - MISSION MERIT FACTOR RESULTS

30-Passenger Aircraft - 185.2 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact: Change in DOC (%) $264/m^3 ($1.00/gal)	Merit Factor Impact: Change in DOC (%) $396/m^3 ($1.50/gal)	Change in Fuel Burned (%)
Engine Weight - kg (lbm)	+6.4 (+14.1)	+.09	+.10	+.16
Engine Price - $1000	+3.9	+.08	+.07	-
Engine Maintenance - $/h	-.23	-.09	-.07	-
Engine SFC* - %	+.5	+.31	+.34	+.63
TOTAL		+.39	+.44	+.79

*Includes performance and scaling effects.

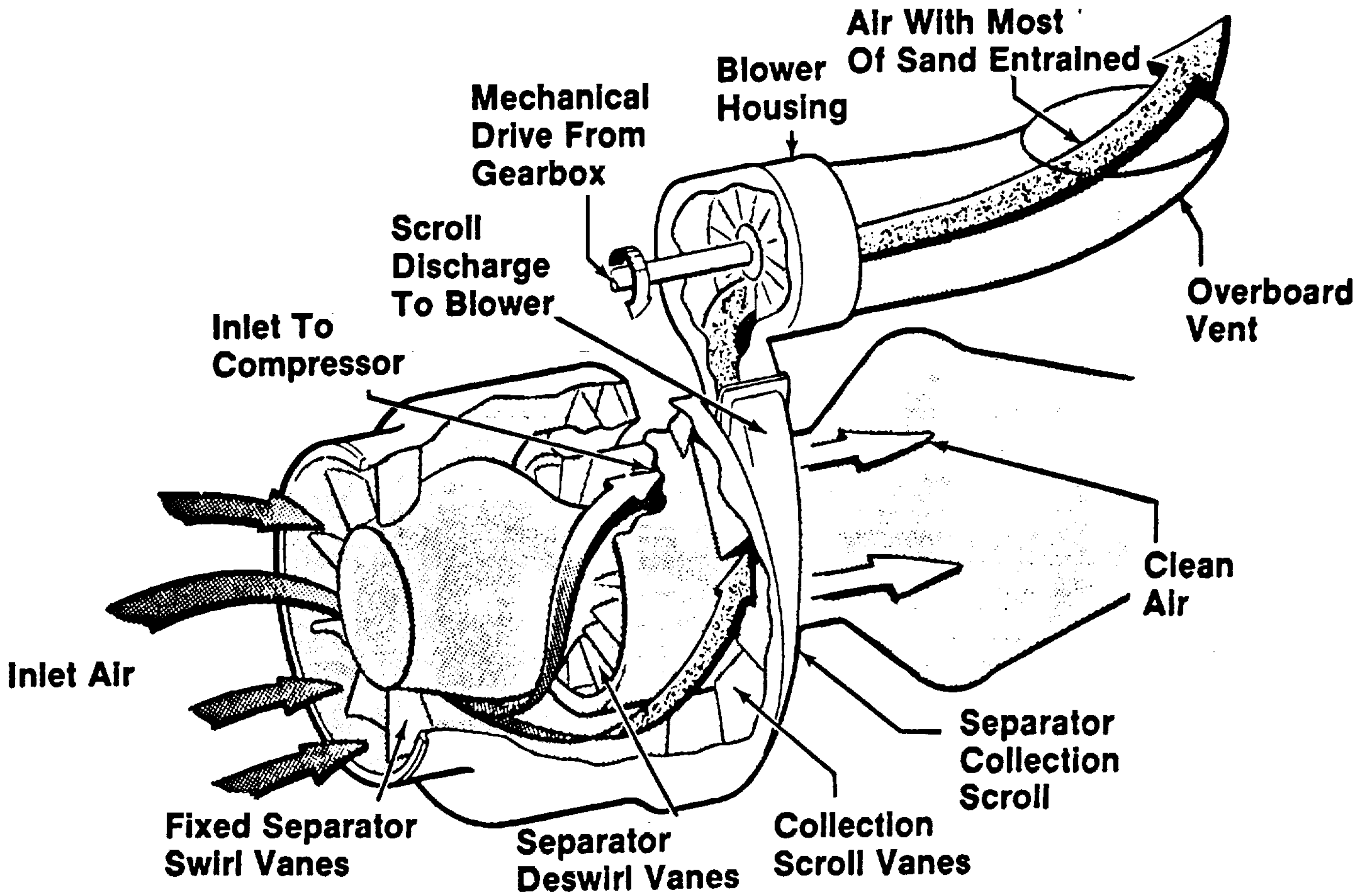


Figure 40. T700 Inlet-Particle Separator.

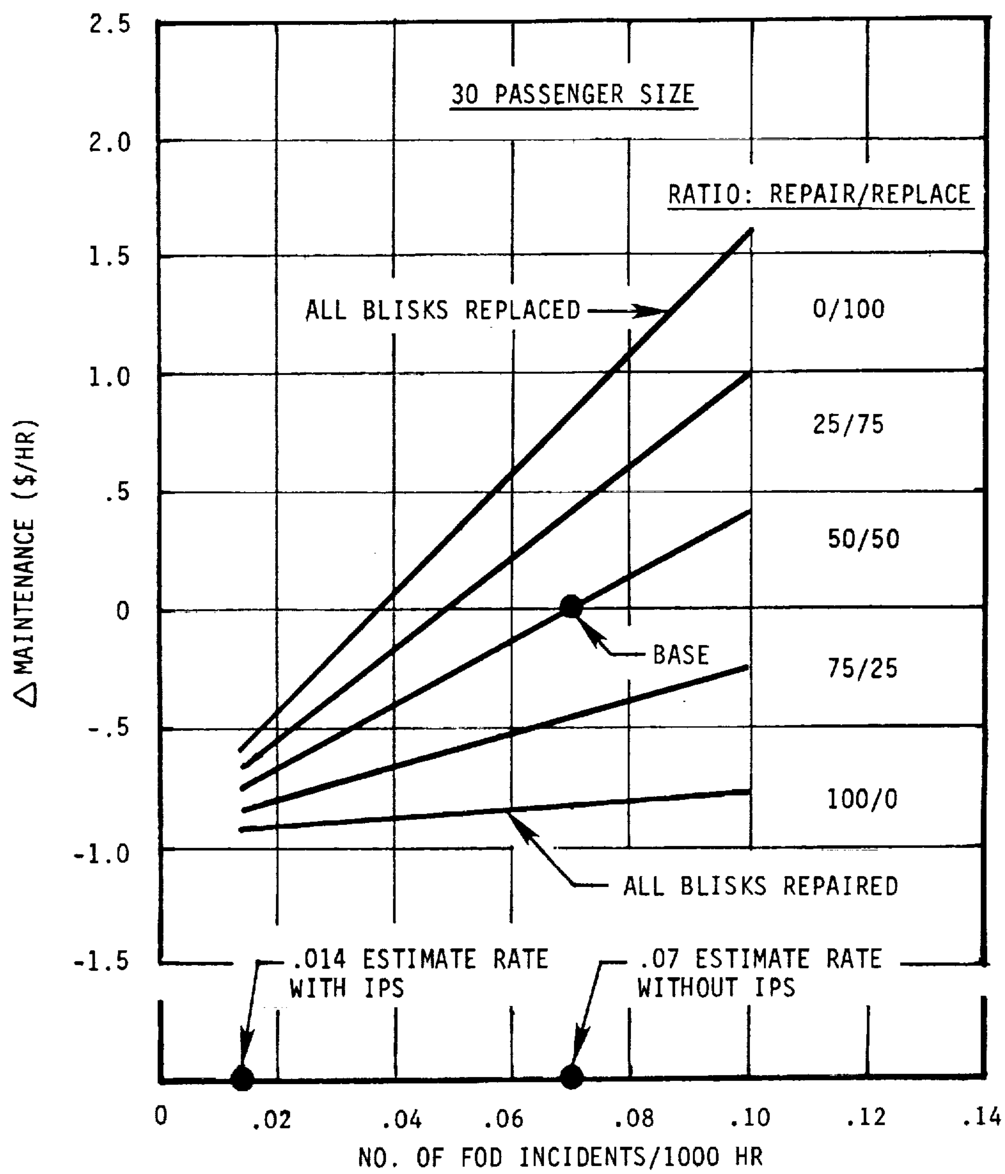


Figure 41. HP Compressor (Blisks) Maintenance Cost vs FOD Rate.

DESIGN FACTORS - Continued

Diagnostic Data Recording

The practice of scheduled engine overhaul based only on the number of hours of use contributes to high maintenance costs. It is a fact, however, that all engines do not deteriorate equally with equal hours of use, because the severity of usage depends on a large number of variables. For example, in warm weather and at high elevations, takeoff and climb power required is much higher relative to capability than in cool weather or low elevations. This characteristic, which leads to the practice of flat rating (discussed in more detail in the following section), significantly affects the rate of deterioration and the need for overhaul of each engine.

The extreme alternative to regular overhauls is to overahul only when each life-limited part requires replacement. Figure 42 shows the variation in maintenance cost and shop visit rate based on the type of life-limited part replacement plan used. It shows that maintenance cost can be minimized at very little increase in the minimum shop visit rate, if some parts are replaced before their lives are completely used up, but not all life-limited parts are replaced at every overhaul.

To do this requires continuous knowledge of the life remaining (or used up) in each life-limited part. Decisions on when to overhaul can then be made for the least disruption of scheduled service.

The design feature evaluated in this study is a diagnostic system called "Diacorder" which records severity of engine operation and time in service and computes the rate of life consumption of each part of interest. The pilot or maintenance crew can retrieve this information as a display on the screen of the output unit, Figure 43 at any time. It provides a continuously updated status of all parts being monitored.

The cost of the system includes cost of the sensors and recorders on each aircraft plus a prorated share of the system operating costs for the fleet.

The merit study of the diagnostic system compared a fixed-time interval maintenance plan to an optimized maintenance plan using the Diacorder. The baseline fixed-time maintenance plan is based on overhaul intervals set by consideration of the most severe operations expected anywhere in the fleet. The interval with the Diacorder is varied according to the severity experienced on each engine, which on average is substantially milder than the most severe conditions used to establish fixed overhaul intervals. Table 43 shows that the diagnostic system and maintenance as required pays off with lower DOC. Figure 44 shows the sensitivity of DOC to the reduced maintenance cost associated with the system.

TABLE 43
DIAGNOSTIC DATA RECORDING - MISSION MERIT FACTOR RESULTS

30-Passenger Aircraft - 185.2 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact: Change in DOC (%) $264/m³ ($1.00/gal)	Merit Factor Impact: Change in DOC (%) $396/m³ ($1.50/gal)	Merit Factor Impact: Change in Fuel Burned (%)
Engine Weight - kg (lbm)	2.7 (6)	.04	.04	.07
Engine Price* - $1000	21.8	.44	.37	-
Engine Maintenance - $/h	-3.70	-1.37	-1.18	-
Engine SFC - %	0	0	0	0
TOTAL		-.89	-.77	.07

*Includes aircraft cockpit mounted "Diacorder" and ground facilities.

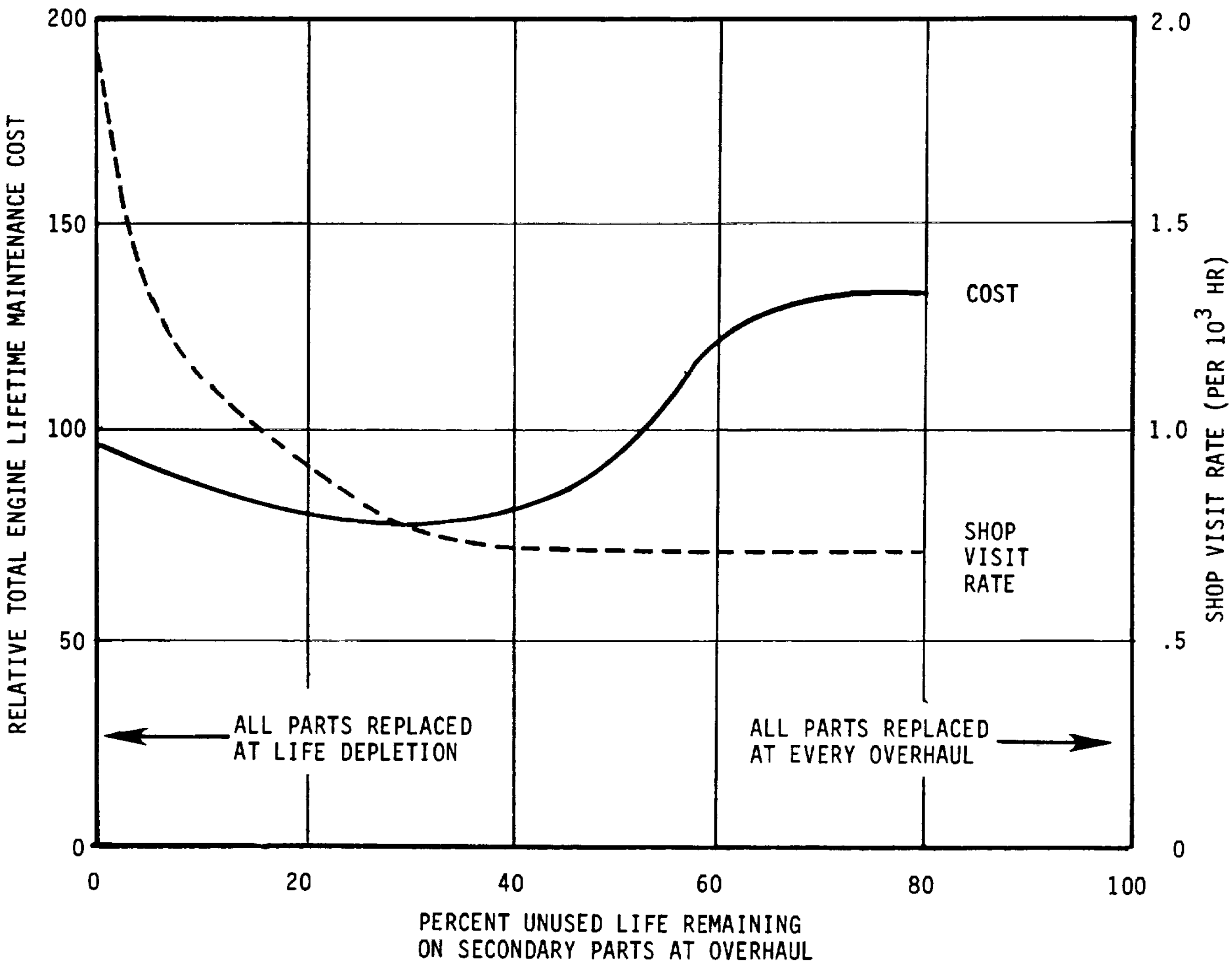
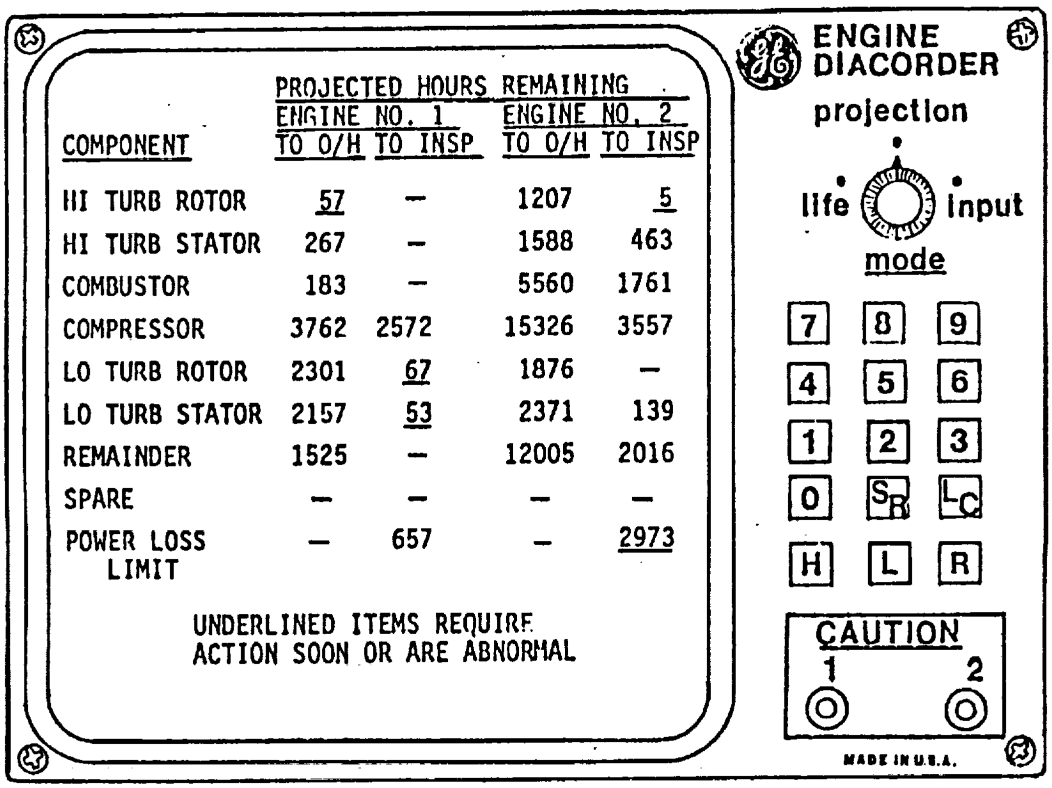


Figure 42. Maintenance Management Effects.



HOURS ARE INTERNALLY COMPUTED BASED ON THE RECENT RATE OF
INCREASE IN APPLICABLE STRESS RUPTURE AND LOW CYCLE FATIGUE INDICES

Figure 43. Example of Projected Hours Remaining Life Display.

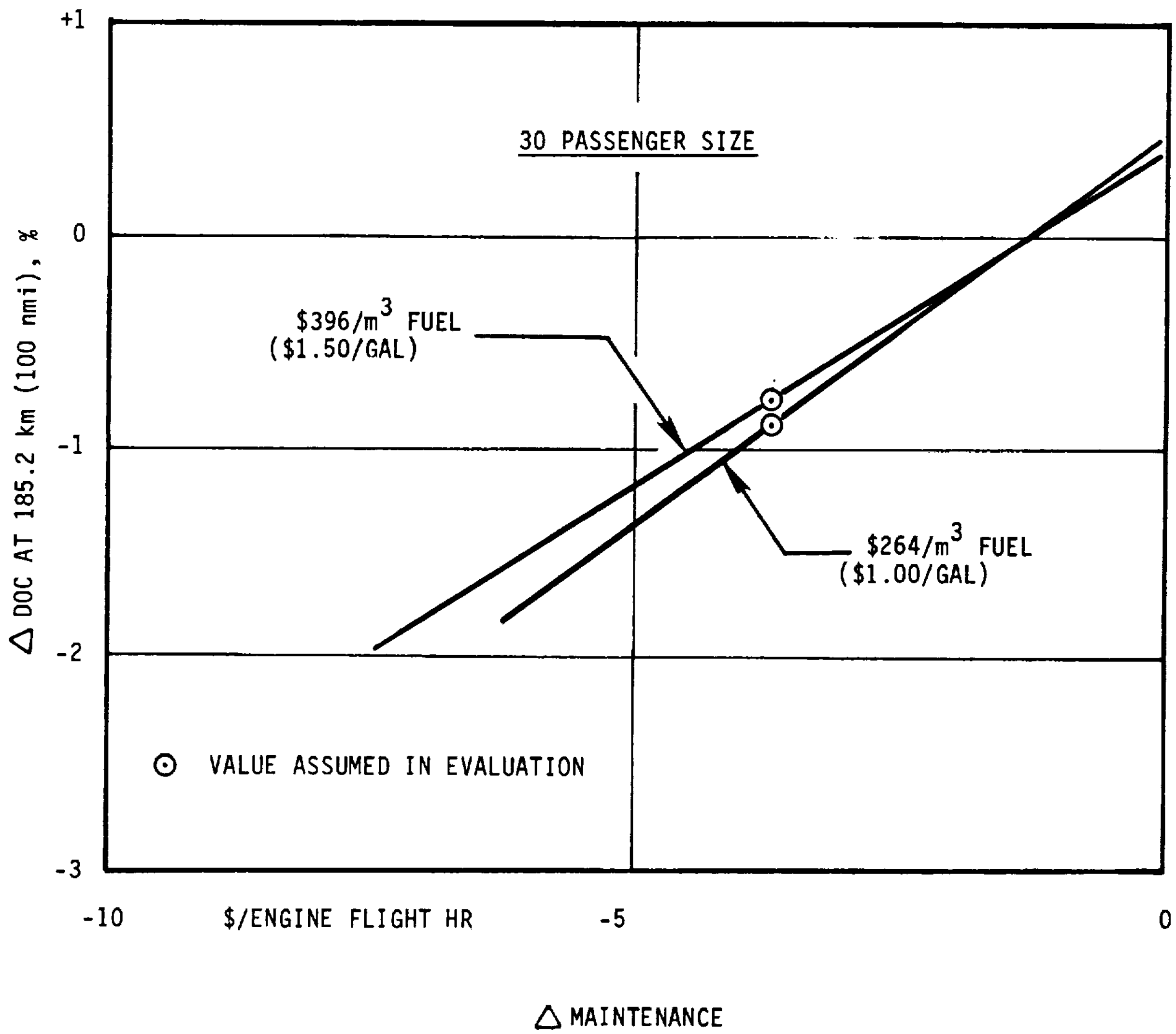


Figure 44. Diagnostic Data Recording - Sensitivity of DOC Payoff to Engine Maintenance Savings.

DESIGN FACTORS - Continued

Alternate Engine Ratings

The power output capability of a turboshaft engine varies with ambient temperature. A basic "full" rating characteristic curve is as shown in Curve "I" of Figure 45. The curve is defined only by maximum allowable turbine temperature and/or maximum rotor speeds. If the aircraft is to meet performance goals at a specified ambient temperature, a surplus of output is available on colder days. Use of full capability at all ambient temperatures produces high maintenance costs because of excessive time at high turbine temperatures. Loading on gearing and propellers is also excessive in cold ambients. Therefore, commercial engines are normally "flat-rated" below the sizing point ambient temperature as shown by Curve "II" of Figure 45. In this range, turboprop engines are typically gearbox torque limited and pilots may set desired power with the aid of applicable tables or curves for various combinations of conditions. With flat rating, engine service is less abusive, on average, than if maximum capability was used for every flight.

Two additional rating methods which may be used separately or in combination for further reduction of maintenance costs are derating and Automatic Provisional Rating (APR). In derating, an engine is used at less than rated capacity. If the engine is always run derated, larger engine size will be required for equivalent performance on a given aircraft. It is more likely, however, that derating will be applied in varying amounts according to prevailing combinations of conditions. Conditions favorable to derating include: cold ambient temperature, lower than maximum gross weight, long runway available, and low altitude airport.

APR is an alternate rating system in which a device on the aircraft detects loss of power on one engine and automatically steps power up to a special rating level, the APR (Automatic Provisional Rating), on the remaining engine(s). This allows smaller, lower cost engines to be used while still meeting aircraft performance requirements.

This study compared four rating types, designated A, B, C, and D:

A. Baseline: flat-rated below 30°C (86°F).

B. 10% average thrust (FN) derate relative to A.

C. APR on an engine scaled 5% smaller than A.

D. 8% average FN derate relative to C.

Baseline Engine A is typical of current commercial practice.

Derated Engine B represents a reasonable average amount of derating, 10%, which may be obtainable without an engine size increase. The derate increases the percentage of time at climb and reduces the percentage at cruise. The net effect is no change in total fuel burned for the 185.2 km (100 nmi) mission, but a small increase in block time. Through time-related factors such as maintenance and crew costs, the increase in block time increases DOC approximately 1% (exclusive of the significant maintenance saving due to reduced severity).

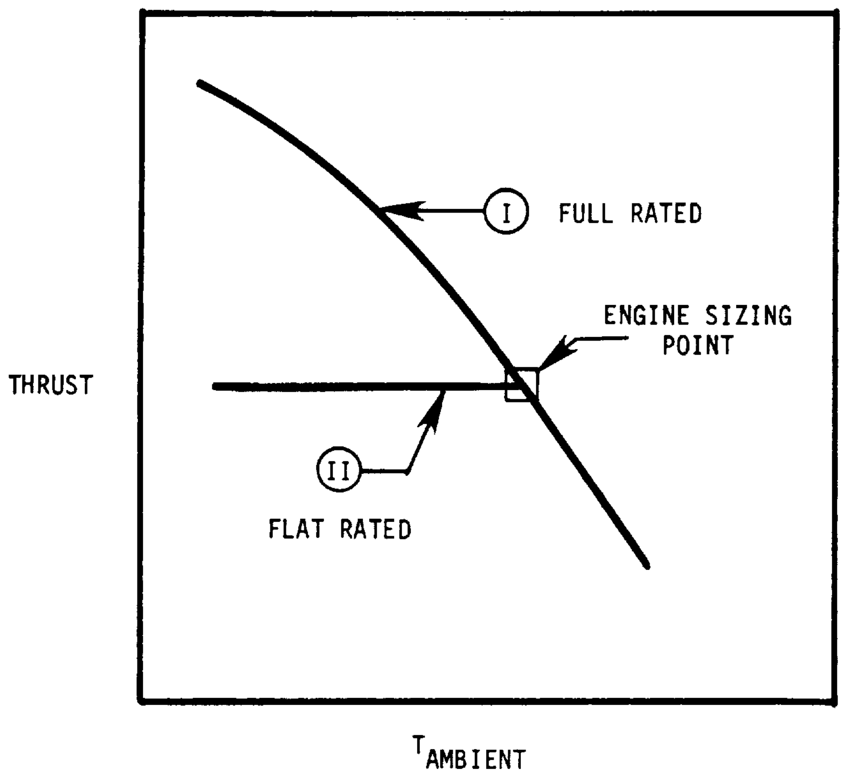


Figure 45. Turboshaft Engine Power for Varying Ambient Temperature.

DESIGN FACTORS - Continued

APR Engine C is scaled down 5%. This amount of scaling was selected to provide the same balanced field length with APR for the nominal size aircraft. Because additional power is available in engine out situations, this smaller engine can satisfy aircraft one engine inoperative (OEI) takeoff field length and minimum rate of climb requirements. Engine C operates at a higher percentage thrust level than he baseline Engine A, to maintain aircraft climb and cruise performance, and therefore has more favorable TSFC for much of the mission. The impact on block time is negligible.

Engine D with APR, and 95% size compared to Engine A, cannot be derated as much, on an average, as Engine A because its smaller size forces the use of a greater percent of its output capacity. The 8% derating represents the estimated usable average for this configuration.

To summarize, two physically different Engines A and C are compared, along with their comparable derated versions, Engines B and D respectively.

Mission profiles for some of these ratings are shown schematically in Figure 46. Total time at takeoff (TO), climb (CL), cruise (CR) and idle (ID) is plotted against turbine temperature (T41). Note that derating is applied at takeoff and climb only and not at cruise. This assumption minimizes effects on aircraft speed and block time.

Takeoff power levels applicable with each rating scheme are shown in Figure 47 versus ambient air temperature (TAMB). Climb power follows a similar pattern. These power differences correlate with severity of operation and therefore with maintenance costs. Figure 48 shows relative maintenance cost of the baseline engine at 100% size with no derating. The solid line shows the favorable effect of derating this engine. The hatched zone shows that the smaller engine with APR has higher maintenance cost because it runs at higher average power. Derating this engine gives a similar trend in maintenance cost.

The net effect of engine size, maintenance costs, fuel consumption and block time for each of the rating choices are charted in Tables 44-46.

Derating is clearly to the operator's advantage whenever conditions permit. The results in Table 44 should be interpreted as applying to an average 10% derate. For operator's flying routes where the average derate is lower, the saving would be correspondingly less.

The APR ratings also reduce DOC, but the result is sensitive to maintenance costs. In fact, DOC would increase if maintenance costs were higher than assumed. This is graphically shown by Figure 49 where the range of DOC change with $264/m^3 ($1.00/gal) fuel already straddles zero.

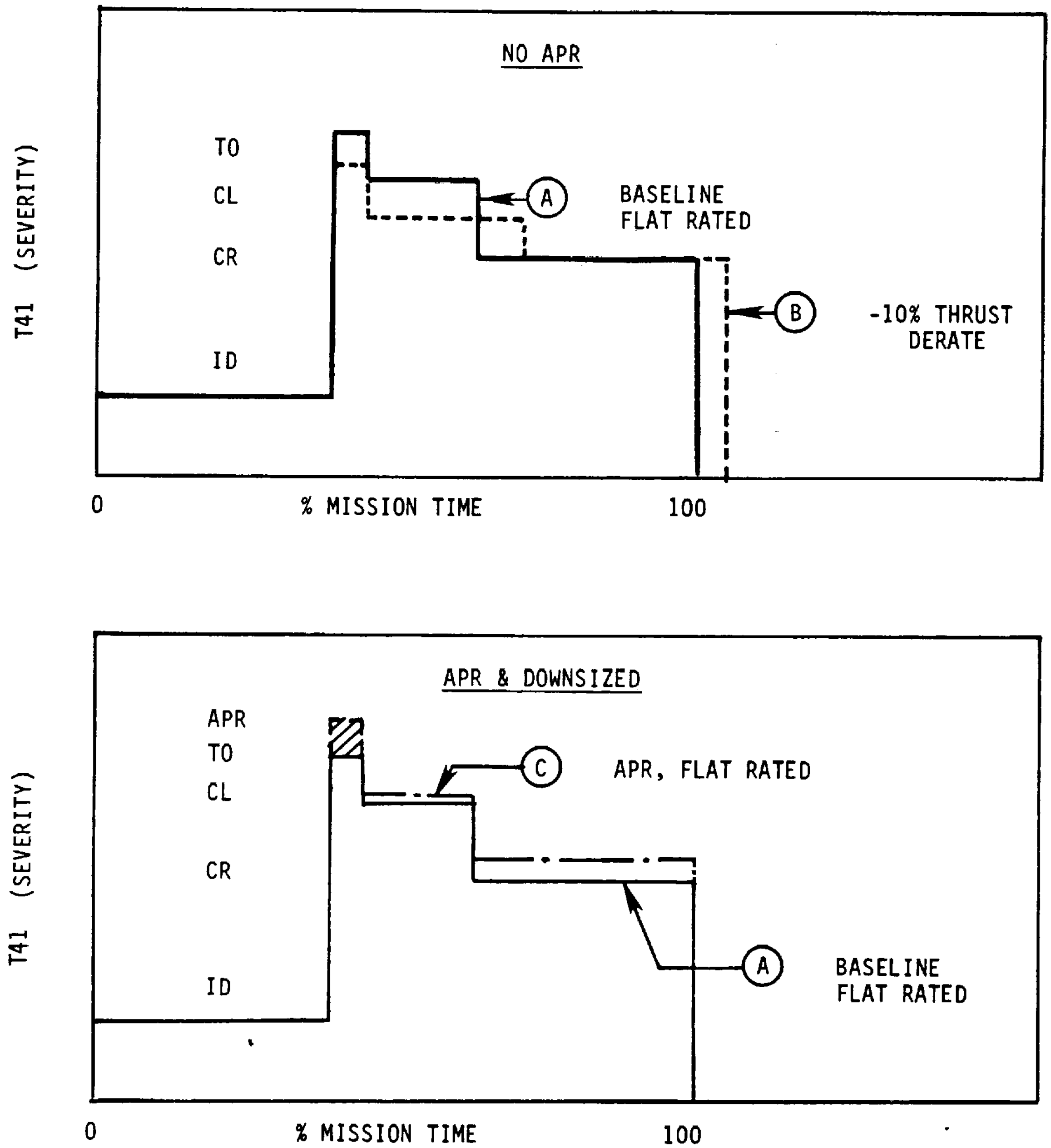


Figure 46. Comparison of Mission Profiles.

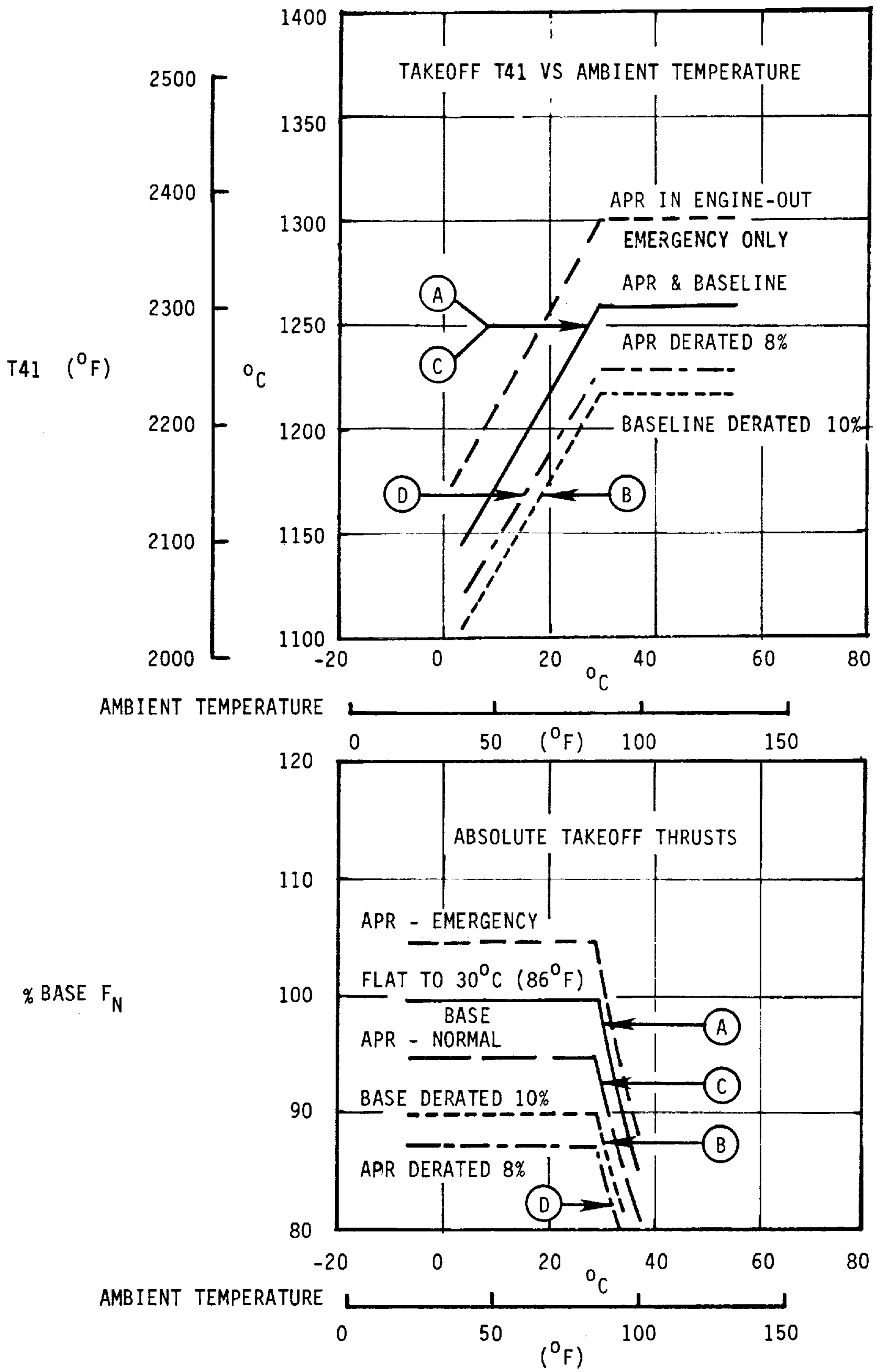


Figure 47. Rating Temperatures and Thrusts.

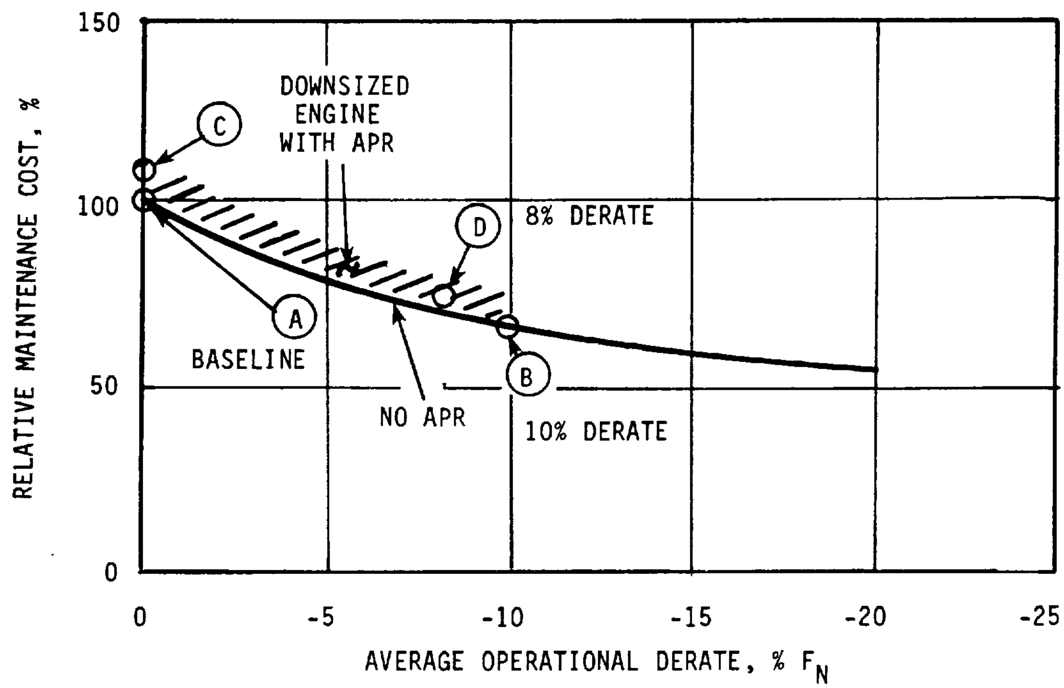


Figure 48. Effect of Ratings and Derate on STAT Maintenance Cost.

TABLE 44

ALTERNATE RATINGS - MISSION MERIT FACTOR RESULTS

10% Derate versus Flat Rating

30-Passenger Aircraft - 185.2 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact: Change in DOC (%) $264/m^3 ($1.00/gal)	Merit Factor Impact: Change in DOC (%) $396/m^3 ($1.50/gal)	Merit Factor Impact: Change in Fuel Burned (%)
Engine Weight - kg (lbm)	0	0	0	0
Engine Price - $1000	0	0	0	-
Engine Maintenance - $/h	-6.90	-2.58	-2.21	-
Fuel Burned	0	0	0	0
Block Time	1.5%	1.0	+.8	-
TOTAL		-1.58	-1.41	0

TABLE 45

ALTERNATE RATINGS - MISSION MERIT FACTOR RESULTS

APR versus Flat Rating

30-Passenger Aircraft - 185.2 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact: Change in DOC (%) $264/m^3 ($1.00/gal)	Merit Factor Impact: Change in DOC (%) $396/m^3 ($1.50/gal)	Merit Factor Impact: Change in Fuel Burned (%)
Engine Weight - kg (lbm)	-5.4 (-12)	-.08	-.09	-.13
Engine Price - $1000	-4.8	-.10	-.08	-
Engine Maintenance - $/h	+1.50 to +2.15	+.56 to +.80	+.48 to .69	-
Fuel Burned	1.22%	-.44	-.55	-1.22
Block Time	0	0	0	-
TOTAL		-.06 to +.18	-.24 to -.03	-1.35

TABLE 46

ALTERNATE RATINGS - MISSION MERIT FACTOR RESULTS

APR + 8% Derate versus 10% Derate

30-Passenger Aircraft - 185.2 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact: Change in DOC (%) $264/m³ ($1.00/gal)	Change in DOC (%) $396/m³ ($1.50/gal)	Change in Fuel Burned (%)
Engine Weight - kg (lbm)	-5.4 (-12)	-.08	-.09	-.13
Engine Price - $1000	-4.8	-.10	-.08	-
Engine Maintenance - $/h	+1.00 to +1.80	+.37 to +.67	+.32 to +.58	-
Fuel Burned	-1.78%	-.61	-.77	
Block Time	-.3%	-.2	-.2	-
TOTAL		-.62 to -.32	-.82 to -.56	-1.91

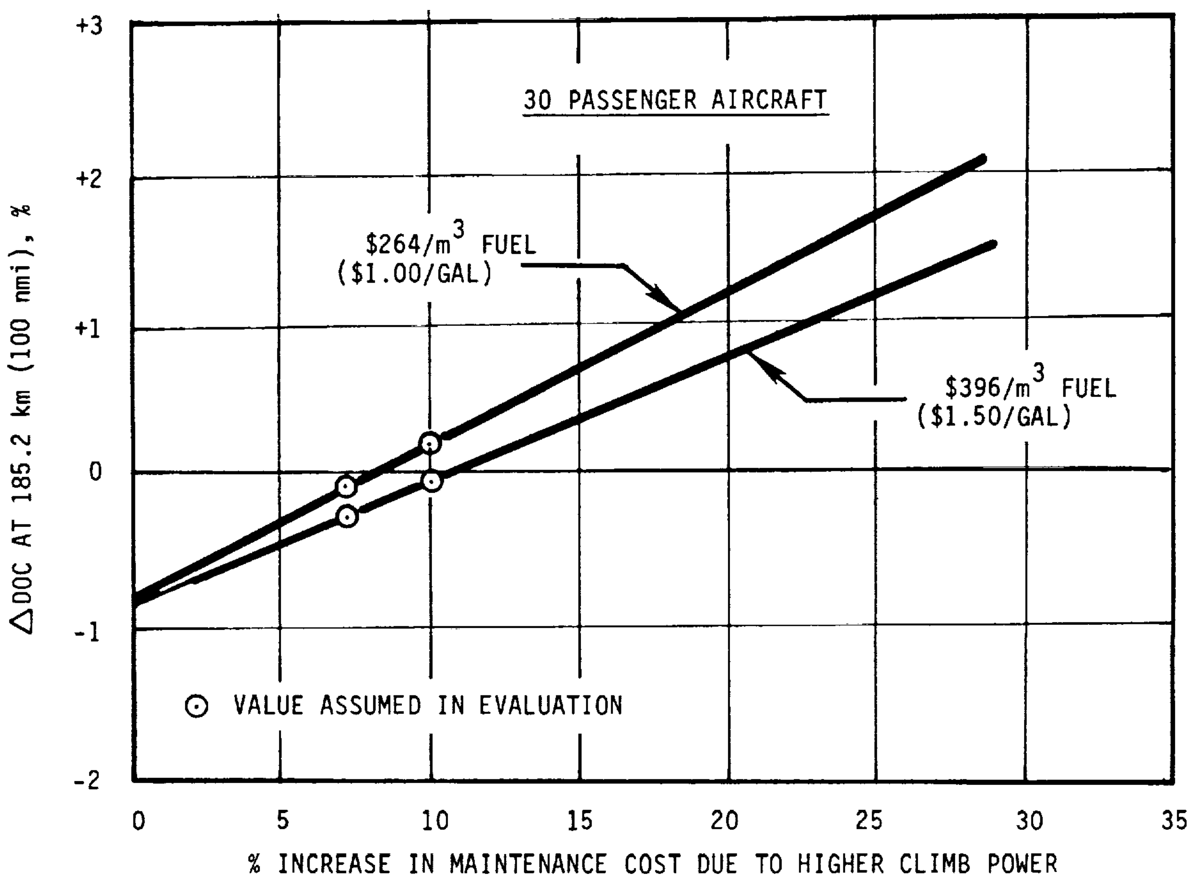


Figure 49. Alternate Ratings - Sensitivity of Downsized APR Engine Maintenance on DOC.

GEARBOX TECHNOLOGY

Gearbox Design

Current and advanced technology gearbox designs appropriate for commuter aircraft have been furnished by Hamilton Standard Division of United Technologies Corporation under subcontract [6,8]. A synopsis of Hamilton Standard's reports are included as Appendix A (pgs 151-158). The two gear trains are shown in Figure 50. The key features of the advanced gearbox are indicated in Table 47. The selected design incorporates four advanced technology features and four design factors not included in state-of-the-art gearbox designs, as follows:

Advanced Technologies	Design Factors
o High Contact Ratio Gearing	o Split Power Gear Train
o Advanced Bearing Materials	o High Filtration
o Advanced Lubricants	o Modular Construction
o Lightweight Housing Material	o On-Condition Maintenance

TABLE 47
HAMILTON STANDARD ADVANCED TECHNOLOGY GEARBOX FEATURES

Feature	Change	Area of Improvement
Gear Train Design	Compound idler system vs offset pinion-bull-star system (6 vs 9 gears).	Efficiency, weight, cost.
Construction	Improved modularity - externally mounted accessories, accessory drive gearbox, lube system components; removable with standard tools.	Maintainability.
Lubricants	Advancements in film strength and viscosity characteristics.	Life.
Filtration	Reduced debris production, finer filtration level.	Life.
Gearing Design	High contact ratio gearing vs conventional tooth profiles.	Weight, noise, and vibration.
Housing	Magnesium vs aluminum.	Weight.
Bearings	Advanced, vacuum melt, high purity steels.	Weight and life.
Operational Procedures	On-condition maintenance vs fixed overhaul intervals.	Maintenance and Cost.

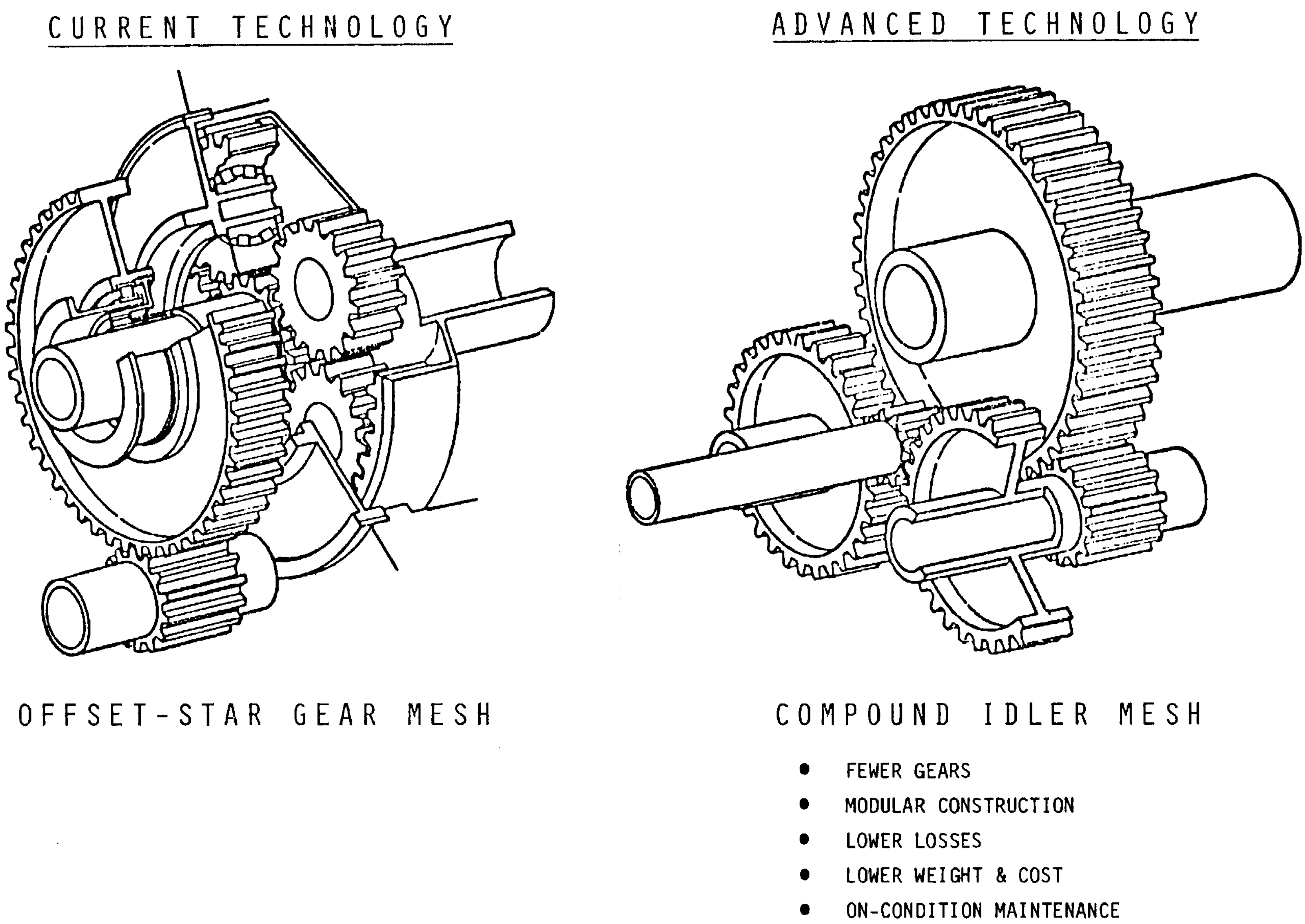


Figure 50. Gearbox Comparison.

GEARBOX TECHNOLOGY - Continued

Important gearbox characteristics as provided by Hamilton Standard are summarized in the Table 48. Weight, cost and maintenance are all assumed to vary directly with maximum continuous gearbox-output torque. Weight and cost are also assumed to vary as $(\text{gear ratio}/15.2)^{.5}$.

TABLE 48
HAMILTON STANDARD DIVISION GEARBOX CHARACTERISTICS

	Current Technology	Advanced Technology
Weight - kg (lbm)	Upper line of Figure 51	Lower line of Figure 51
Price - $/kg ($/lbm)	506 (230)	396 (180)
Maintenance Material at 8508 N·m (6275 ft·lb) torque - $/h	.37	.077
Maintenance labor at 8508 N·m (6275 ft·lb) torque - man·h/h	.021	.0056
Mechanical Efficiency*	.978	.983

*Including accessory drive gearbox and lube pump, but not aircraft accessories.

The current technology gearbox has an assumed Time Between Overhauls (TBO) of 7000 hours (typical of current service) while the advanced technology gearbox has on-condition maintenance assumed. Of the overall maintenance savings, roughly 3/4 is due to advanced technology and design features and 1/4 due to the on-condition assumption. The largest contributions to the maintenance improvement arise from the reduction in the number of gears and bearings, modular construction, and advances in bearings, lubricants, and filtration.

Gearbox Mission Merit Factor Results

To evaluate the advanced technology gearbox, both state-of-the-art and advanced designs were matched to the STAT baseline aircraft, engine, and propeller. Changes in propulsion system weight, cost, maintenance, and performance were calculated for both the 30- and 50-passenger aircraft, and mission sensitivity factors used to estimate the impact on gross weight, mission fuel consumption and DOC. Table 49 summarizes the results. The net result of the advanced technology gearbox is a savings of 1% in fuel and 1.2% in DOC for the 30-passenger aircraft, 1.3% fuel and 1.7% DOC in the 50-passenger.

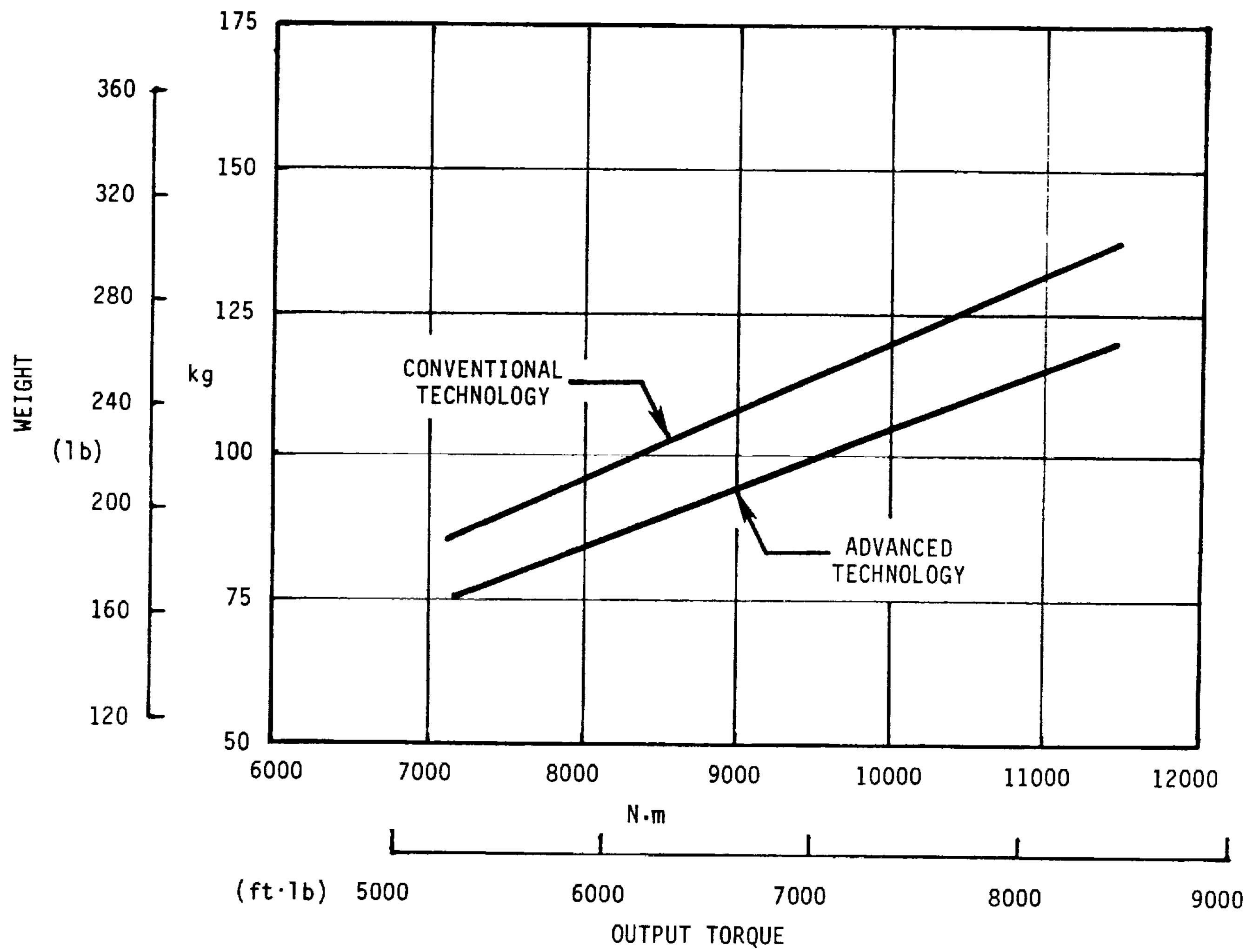


Figure 51. Gearbox Weight Generalization.

TABLE 49

ADVANCED GEARBOX - MISSION MERIT FACTOR RESULTS

30-Passenger Aircraft - 185.2 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact: Change in DOC (%) $264/m^3 ($1.00/gal)	Change in DOC (%) $396/m^3 ($1.50/gal)	Change in Fuel Burned (%)
Gearbox Weight - kg (lbm)	-16 (-36)	-.2	-.3	-.4
Gearbox Price - $1000	-21	-.4	-.3	
Gearbox Maintenance - $/h	-.62	-.2	-.2	
Gearbox Efficiency* - %	+.5	-.4	-.4	-.6
TOTAL		-1.2	-1.2	-1.0

50-Passenger Aircraft - 185.2 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact: Change in DOC (%) $264/m^3 ($1.00/gal)	Change in DOC (%) $396/m^3 ($1.50/gal)	Change in Fuel Burned (%)
Gearbox Weight - kg (lbm)	-34 (-76)	-.4	-.4	-.6
Gearbox Price - $1000	-45	-.6	-.6	
Gearbox Maintenance - $/h	-1.29	-.3	-.2	
Gearbox Efficiency* - %	+.5	-.4	-.5	-.7
TOTAL		-1.7	-1.7	-1.3

*Includes performance and scaling effects.

PROPELLER TECHNOLOGY

All data relative to both conventional and advanced technology propellers were obtained from reports prepared for the STAT program under contract to NASA by Hamilton Standard Division, United Technologies Corporation[5,9]. Extracts from these reports are incorporated as Appendix B (pgs 159-175).

Propeller Selection

The propeller data provided by Hamilton Standard Division covers a range of propeller designs appropriate to the commuter turboprop mission. General Electric's choice of a low speed (0.45 Mach cruise) baseline aircraft dictated the choice of a conventional, low flight speed propeller rather than a prop-fan or high flight speed propeller (see pgs 23-24). For this type, performance over a range of blade activity factors and integrated lift coefficients is available for 3- and 4-bladed propellers.

In selecting a propeller for the STAT mission analysis, it was desired to choose one that was near the optimum for the application, without doing an exhaustive study of all the possibilities. To this end, a propeller in the mid range of the data provided was selected as a base, and the impact on DOC at 185.2 km (100 nmi) of variations in number of blades, activity factor, lift coefficient, tip speed, and power loading was estimated. As a result of this study, a 228.6 m/s (750 ft/sec) tip speed, 4-bladed propeller was selected with a 100 activity factor and 0.55 lift coefficient. Its power loading (power/D^2) at 90°F day takeoff conditions is approximately 80 kW/m^2 (10 hp/ft^2).

This selected propeller design was used throughout the study to provide consistency between current, derivative, and advanced powerplants.

Following completion of the technical effort on this study by General Electric, further input relative to propeller selection and advanced technology payoff was received from Hamilton Standard via NASA. That material is covered in Appendix D (pgs 201-202).

Propeller Characteristics

Performance: Propeller performance, in the non-dimensional form of net thrust coefficient (CT_{net}) versus power coefficient (C_p) and advance ratio (J) was provided by Hamilton Standard in tabular form. For a given propeller design, this basic performance characteristic is identical for conventional and advanced technology. For the advanced technology propeller, performance may be modified by the addition of blade tip sweep or blade tip airfoils ("proplets"). Blade tip sweep can eliminate compressibility losses, but is generally not necessary to improve the propeller performance for low speed airplanes. The major benefit of sweep is to effect relative Mach numbers which are below the critical Mach numbers of the airfoil sections. The addition of blade tip proplets provides a performance improvement of varying magnitude over most regimes of propeller operation. A correction to CT_{net} as a function of C_p and J has been provided. (See Appendix B, for a detailed description of the performance calculation procedure.)

PROPELLER TECHNOLOGY - Continued

Weight: Generalized weight equations are shown below for both conventional and advanced propellers. The addition of proplets increases the weight 5%.

For the single acting, solid aluminum conventional technology propeller,

$$Wt = KW\left[\left(\frac{D}{10}\right)^{2}\left(\frac{B}{4}\right)^{0.7}\left(\frac{AF}{100}\right)^{0.7}\left(\frac{ND}{20000}\right)^{0.4}\left(\frac{SHP}{10D^{2}}\right)^{0.12}(M+1)^{0.5}\right]+CW$$

where
$$CW=\left[5\left(\frac{D}{10}\right)^{2}\left(\frac{B}{4}\right)\left(\frac{AF}{100}\right)^{2}\left(\frac{20000}{ND}\right)^{0.3}\right]$$

For the advanced technology, double acting propeller,

$$Wt = KW\left[\left(\frac{D}{10}\right)^{2}\left(\frac{B}{4}\right)^{0.7}\left(\frac{AF}{100}\right)^{.75}\left(\frac{ND}{20000}\right)^{0.5}\left(\frac{SHP}{10D^{2}}\right)^{0.12}(M+1)^{0.5}\right]$$

where: Wt = propeller weight, lb

CW = counterweights weight, lb

D = propeller diameter, ft

B = number of blades

AF = blade activity factor

N = propeller speed, rpm (takeoff)

SHP = shaft horsepower, hp (takeoff)

M = Mach number at max power cruise

KW = 220 for conventional aluminum blades

= 215 for advanced aluminum blades

= 159 for advanced composite blades

Note that in these equations, if the propeller design is held constant (i.e., constant activity factor, number of blades, tip speed, power loading), the weight is directly proportional to D^2 and therefore to SHP since SHP/D^2 is held constant. Thus, in the mission analysis, propeller weight is varied directly as power.

Price: OEM propeller price is calculated as:

$$PR= CZ\ (3B^{0.75} + 3.5)$$

where: PR= OEM price, $/lb

C = 6.7 for single acting, conventional technology, aluminum blades

= 8.8 for double acting, advanced aluminum blades

= 16 for double acting, advanced composite blades

PROPELLER TECHNOLOGY - Continued

B = No. of blades

Z = learning curve factor

= 0.48 for assumed production rate of 100 units per year.

Proplets increase the cost by 10%.

Maintenance: An on-condition maintenance philosophy was assumed for both conventional and advanced technology propellers. The total maintenance costs are (expressed as dollars per flight hour per $1000 of OEM price) 0.015 for the conventional propeller and 0.036 for the advanced composite propeller. No maintenance cost estimate is available for the advanced technology, aluminum propeller, but it is expected to be only slightly higher than for the conventional aluminum.

Advanced Propeller Technology Evaluation

Various advanced technology propeller features were evaluated based on their impact on DOC at 185.2 km (100 nmi) in the same way that advanced technology engine features were.

Blade tip sweep was eliminated from consideration because the selected design did not have any performance losses due to compressibility effects at any of the STAT baseline mission flight conditions.

The advanced, aluminum, double acting pitch change propeller was evaluated against the conventional, aluminum, single acting propeller. Although the maintenance cost of the double acting aluminum blade is not available, it is expected to be similar to that of the single acting conventional, aluminum airfoil and less than that of the double acting, advanced, composite design (i.e., between 0.015 and 0.036 dollars per flight hour per $1000 of OEM price). Table 50 presents the evaluation results for the 30-passenger aircraft size.

An evaluation of composite versus aluminum airfoils was made with the same maintenance cost assumption. Several composite blade configurations are under consideration by Hamilton Standard, including fabricated metal spars, hollow spars of Boron and aluminum, resin-matrix spars, and composite shells of materials such as carbon or Kevlar. The cost, weight, and maintenance estimates are expected to be representative of a final, production design. Table 51 shows the result of the evaluation of composite blades.

The addition of blade tip proplets improves the performance of the propeller, thereby allowing the entire propulsion system to be scaled down while meeting the same thrust requirements. The impact of this size reduction on engine and gearbox price and weight overrides the inherent propeller price and weight increases due to proplets, resulting in a net savings (Table 52).

Based on the results detailed here, a composite airfoil design with proplets and a double acting pitch change mechanism was selected as the advanced propeller.

TABLE 50

ADVANCED PROPELLER - MISSION MERIT FACTOR RESULTS

Aluminum Blade, Double Acting versus Single Acting Pitch Change

30-Passenger Aircraft - 185.2 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact: Change in DOC (%) $264/m^3 ($1.00/gal)	$396/m^3 ($1.50/gal)	Change in Fuel Burned (%)
Propeller Weight - kg (lbm	-12.7(-28)	-.18	-.20	-.31
Propeller Price - $1000	+2.7	+.05	+.05	-
Propeller Maintenance - $/h	+.04 to +.38	+.01 to +.14	+.01 to +.12	-
Propeller Efficiency - %	0	0	0	0
TOTAL		-.12 t0 +.01	-.14 to -.03	-.31

TABLE 51

ADVANCED PROPELLER - MISSION MERIT FACTOR RESULTS

Composite Blade vs Aluminum Blade, Double Acting Pitch Change

30-Passenger Aircraft - 185.2 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact: Change in DOC (%) $264/m^3 ($1.00/gal)	$396/m^3 ($1.50/gal)	Change in Fuel Burned (%)
Propeller Weight - kg (lbm)	-38 (-83)	-.52	-.59	-.91
Propeller Price - $1000	+5.6	+.11	+.10	-
Propeller Maintenance - $/h	+.20 to +.54	+.07 to +.20	+.06 to +.17	-
Propeller Efficiency - %	0	0	0	0
TOTAL		-.36 to -.21	-.43 to -.32	-.91

TABLE 52
ADVANCED PROPELLER - MISSION MERIT FACTOR RESULTS

Proplets

30-Passenger Aircraft - 185.2 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact: Change in DOC (%) $264/m^3 ($1.00/gal)	Change in DOC (%) $396/m^3 ($1.50/gal)	Change in Fuel Burned (%)
Propeller Weight - kg (lbm)	+5.4(+12)	+.08	+.09	+.13
Propeller Price - $1000	+3.4	+.07	+.06	-
Propeller Maintenance - $/h	+.12	+.04	+.04	-
Propeller Efficiency* - %	+1.2	-.87	-.98	-1.64
Total		-.68	-.79	-1.51

*Includes performance and scaling effects.

Propeller Mission Merit Factor Results

To evaluate the overall impact of the advanced technology propeller, both current technology and advanced technology propellers were matched to the STAT baseline aircraft, engine, and gearbox. Changes in propulsion system weight, performance, and economics were calculated for both the 30- and 50-passenger aircraft, and mission sensitivities used to estimate the savings in weight, fuel, and operating cost. Table 53 shows the results. In the 30-passenger aircraft, the advanced propeller saves 1.0 to 1.3% DOC and 2.7% fuel. In the 50-passenger, the savings are 1.3 to 1.6% DOC and 3.0% fuel.

TABLE 53
ADVANCED PROPELLER - MISSION MERIT FACTOR RESULTS

30-Passenger Aircraft - 185.2 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact: Change in DOC (%) $264/m^3 ($1.00/gal)	Change in DOC (%) $396/m^3 ($1.50/gal)	Change in Fuel Burned (%)
Propeller Weight - kg (lbm)	-45 (-99)	-.6	-.7	-1.1
Propeller Price - $1000	+12	+.2	+.2	-
Propeller Maintenance - $/h	+.70	+.3	+.2	-
Propeller Efficiency* - %	+1.2	-.9	-1.0	-1.6
Total		-1.0	-1.3	-2.7

*Includes performance and scaling effects.

TABLE 53 - Continued

ADVANCED PROPELLER - MISSION MERIT FACTOR RESULTS

50-Passenger Aircraft - 185.2 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact: Change in DOC (%) $264/m^3 ($1.00/gal)	$396/m^3 ($1.50/gal)	Change in Fuel Burned (%)
Propeller Weight - kg (lbm)	-73(-161)	-.8	-.9	-1.3
Propeller Price - $1000	+19	+.3	+.2	-
Propeller Maintenance - $/h	+1.14	+.3	+.2	-
Propeller Efficiency* - %	+1.2	-1.1	-1.18	-1.7
Total		-1.3	-1.6	-3.0

*Includes performance and scaling effects.

Noise

The subject of fuselage acoustic treatment for interior noise control, the associated aircraft weight penalty, and the potential benefits of advanced technology propeller systems is one which requires a considerable degree of further analysis. The advanced technology powerplant benefits would be increased if noise reduction features such as synchrophasers were taken into account. The approach taken here has been to treat noise as a separate issue and try to estimate its potential impact on the STAT aircraft and their operating economics independently of the more easily determined performance, weight, and cost influences.

Far-field noise is not expected to present a problem. The propeller tip speed selected for this study (228.6 m/s) (750 ft/sec) is representative of what is being used in modern commuter applications (the SAAB/Fairchild SF-340, for example) and of the tip speeds selected by the STAT airframe contractors. Far-field noise level estimates for the STAT advanced propellers are compared in Table 54 to the STAT requirements (FAR36-8 EPNdB). Both the 30- and 50-passenger aircraft meet all requirements. All noise calculations have been done using the procedures provided by Hamilton Standard, which assume propeller noise dominates aircraft and engine noise.

Hamilton Standard Division's studies of cabin interior noise have shown significant DOC payoffs for reduced source noise. Their studies have indicated, for example, that precision synchrophasing in the 30-passenger aircraft can reduce source noise by 6 to 8 dB, fuselage weight by over 272 kg (600 lb), and DOC by over 2%, at a cost of $5000 per engine. (The weight and cost impact on DOC is consistent with General Electric's baseline sensitivities.)

PROPELLER TECHNOLOGY - Continued

The benefit is highly sensitive to the assumed baseline acoustic treatment weight and the assumed tradeoff between noise and weight. The 30-passenger baseline aircraft used in this study contains 272 kg (600 lb) of acoustic treatment weight in total, against 383 kg (844 lb) in the baseline used by Hamilton Standard. Based on Reference 4, it is estimated that a propeller noise reduction of 10 dB could save on the order of 1% TOGW in acoustic treatment on the General Electric 30-passenger baseline aircraft. A 10 dB reduction is a reasonable estimate of the total obtainable with tip sweep and synchro phasing, and the weight saving translates into a 1% DOC saving also.

See Appendix D (pgs 199-200) for more details of Hamilton Standard's results.

TABLE 54
FAR FIELD NOISE LEVELS

	Takeoff	Approach	Sideline
Altitude - m (ft)	914 (3000)	122 (400)	0 (0)
True Air Speed - m/s (Knots)	59.2 (115)	63.3 (123)	59.2 (115)
Power Setting	Takeoff	40% Max Climb	Takeoff
Noise Limit, EPNdB (FAR-36 Limit-8)	81	90	86
Adv 30-Passenger T/P Noise Level, EPNdB	80.5	89.0	86.0
Adv 50-Passenger T/P Noise Level, EPNdB	80.0	88.5	85.5

RECOMMENDED ADVANCED ENGINES

Cycle Selection

The 30-passenger aircraft DOC trends of Figure 16 (pg 38) show only a small payoff for increasing either pressure ratio or T41 beyond the nominal, 17:1, 1260°C (2300°F) cycle. The magnitude of the payoff is not considered sufficient to overcome the increased development cost and higher technical risk likely to be associated with increases in either parameter. Therefore, the nominal advanced cycle was selected for the 30-passenger advanced engine. An increase in T41 or an increase in pressure ratio through use of a low pressure compressor stage may be held in reserve for power growth, with the assurance that the growth cycle will provide improved operating economics.

Figure 17 (pg 39) shows somewhat greater improvements in DOC for the 50-passenger aircraft for increases in pressure ratio and T41. Here a somewhat more complicated engine was selected; a single compression stage was added to the output shaft of the nominal cycle to bring the pressure ratio to 20:1, and T41 was increased 56° to 1316°C (100° to 2400°F). A growth scenario for this cycle may be envisioned wherein a second booster stage and/or T41 increase is used to obtain more power.

Advanced Technology Selections

Based on the DOC and fuel burned results shown in the Table 20 (pg 48), the advanced technology items of Table 55 were incorporated in the advanced engine designs. All items except the advanced high-pressure turbine blade were included in both engine sizes. None of the turbine blade concepts shows a DOC payoff in the 30-passenger cycle. In the 1316°C (2400°F), 50-passenger cycle, the impingement cooled ("cold bridge") blade shows a slight loss in DOC at $264/m^3 ($1.00/gallon) fuel, and breaks even at $396/m^3 ($1.50/gallon). Because it offers a significant fuel savings (1%) it has been included in the 50-passenger engine.

TABLE 55
SUMMARY OF TECHNOLOGY PAYOFF ITEMS FOR ADVANCED ENGINES

Compressor	Highly loaded axial stages.
	Multiblade centrifugal impeller.
	Advanced centrifugal diffuser.
	Closed loop accel schedule and reduced stall margin
Combustor	Thermal barrier coating.
HP Turbine	Active clearance control.
	Advanced cooled blade*.
LP Turbine	Integrally cast blisks.
	Metal matrix shaft.

*50-passenger size engine only.

RECOMMENDED ADVANCED ENGINES - Continued

Advanced Engine Descriptions

All the design work on the advanced engines was done in a size calculated to match the power of the baseline power plants in the baseline mission analysis. (See Table 5, pg 14.) This will be referred to hereafter as the "design size" of the advanced engines. The improvements in power plant characteristics result ultimately in a lighter aircraft requiring somewhat smaller powerplants. The final advanced engines required to perform the mission will be referred to as "mission size".

Preliminary designs were carried out on the aerodynamic components of the selected advanced engines. The 30-passenger engine has a 3 axial + 1 centrifugal stage compressor driven by a single stage high-pressure turbine. The cycle pressure ratio is 17 to 1, resulting in a high-pressure turbine pressure ratio of 4.2, which is considered the practical limit that can be obtained with a single stage turbine. The low-pressure turbine is a two stage, counter-rotating design.

The 50-passenger engine utilizes the same core design as the 30-passenger engine, scaled up as necessary. A single, axial compressor stage ("booster") is added to the output shaft, driven by the low-pressure turbine. The booster and core are matched such that the HP turbine pressure ratio is approximately 4.2. The low-pressure turbine in this engine is also counter-rotating, and has three stages.

Tables 56-57 provide cycle and performance summaries of the advanced engines. Advanced engine performance in terms of equivalent power and fuel flow vs. altitude, Mach number, ambient temperature and power setting is provided in Appendix C (pgs 177-197).

TABLE 56
ADVANCED, 30-PASSENGER SIZE ENGINE CYCLE - SEA LEVEL, STATIC

(No Inlet Protection)

Ambient Temperature	°C (°F)	15 (59)	32.2 (90)
Power Setting		Takeoff*	Takeoff
Turbine Inlet Temp.	°C (°F)	1260 (2300)	1260 (2300)
Cycle Pressure Ratio		17.0	15.3
Output Power	kW (hp)	1107 (1485)	943 (1265)
Specific Fuel Consumption	kg/kW·h (lbm/hp·h)	.267 (.439)	.278 (.457)
Inlet Corrected Flow	kg/s (lbm/sec)	3.55 (7.8)	3.28 (7.2)
Inlet Flow	kg/s (lbm/sec)	3.55 (7.8)	3.18 (7.0)

*Data in this column, at full rated turbine inlet temperature on a standard day, is provided for reference only. The engine is intended to be flat rated to 30°C (86°F).

TABLE 57

ADVANCED, 50-PASSENGER SIZE ENGINE CYCLE - SEA LEVEL, STATIC

(No Inlet Protection)

Ambient Temperature	°C (°F)	15 (59)	32.2 (90)
Power Setting		Takeoff*	Takeoff
Turbine Inlet Temp.	°C (°F)	1315.6 (2400)	1315.6 (2400)
Cycle Pressure Ratio		20.2	17.6
Output Power	kW (hp)	1831 (2455)	1510 (2025)
Specific Fuel Consumption	kg/kW·h (lbm/hp·h)	.252 (.415)	.265 (.435)
Inlet Corrected Flow	kg/s (lbm/sec)	5.35 (11.8)	4.82 (10.6)
Inlet Flow	kg/s (lbm/sec)	5.35 (11.8)	4.68 (10.3)
Core Corrected Flow	kg/s (lbm/sec)	4.23 (9.3)	3.96 (8.7)

*Data in this column, at full rated turbine inlet temperature on a standard day, is provided for reference only. The engine is intended to be flat rated to 30°C (86°F).

The mechanical designs of the two STAT engines for 30-passenger and 50-passenger aircraft are based on advanced turboshaft engine concepts currently under study by General Electric. Except as noted, the following descriptions apply to both engines. Cross-sections of the 2 engines are shown in Figures 52-53. For comparison, the cross-section of the base CT7-5 engine scaled to the same relative power has been added. The advanced engines are two-sump, two-frame, dual rotor designs, with counter-rotating shafts. The HP spool is supported on two bearings and the LP shaft on three bearings. Mounting of the engine is accomplished by two front mounts cast integrally with the aluminum front frame and one aft mount on the rear frame. Individual components use advanced technology features obtainable by the mid 1980's.

Special attention has been given to simple construction and ease of maintenance. This is reflected in the low maintenance cost and in a reduction in the total number of engine parts. Compared to the CT7-5 engine, the 30-passenger engine has 27% fewer parts and the boosted 50-passenger engine has 11% fewer engine parts. (Also see Figure 54.) No inlet protection system is currently shown, as discussed earlier (see pgs 7 and 87), although one may be required regardless of cost to satisfy FAA ingestion test requirements.

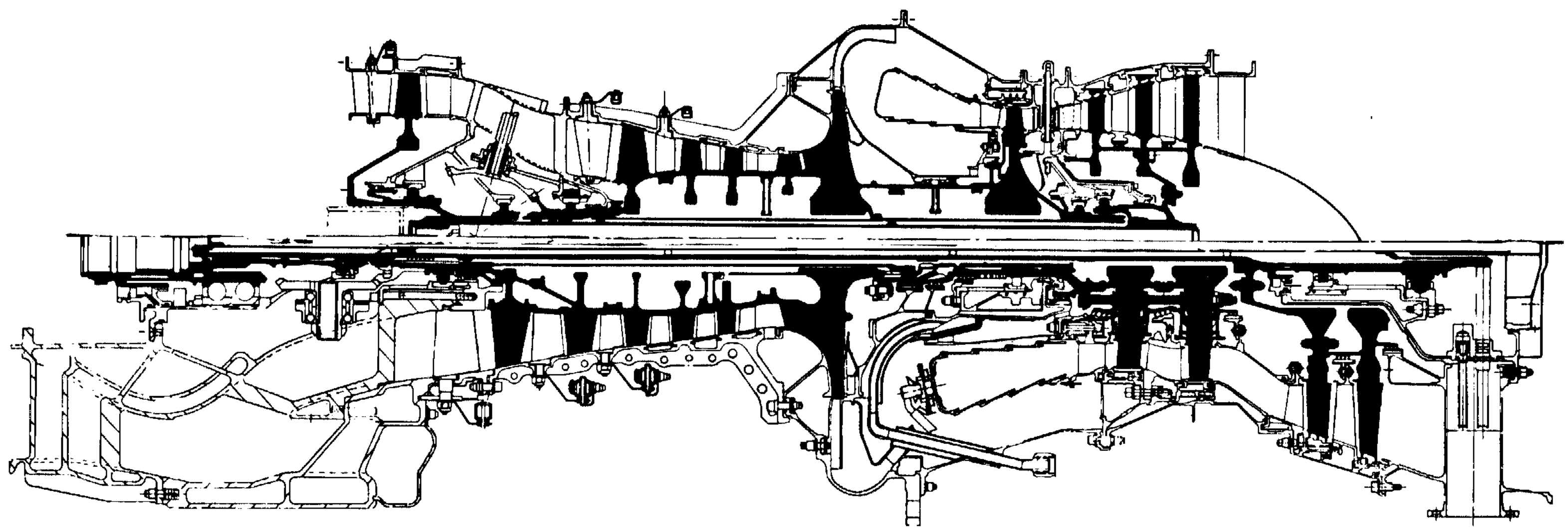


Figure 52. CT7 Base Engine Compared to 50-Passenger Advanced Turboshaft Engine Scaled to Equal SHP.

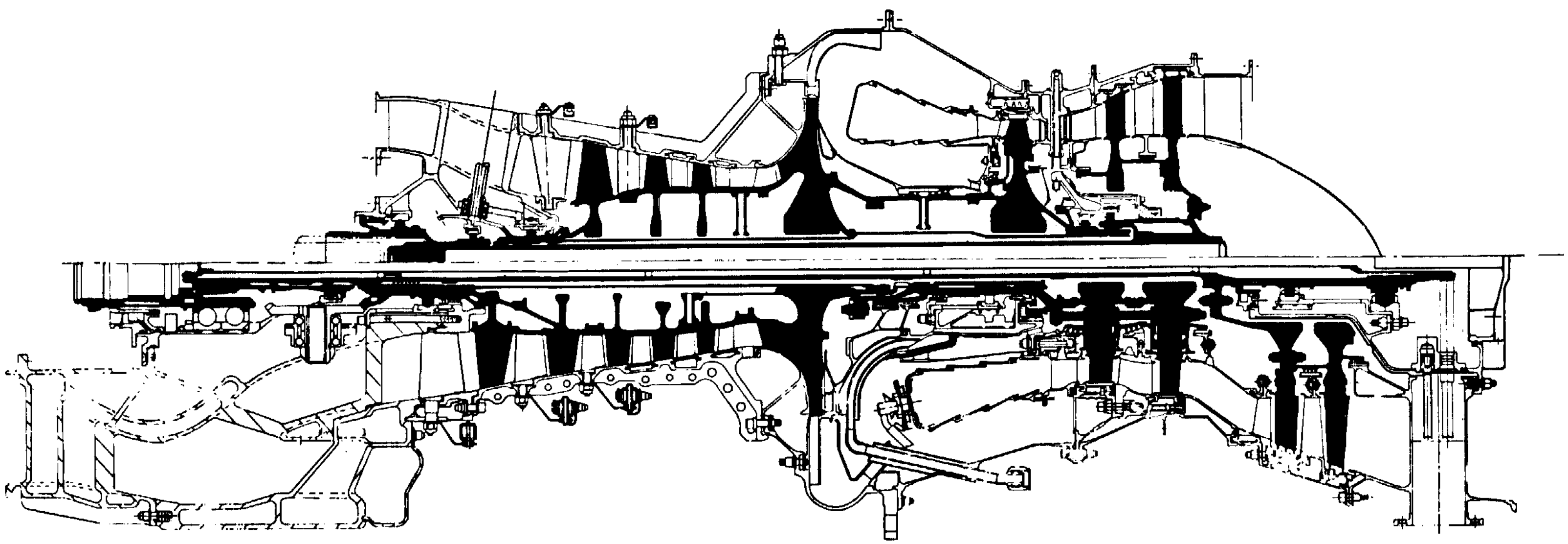


Figure 53. CT7 Base Engine Compared to 30-Passenger Advanced Turboshaft Engine Scaled to Equal SHP.

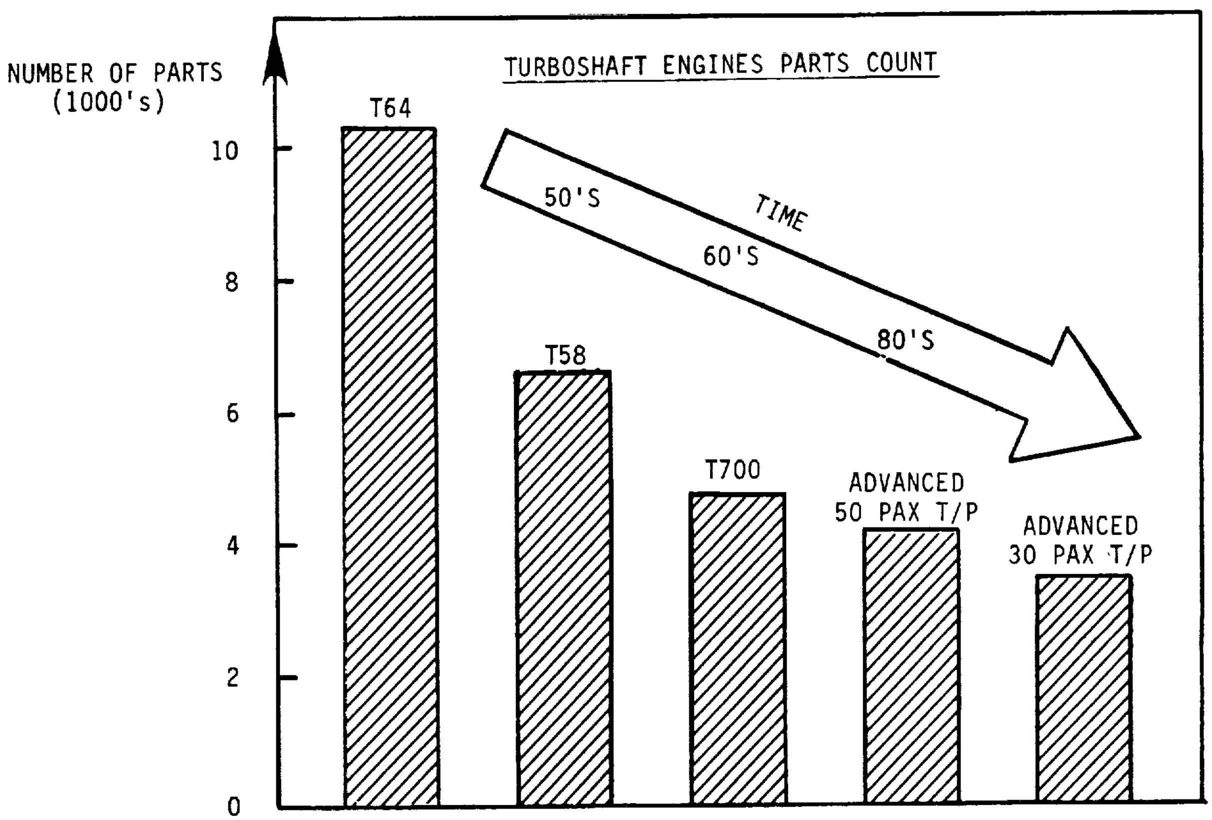


Figure 54. Reduction of Parts Count Through Design Simplicity.

RECOMMENDED ADVANCED ENGINES - Continued

The compressor has three axial stages and one centrifugal stage. The axial stages have highly loaded, low aspect ratio, high speed airfoils [472.4 m/s (1550 ft/sec) tip speed]. Blades and disks are cast integrally in Custom 450 material. Stages 2 and 3 are cast as a unit, and the remaining stages are single blisks. The centrifugal impeller is a multibladed Inconel 718 casting (split into inducer and impeller blades) allowing a better aerodynamic match than possible with continuous blades. All stages have curvic couplings and are connected by a central tie bolt. Inlet guide vanes and Stage 1 vanes are variable and made of A286. Stages 2 and 3 vanes are fixed and are made up of cast Inconel 718 segments.

The centrifugal compressor diffuser is of the advanced "trumpet" design, replacing the more conventional "dump" diffuser. After passing through a radial diffuser ring, the air is turned axially in a number of individual passages (trumpets) made of thin-wall plasma sprayed Inconel 718. Excellent finish on the flowpath surface guarantees a high diffuser efficiency.

The aero-thermo design of the combustor is based on the CT7-5 configuration, discussed in the CT7-5 Baseline Engine section (pg 7). For improved life and lower maintenance cost, thermal barrier coating and local impingement cooling shields have been added.

The HP turbine is a single stage high-pressure ratio design similar to the General Electric F101 engine (B1 bomber) design. Blades and disk rim are cooled with compressor discharge air. Turbine blade cooling is achieved by convection through radial holes for the 30-passenger engine, and by a "cold bridge" convection plus impingement plus film cooling design for the 50-passenger engine. The rotor disk is made of direct aged Inconel 718, the blades are cast Rene' 125 and the nozzle assembly is an Inconel 713 casting. A through-bolt curvic coupling design allows for ease of assembly and maintenance.

The aero design for the LP turbine is a 2-stage (3-stage for 50-passenger aircraft engine) turbine with a turbine midframe. The frame has struts with compressor discharge air cooled flowpath walls and service tubes. Surfaces exposed to hot gases are protected by a thermal barrier coating. Special "flexlink" attachment of the struts allows radial thermal growth while still providing axial stiffness. All rotor stages are integrally cast Inconel 792 blisks with shrouded airfoils. This configuration has both a cost and weight advantage over the conventional blade/disk configuration. An additional weight advantage is obtained by using a metal matrix composite shaft.

Controls and accessories are bottom-mounted off the front frame. They are similar to those currently on the CT7-5 engine except for the change to a FADEC. Use of a FADEC will allow optimum control of compressor operating line with additional payoffs through the capacity to schedule active clearance control and provide input for the diagnostic data and history recorder.

RECOMMENDED ADVANCED ENGINES - Continued

Weight, Price and Maintenance Trends

The design size weight of the 30-passenger aircraft engine including accessories and margin has been calculated to be 141 kg (310 lbm) and of the boosted 50-passenger aircraft engine to be 193 kg (425 lbm). Trend curves and comparison to the current CT7-5 (with and without inlet foreign object protection) are shown in Figure 55. Also shown is a boosted CT7 derivative engine. The boosted 50-passenger aircraft engine shows a slight weight advantage (approximately 7% at the same airflow size) over the 30-passenger aircraft engine, but both engines are very close to CT7 characteristic without inlet protection. However, when compared at the same power, they show a 12% to 15% weight advantage over the CT7 due to improved component performance.

Figure 56 shows a price comparison of the same four engines. Prices of all engines are based on 1979 dollars and are for an assumed total production quantity of 1000 engines. Again, the 50-passenger aircraft engine is slightly better than the 30-passenger engine, and both are approximately 7% to 10% better than their CT7 counterpart.

Maintenance costs for all four engines are shown in Figure 57. They do not include cost of foreign object protection devices. The model used for estimating the maintenance cost is based on actual experience with commercial engines. First, engine cost is broken down into major components. Then, the material cost over the life of the engine is determined considering the expected replacement rate of each individual part. Next, labor cost is calculated as a percentage of material cost (ranging in value from 20% to 85% depending on accessibility of each part). Finally, the maintenance cost in dollars per engine flight hour is determined by dividing the total of material and labor cost by the projected number of flight hours (i.e., 33,600 hours in 12 years).

Parts replacement rates are based on currently used time between overhauls and could possibly be reduced with the introduction of "On-Condition" maintenance, but this would affect all four engines equally and hence not change their relative position.

In Figures 55-57, the CT7-5 has been adjusted to exclude the foreign object protector and associated parts. The derivative engine characteristics include the addition of a low-pressure compressor and a redesigned low-pressure turbine.

Engine Life and Reliability

The CT7-5 engine life prediction is based on the analysis for the T700 Army Blackhawk engine which has a design life of 5000 hours with 15% (i.e., 750 hours) at maximum turbine inlet temperature. Using an average Army mission mix, this is equivalent to operating for 3 1/2% of total time at 95% to 100% IRP. Compared to this value, the STAT baseline mission is about 10% less severe. Combined with the advanced engine technology concept used for the two STAT engines, this will translate into improved engine life.

The three key measures of reliability are "Shop Visit Rate", "In Flight Shutdowns" and "Unscheduled Engine Removals". Predicted values for the CT7-5 are as follows:

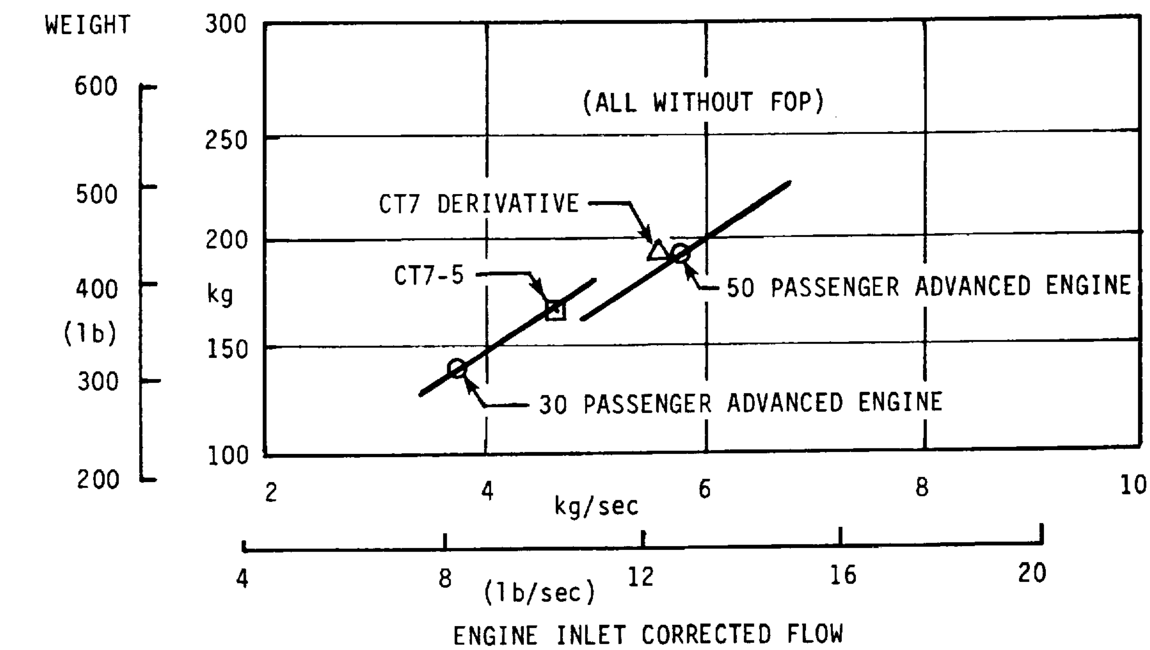


Figure 55. Engine Weight vs Airflow.

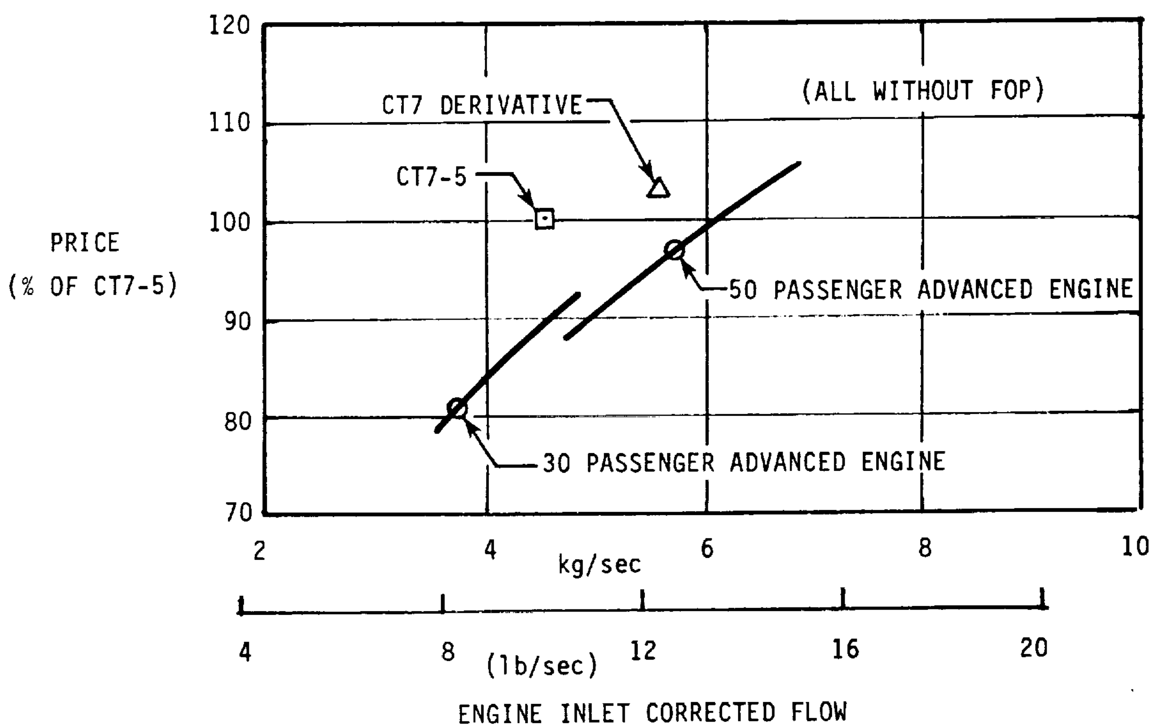


Figure 56. Engine Price vs Airflow.

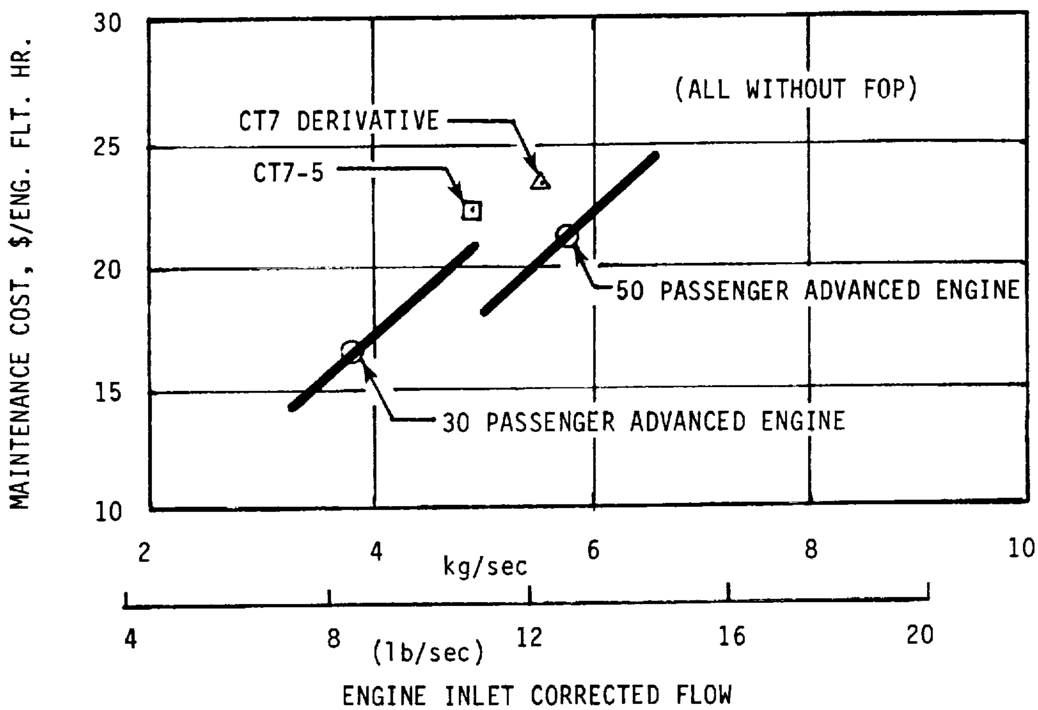


Figure 57. Engine Maintenance Cost vs Airflow.

RECOMMENDED ADVANCED ENGINES - Continued

	Events per 1000 Engine Flight Hours	
	Max Initial	Mature
Shop Visit Rate (on condition maintenance)	0.55	0.45
Unscheduled Engine Removals	0.50	0.12
In Flight Shut Downs	0.18	0.05

These values reflect the advantage obtained from extensive engine flight experience with the T700 engine family prior to service introduction. The advanced STAT engines having a much simpler core and 11% to 25% fewer parts are expected to obtain these objectives at a much earlier stage.

Installation Factors

In performing the mission analysis, it has been assumed for both the conventional and advanced technology engines that aircraft accessory power and cabin conditioning requirements can be met by the extraction of 37 or 56 kW (50 or 75 horsepower) from the propeller gearbox for the 30- and 50-passenger aircraft, respectively. The impact of this power extraction on installed performance is summarized in Table 58.

Although no core engine customer bleed was assumed in the mission analysis, it may at times be required for aircraft anti-icing. Table 59 gives bleed air properties and engine performance effects for bleed extraction at the maximum permissible rate (6.5%) at a representative cruise condition.

TABLE 58
POWER EXTRACTION EFFECTS
Advanced Technology Propulsion System
Power Extracted from Propeller Gearbox

	30-Passenger		50-Passenger	
Power Extraction - kW (hp)	37 (50)	0	56 (75)	0
System Thrust at Takeoff, SLS, 32.1°C (89.8°F)	Base	+3.6%	Base	+3.5%
System Thrust at Max Cruise, 3048 m (10,000 ft)/.45 Mach	Base	+4.5%	Base	+3.6%
TSFC at Avg. Cruise Thrust, 3048 m (10,000 ft)/.45 Mach	Base	-4.0%	Base	-3.4%

TABLE 59

BLEED AIR EXTRACTION EFFECTS AND BLEED AIR PROPERTIES

3048 m (10,000 ft), Mach .45, Standard Day

	Advanced 30-Passenger Turboprop		
Power Setting	Max Cruise	75% Max Cruise	50% Max Cruise
Max W_{Bleed} - kg/s (lbm/sec)	.20 (.43)	.17 (.37)	.14 (.31)
P_{Bleed} - kN/m^2 (lb/in^2)	1,110 (161)	917 (133)	731 (106)
T_{Bleed} °C (°F)	371 (700)	338 (640)	302 (575)
Power Loss at Constant T41 - %	-22%	-	-
SFC Increase at Constant Power - %	-	+8.6	+8.8

Mission Merit Factor Results

To evaluate the overall impact of the advanced technology engine, the baseline and advanced engines were matched to a common propeller and gearbox and scaled to the same thrust at takeoff. Changes in propulsion system weight, performance, and costs were calculated for both aircraft sizes, and mission sensitivities used to estimate the savings in weight, fuel, and operating cost. Tables 60-61 give the results. The advanced engine results in a DOC saving of about 6% in the 30-passenger aircraft and 7.5 to 8% in the 50-passenger aircraft. The corresponding fuel savings are 9% and 13%.

Note that the results of this section and the Gearbox and Propeller sections (Tables 51 and 55), are based on sensitivities, and as such are estimates, which do not give exactly the same total results reported in the Aircraft Benefit Analysis section.

TABLE 60
ADVANCED TECHNOLOGY ENGINE - MISSION MERIT FACTOR RESULTS

30-Passenger Aircraft - 185.2 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact		
		Change in DOC (%)		Change in Fuel Burned (%)
		$264/m³ ($1.00/gal)	$396/m³ ($1.50/gal)	
Engine Weight - kg (1bm) Gearbox Weight* - kg (1bm)	-7.7 (-17) +9.5 (+21)	0	0	0
Engine Price - $1000 Gearbox Price* - $1000	-56 +4	-1.0	-.9	-
Engine Maintenance - $/h Gearbox Maintenance* - $/h	-4.26 +.02	-1.6	-1.4	-
Engine SFC** - %	-8.0	-3.1	-3.9	-8.9
Total		-5.7	-6.2	-8.9

*The gear ratio is higher for the advanced engine, resulting in a heavier, more costly gearbox for the same SHP and thrust.

**Includes performance and scaling effects.

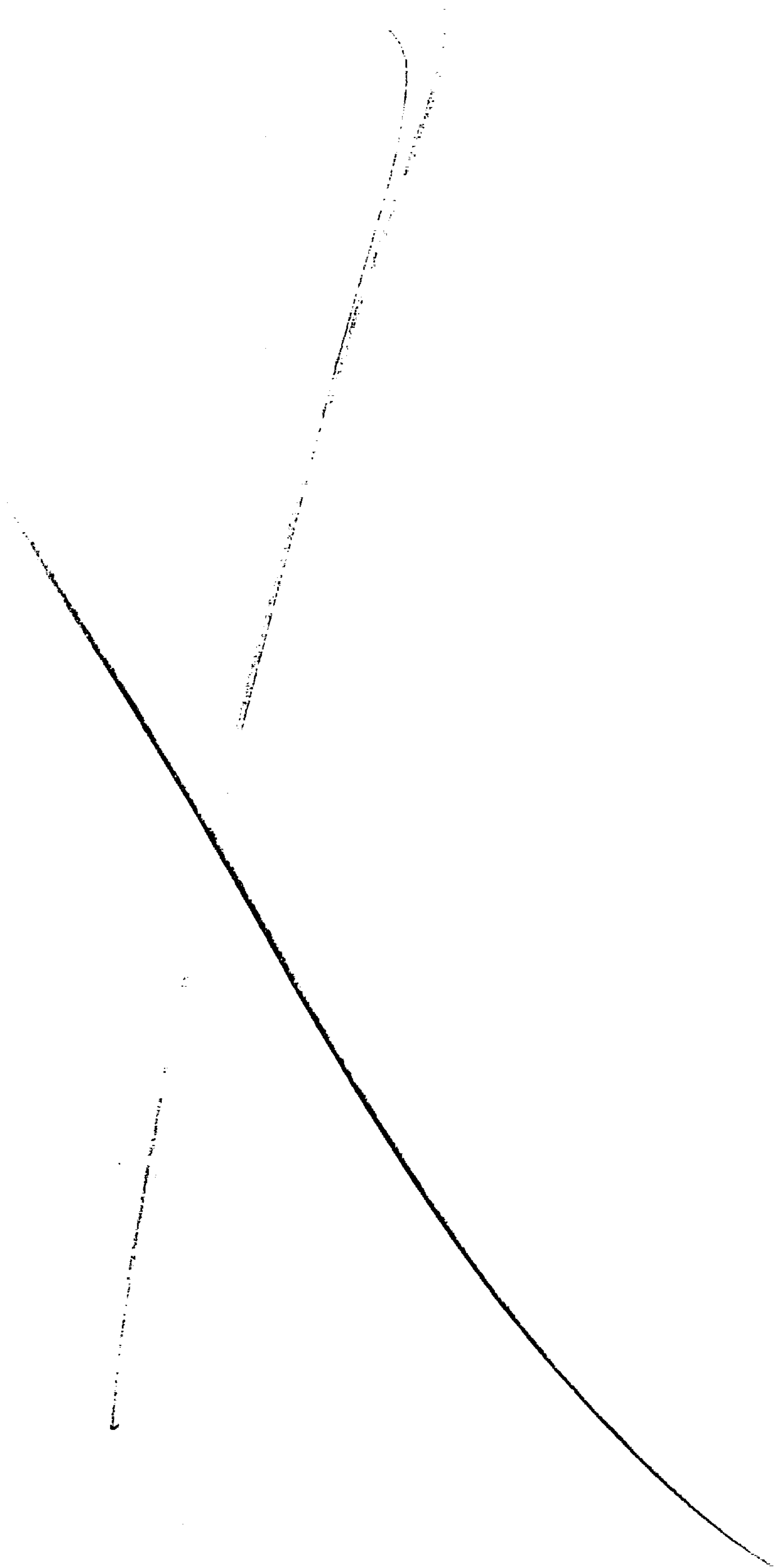
TABLE 61
ADVANCED TECHNOLOGY ENGINE - MISSION MERIT FACTOR RESULTS

50-Passenger Aircraft - 185.2 km (100 nmi) Mission

Parameter	Change	Merit Factor Impact		
		Change in DOC (%)		Change in Fuel Burned (%)
		$264/m³ ($1.00/gal)	$396/m³ ($1.50/gal)	
Engine Weight - kg (1bm) Gearbox Weight* - kg (1bm)	-39 (-86) +22 (+49)	-.2	-.2	-.3
Engine Price - $1000 Gearbox Price* - $1000	-76 +9	-.9	-.8	-
Engine Maintenance - $/h Gearbox Maintenance* - $/h	-4.91 +.04	-1.3	-1.1	-
Engine SFC** - %	-11.1	-5.0	-6.2	-12.5
Total		-7.4	-8.3	-12.8

*The gear ratio is higher for the advanced engine, resulting in a heavier, more costly gearbox for the same SHP and thrust.

**Includes performance and scaling effects.



COMPARATIVE BENEFIT ANALYSIS

CT7 DERIVATIVE ENGINE

The booster stage concept has been demonstrated on a T700 engine. It provides significant power growth at a very small increase in engine weight and cost and with no increase in overall engine dimensions. A boosted version of the CT7 engine is expected to enter service 2 to 3 years later than the CT7-5. The engine selected as a derivative engine for comparison with the current and advanced engines in the STAT baseline aircraft and missions is an example of a possible boosted growth version of the CT7-5. A performance summary is provided in Table 62. A cycle and configuration comparison of the CT7-5, its booster derivative, and the two advanced engines is provided in Tables 63-64 .

At takeoff, the core of the boosted engine operates at 3% higher speed and 55.6% (100°F) higher T41 than the basic CT7. To accommodate this increased severity with durability equivalent to the basic CT7, HP turbine cooling flow is increased, the HP turbine blade material is changed, the core rotating components are modified to accommodate the increased speed, and casings and structures are modified to allow for T3 and P3 increases.

The power turbine of the derivative engine is a new, two stage design, somewhat larger in pitch diameter and annulus area than the base CT7 turbine. The output shaft speeds of the two engines are the same but the pitch diameter increase results in a turbine with moderate loading and good efficiency. The alternate approach of adding a third LP turbine stage, which was taken on the Advanced 50-passenger engine, is a less desirable design for a growth or derivative engine. Thus a significant growth step can be obtained without increasing engine length or changing the engine envelope.

The boosted engine requires more variable geometry and different control schedules than the basic engine. Flow matching between the booster and core is obtained by a combination of three approaches. At high power, output shaft speed is constant and booster flow is controlled through use of variable inlet guide vanes (IGV's). At low part power, the IGV's are held at a partially closed position and output shaft speed reduced. This approach has been found to yield a favorable trade between booster stage efficiency and propeller efficiency. For idle and starting there is provision for intercompressor bleed. Steady state and transient control of the IGV and variable bleed functions has been demonstrated on the T700 booster demonstrator.

A similar control scheme would also be applied to the advanced 50-passenger turboprop engine.

Preceding page blank

TABLE 62

CT7 DERIVATIVE CYCLE - SEA LEVEL, STATIC

(No Inlet Protection)

Ambient Temperature	°C (°F)	15 (59)	32.2 (90)
Power Setting		Takeoff*	Takeoff
Turbine Inlet Temp	°C (°F)	1310 (2390)	1310 (2390)
Cycle Pressure Ratio	- -	20.8	18.3
Output Power	kW (hp)	1734 (2325)	1443 (1935)
Specific Fuel Consumption	kg/kW-h (lbm/hp-h)	.269 (.443)	.281 (.463)
Inlet Corrected Flow	kg/s (lbm/sec)	5.7 (12.5)	5.1 (11.3)
Inlet Flow	kg/s (lbm/sec)	5.7 (12.5)	5.0 (11.0)
Core Corrected Flow	kg/s (lbm/sec)	4.5 (9.9)	4.2 (9.3)

*Data in this column, at full rated turbine inlet temperature on a standard day, is provided for reference only. The engine is intended to be flat rated to 30°C (86°F).

TABLE 63

CYCLE AND CONFIGURATION COMPARISON

BASELINE, DERIVATIVE, AND ADVANCED ENGINES

30-Passenger Size, Sea Level, Static, Std Day

Takeoff Power

Parameter	ENGINE Scaled CT7-5	Scaled CT7 Derivative	Advanced Engine
Turbine Inlet Temperature - °C (°F)	1254 (2290)	1310 (2390)	1260 (2300)
Cycle Pressure Ratio	16.9	20.8	17.0
Output Power, 15°C (59°F) - kW (hp)	1208 (1620)	1294 (1735)	1107 (1485)
Output Power, 32.2°C (90°F) - kW (hp)	1059 (1420)	1073 (1440)	943 (1265)
Specific Power - kW/kg/s (hp/lbm/sec)	288 (175)	306 (186)	312 (190)
SFC - kg/kW·h (lbm/hp·h)	.283 (.466)	.269 (.443)	.267 (.439)
Net Thrust - N (lbf)	600 (135)	609 (137)	765 (172)

TABLE 63 - Continued
CYCLE AND CONFIGURATION COMPARISON
BASELINE, DERIVATIVE, AND ADVANCED ENGINES
30-Passenger Size, Sea Level, Static, Std Day
Takeoff Power

Parameter	Scaled CT7-5	Scaled CT7 Derivative	Advanced Engine
BOOSTER			
Number of Stages	None	1	None
Inlet Flow - kg/s (lbm/sec)		4.2 (9.3)	
Inlet Corrected Flow - kg/s (lbm/sec)		4.2 (9.3)	
Pressure Ratio		1.35	
COMPRESSOR			
Number of Stages	5 Ax + 1 Cent	5 + 1	3 + 1
Inlet Flow - kg/s (lbm/sec)	4.2 (9.3)	4.2 (9.3)	3.5 (7.8)
Inlet Corrected Flow - kg/s (lbm/sec)	4.2 (9.3)	3.4 (7.4)	3.5 (7.8)
Pressure Ratio	16.9	15.7	17.0
HP TURBINE			
Number of Stages	2	2	1
Pressure Ratio	4.4	4.6	4.1
LP TURBINE			
Number of Stages	2	2	2
Co-Rotating or Counter-Rotating	Co	Co	Counter
Inlet Temperature - °C (°F)	835 (1535)	868 (1595)	866 (1590)
Pressure Ratio	3.3	3.9	3.5
EXHAUST NOZZLE			
Pressure Ratio	1.045	1.045	1.10
Exit Area - m^2 (in^2)	.07 (109)	.072 (112)	.04 (62)

TABLE 63 - Continued
CYCLE AND CONFIGURATION COMPARISON
BASELINE, DERIVATIVE, AND ADVANCED ENGINES
30-Passenger Size, Sea Level, Static, Std Day
Takeoff Power

Parameter	Scaled CT7-5	Scaled CT7 Derivative	Advanced Engine
GENERAL ARRANGEMENT	3 Sump Mid-Frame	3 Sump Mid-Frame	2 Sump Inter-Turb Frame
DIMENSIONS			
Engine Length - m (in)	1.021 (40.2)	1.024 (40.3)	.658 (25.9)
Engine Max Dia - m (in)	.556 (21.9)	.505 (19.9)	.406 (16.0)
Engine Weight - kg (lb)	152 (335)	142 (314)	129 (284)
Propeller Dia - m (ft)	3.66 (12.0)	3.69 (12.1)	3.51 (11.5)

TABLE 64
CYCLE AND CONFIGURATION COMPARISON
BASELINE, DERIVATIVE, AND ADVANCED ENGINES
50-Passenger Size, Sea Level, Static, Std Day
Takeoff Power

Parameter	ENGINE Scaled CT7-5	Scaled CT7 Derivative	Advanced Engine
Turbine Inlet Temperature - °C (°F)	1254 (2290)	1310 (2390)	1316 (2400)
Cycle Pressure Ratio	16.9	20.8	20.2
Output Power, 15°C (59°F) - kW (hp)	2095 (2810)	2203 (2955)	1831 (2455)
Output Power, 32.2°C (90°F) - kW (hp)	1834 (2460)	1834 (2460)	1510 (2025)
Specific Power - kW/kg/s (hp/lbm/sec)	288 (175)	306 (186)	342 (208)
SFC - kg/kW·h (lbm/hp·h)	.281 (.462)	.269 (.443)	.252 (.415)
Net Thrust - N (lbf)	1041 (234)	1041 (234)	1156 (260)
BOOSTER			
Number of Stages	None	1	1
Inlet Flow - kg/s (lbm/sec)		7.2 (15.9)	5.4 (11.8)
Inlet Corrected Flow - kg/s (lbm/sec)		7.2 (15.9)	5.4 (11.8)
Pressure Ratio		1.35	1.35
COMPRESSOR			
Number of Stages	5 Ax + 1 Cent	5 + 1	3 + 1
Inlet Flow - kg/s (lbm/sec)	7.3 (16.0)	7.2 (15.9)	5.4 (11.8)
Inlet Corrected Flow - kg/s (lbm/sec)	7.3 (16.0)	5.7 (12.6)	4.2 (9.3)
Pressure Ratio	16.9	15.7	15.2
HP TURBINE			
Number of Stages	2	2	1
Pressure Ratio	4.4	4.6	4.0

TABLE 64 - Continued
CYCLE AND CONFIGURATION COMPARISON
BASELINE, DERIVATIVE, AND ADVANCED ENGINES
50-Passenger Size, Sea Level, Static, Std Day
Takeoff Power

	Scaled CT7-5	Scaled CT7 Derivative	Advanced Engine
LP TURBINE			
Number of Stages	2	2	3
Co-Rotating or Counter-Rotating	Co	Co	Counter
Inlet Temperature - °C (°F)	835 (1535)	868 (1595)	916 (1680)
Pressure Ratio	3.3	3.9	4.2
EXHAUST NOZZLE			
Pressure Ratio	1.045	1.045	1.10
Exit Area - m^2 (in^2)	.123 (191)	.122 (190)	.061 (94)
GENERAL ARRANGEMENT	3 Sump Mid-Frame	3 Sump Mid-Frame	2 Sump Inter-Turb Frame
DIMENSIONS			
Engine Length - m (in)	1.306 (51.4)	1.3 (51.2)	.851 (33.5)
Engine Max Dia - m (in)	.732 (28.8)	.838 (33.0)	.46 (18.1)
Engine Weight - kg (lb)	264 (581)	243 (536)	180 (397)
Propeller Dia - m (ft)	4.82 (15.8)	4.82 (15.8)	4.51 (14.8)

AIRCRAFT MISSION AND BENEFIT ANALYSIS

Integrated Propulsion System Comparison

Each of the four study engines (CT7-5, CT7 Derivative, Advanced 30-Passenger Turboprop, and Advanced 50-Passenger Turboprop) was matched with a propeller of the selected design (see the Propeller Selection section, pg 110) and an appropriate gearbox. The two current technology engines (i.e., the CT7-5 and derivative engines) were matched with current technology propellers and gearboxes, and the advanced engines with advanced technology propellers and gearboxes. Some of the major characteristics of the resulting propulsion systems are shown on Table 65 in the design size. Table 66 compares the propulsion systems weight, price, and maintenance when all are scaled to a common 32.2°C (90°F) day, takeoff shaft power size.

The installed thrust SFC characteristics of the four powerplants are shown in Figure 58 at the STAT 185.2 km (100 nmi) mission cruise condition; 3048 m (10000 ft) at 0.45 Mach number. Note that this is the design size SFC characteristic. When these engines are scaled up or down, the SFC trend of Figure 13 (pg 34) is applied.

TABLE 65
POWERPLANT COMPARISON
BASELINE, DERIVATIVE, AND ADVANCED ENGINES
DESIGN SIZE

	CT7-5 Baseline	CT7-5 Derivative	Adv 30-Passenger Turboprop	Adv 50-Passenger Turboprop
Propeller and Gearbox Technology	Current	Current	Advanced	Advanced
Nominal Gearbox Efficiency	.978	.978	.983	.983
Gear Ratio	18.5	21.2	22.1	22.9
Propeller Tip Speed - m/s (ft/sec)	228.6 (750)	228.6 (750)	228.6 (750)	228.6 (750)
Propeller Loading - kW/m^2 (hp/ft^2) (Std Day Takeoff)	90.7 (11.3)	95.5 (11.9)	89.9 (11.2)	89.9 (11.2)
Propeller Thrust/Power - N/kW (lb/hp) (Std Day Takeoff)	17.9 (3.0)	17.9 (3.0)	18.5 (3.1)	18.5 (3.1)
Installed TSFC - kg/N·h (lbm/lbf·h) [3048 m (10,000 ft)/ .45 Avg Cruise]	.049 (.483)	.046 (.456)	.044 (.430)	.041 (.406)
Propeller Efficiency [3048 m (10,000 ft)/ .45 Max Cruise]	.888	.884	.898	.900

TABLE 66
POWERPLANT COMPARISON - CONSTANT HORSEPOWER

	CT7-5 Baseline	CT7-5 Derivative	Adv 30-Passenger Turboprop	Adv 50-Passenger Turboprop
Output Power - kW (hp) [SLS, 32.2°C (90°F) Day, Takeoff]	1208 (1620)	1208 (1620)	1208 (1620)	1208 (1620)
Powerplant Weight - kg (lbm)	485 (1070)	519 (1144)	440 (969)	434 (956)
Powerplant Weight - %	Base	+6.9	-9.4	-10.7
Powerplant Price - %	Base	-1.1	-11.4	-11.8
Powerplant Maintenance Cost - %	Base	-3.7	-20.6	-16.9

Aircraft Benefit Analysis

The baseline 30- and 50-passenger aircraft were resized incorporating the advanced powerplants described above, while satisfying all the baseline mission requirements and holding the airframe technology level constant. These resized baseline aircraft offer significant improvements in both fuel consumption and operating economics over the (scaled) CT7-5 powered aircraft.

In the 30-passenger size, fuel consumption is reduced 13% at 185.2 km (100 nmi), 15% at 1111 km (600 nmi), DOC at 185.2 km (100 nmi) is down 8% at both fuel costs and 5-year cost of ownership is reduced by 7% to 7.5%. (Cost of ownership was calculated based on direct operating costs, assuming financing of 60% of the initial cost; 12% interest rate on financing; 12 years nominal payback; and resale at 65% value at the end of five years.)

For the 50-passenger aircraft, the mission fuel burn improvement is 17% at 185.2 km (100 nmi), 20% at 1111 km (600 nmi), DOC at 185.2 km (100 nmi) is reduced 11% to 12%, depending on fuel cost, and 5-year cost of ownership is down 9 to 10%. Table 67 summarizes the improvements in powerplant and aircraft characteristics obtained with the advanced engine, propeller and gearbox and also with the CT7 derivative engine. The savings associated with the derivative power plants (derivative engine + current technology propeller and gearbox) are about 1/6 of the advanced powerplant savings.

The fuel savings due to the advanced powerplants are broken down into mission segments in Table 68. In Table 69 the changes in DOC for the 185.2 km (100 nmi) mission are broken down to show the sources of the improvement. Approximately 45% to 60% of the DOC reduction is associated with reduced fuel useage, the percentage increasing with both fuel cost and aircraft size. The balance of the improvement is almost entirely due to powerplant cost reductions.

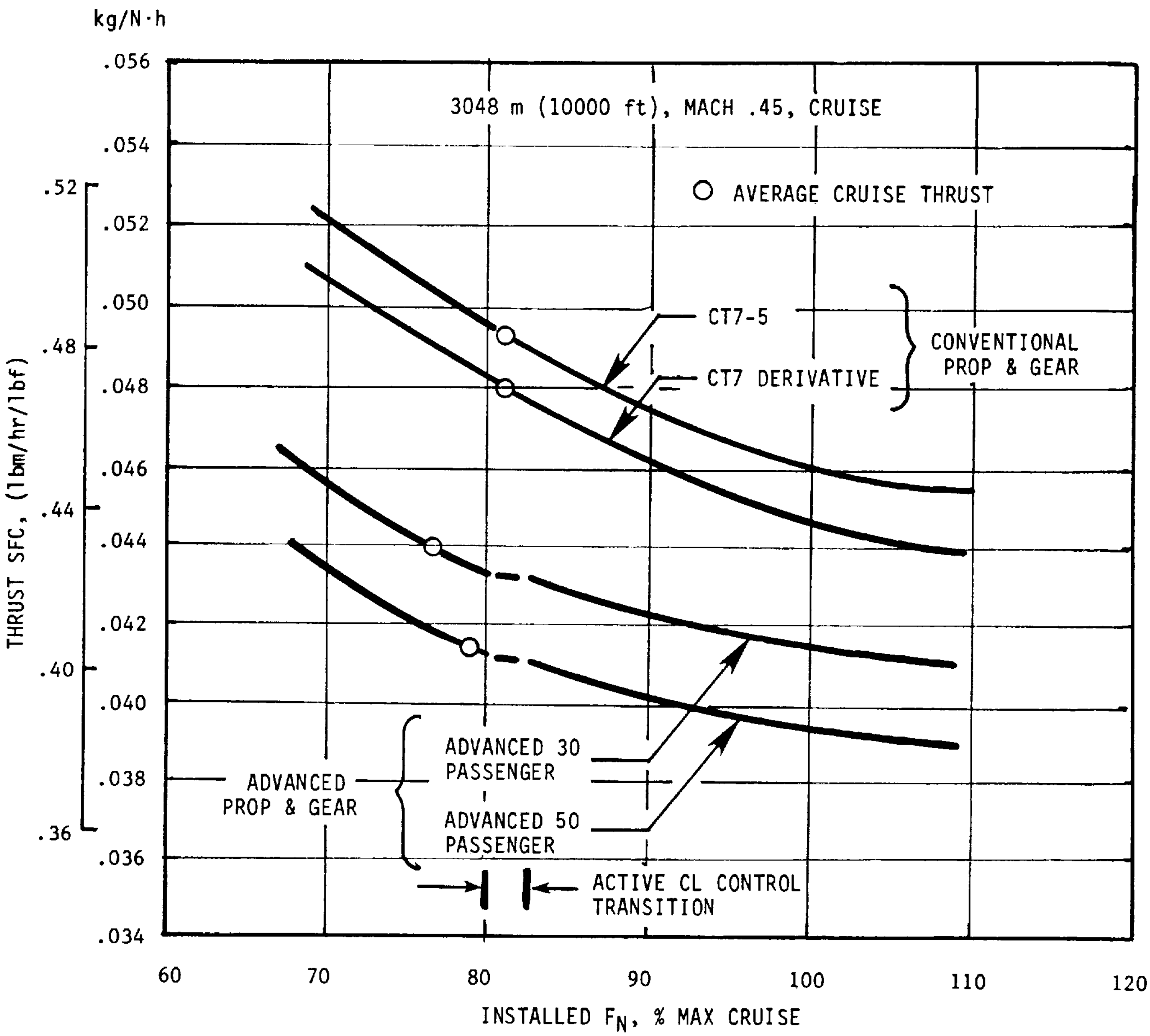


Figure 58. Propulsion System Comparison - Design Size.

AIRCRAFT MISSION AND BENEFIT ANALYSIS - Continued

The changes in DOC and fuel burned are relatively insensitive to mission length, as can be seen from Figures 59-62.

TABLE 67
POWERPLANT AND AIRCRAFT IMPROVEMENTS RELATIVE TO CT7-5 POWERED BASELINE

Parameter	% Change			
	30-Passenger Aircraft		50-Passenger Aircraft	
	Adv Eng	Deriv Eng	Adv Eng	Deriv Eng
Takeoff Gross Weight	-3	Approx 0	-5	Approx 0
32.2°C (90°F) Takeoff Power	-11	+1	-18	Approx 0
Airframe Weight	Approx 0	Approx 0	-1	Approx 0
Engine Weight	-15	-6	-32	-8
Powerplant Weight	-23	+1	-30	Approx 0
Airframe Price	-5	Approx 0	-7	Approx 0
Engine Price	-19	-5	-23	-6
Powerplant Price	-18	-3	-23	-3
Engine Maintenance Cost	-27	-4	-26	-5
Powerplant Maintenance Cost	-26	-4	-25	-5
Fuel Burned				
111 km (600 nmi) Mission	-15	-2	-20	-3
185.2 km (100 nmi) Mission	-13	-2	-17	-3
DOC, 185.2 km (100 nmi) Mission				
$264/m^3 ($1.00/gal) Fuel	-8	-1	-11	-2
$396/m^3 ($1.50/gal) Fuel	-8	-1	-12	-2
5-Year Cost of Ownership				
$264/m^3 ($1.00/gal) Fuel	-7	-1	-10	-1
$396/m^3 ($1.50/gal) Fuel	-8	-1	-10	-2

TABLE 68

FUEL SAVINGS DUE TO ADVANCED POWERPLANT

Mission Segment	Fuel Saving - % of Total	
	30-Passenger Aircraft	50-Passenger Aircraft
185.2 km (100 nmi) Mission		
Takeoff and Climb	-4.8	-7.6
Cruise	-5.1	-6.9
Descent and Taxi	-2.7	-2.9
Total	-12.6	-17.4
1111 km (600 nmi) Mission		
Takeoff and Climb	-4.3	-7.1
Cruise	-9.6	-11.8
Descent and Taxi	-1.3	-1.3
Total	-15.2	-20.2
Reserves		
Climb	-1.6	-2.9
Cruise to Alternate	-1.2	-5.8
Loiter	-4.5	-9.0
Descent	-0.6	-0.6
Total	-7.9	-18.3

TABLE 69

DOC SAVINGS DUE TO ADVANCED POWERPLANT

185.2km (100 nmi) Mission

	DOC Savings - % of Total			
	30-Passenger Aircraft		50-Passenger Aircraft	
	Fuel Cost $264/m^3$ ($1.00/gal)	Fuel Cost $396/m^3$ ($1.50/gal)	Fuel Cost $264/m^3$ ($1.00/gal)	Fuel Cost $396/m^3$ ($1.50/gal)
Powerplant Depreciation	-1.6	-1.4	-2.0	-1.7
Airframe Depreciation	0	0	-0.3	-0.2
Powerplant Insurance	-0.3	-0.2	-0.3	-0.3
Airframe Insurance	0	0	0	0
Powerplant Maintenance	-2.3	-2.1	-2.2	-1.9
Airframe Maintenance	0	0	-0.1	-0.1
Crew	0	0	0	0
Fuel	-3.6	-4.7	-5.9	-7.5
Total	-7.8	-8.4	-10.8	-11.7

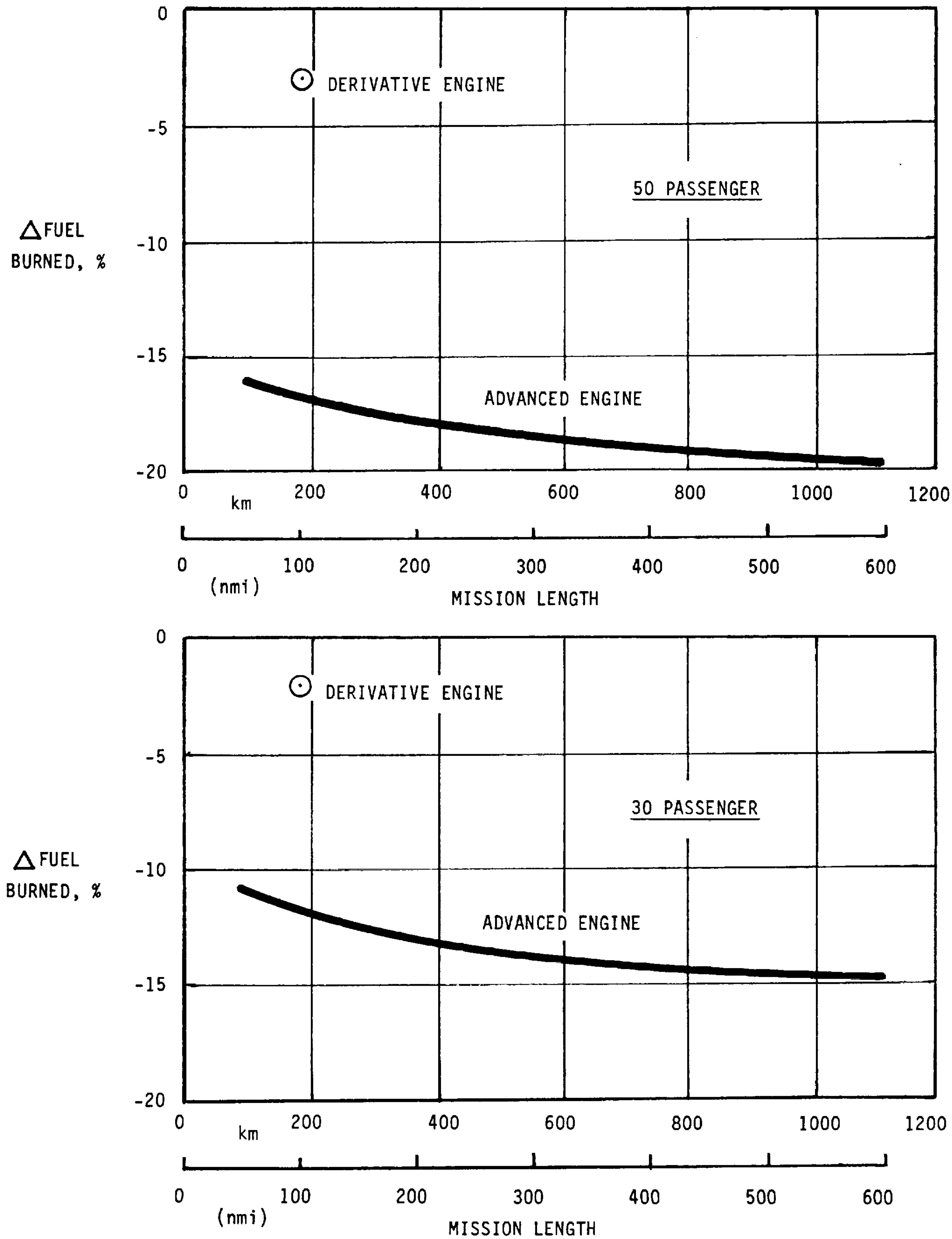
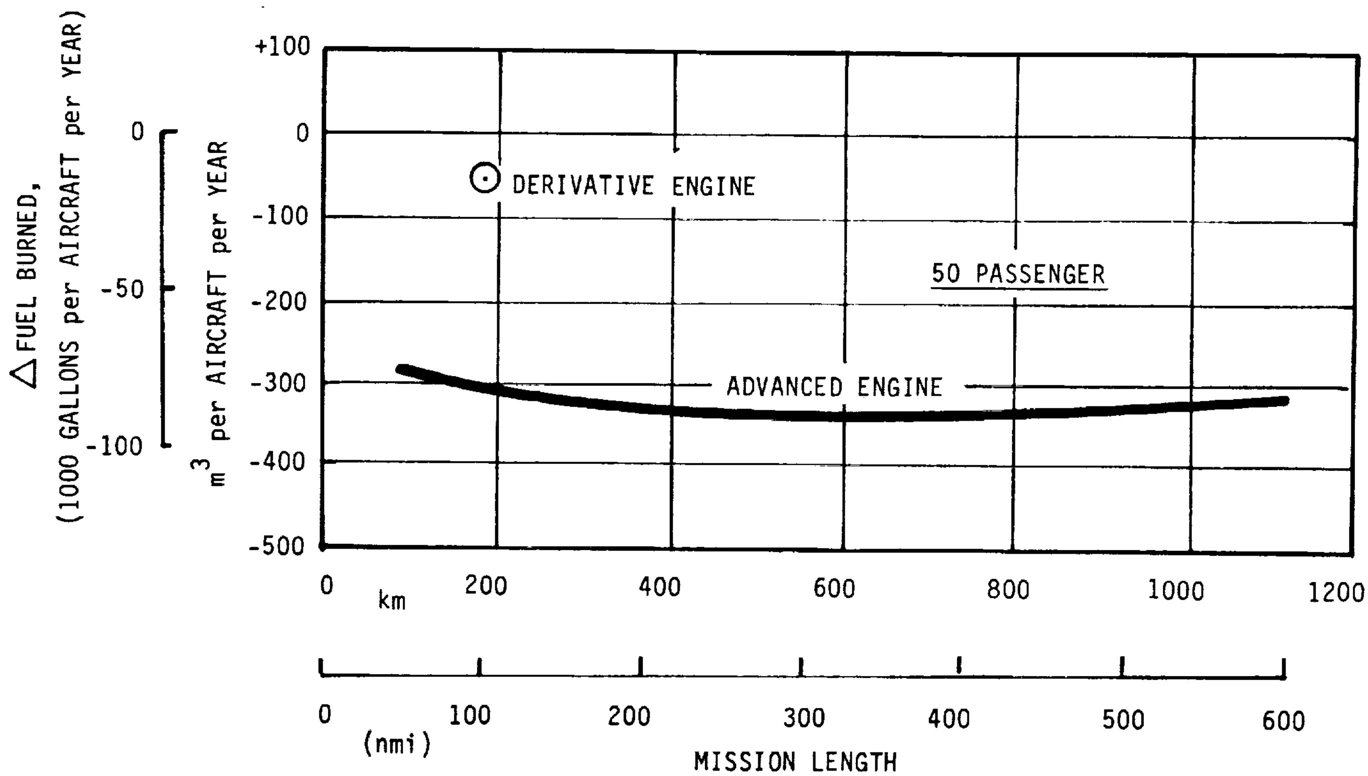


Figure 59. Fuel Burned Improvement vs CT7-5 Powered Baseline.



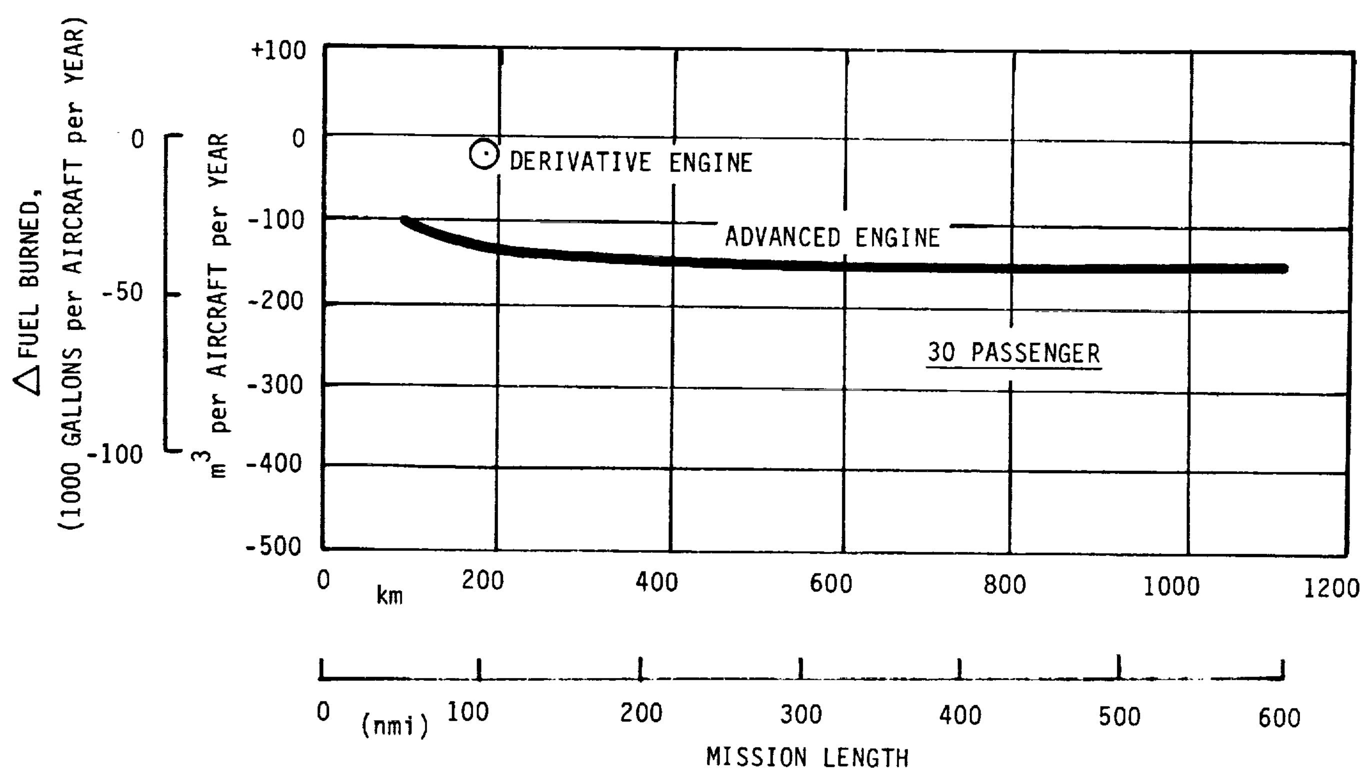


Figure 60. Fuel Burned Improvement vs CT7-5 Powered Baseline.

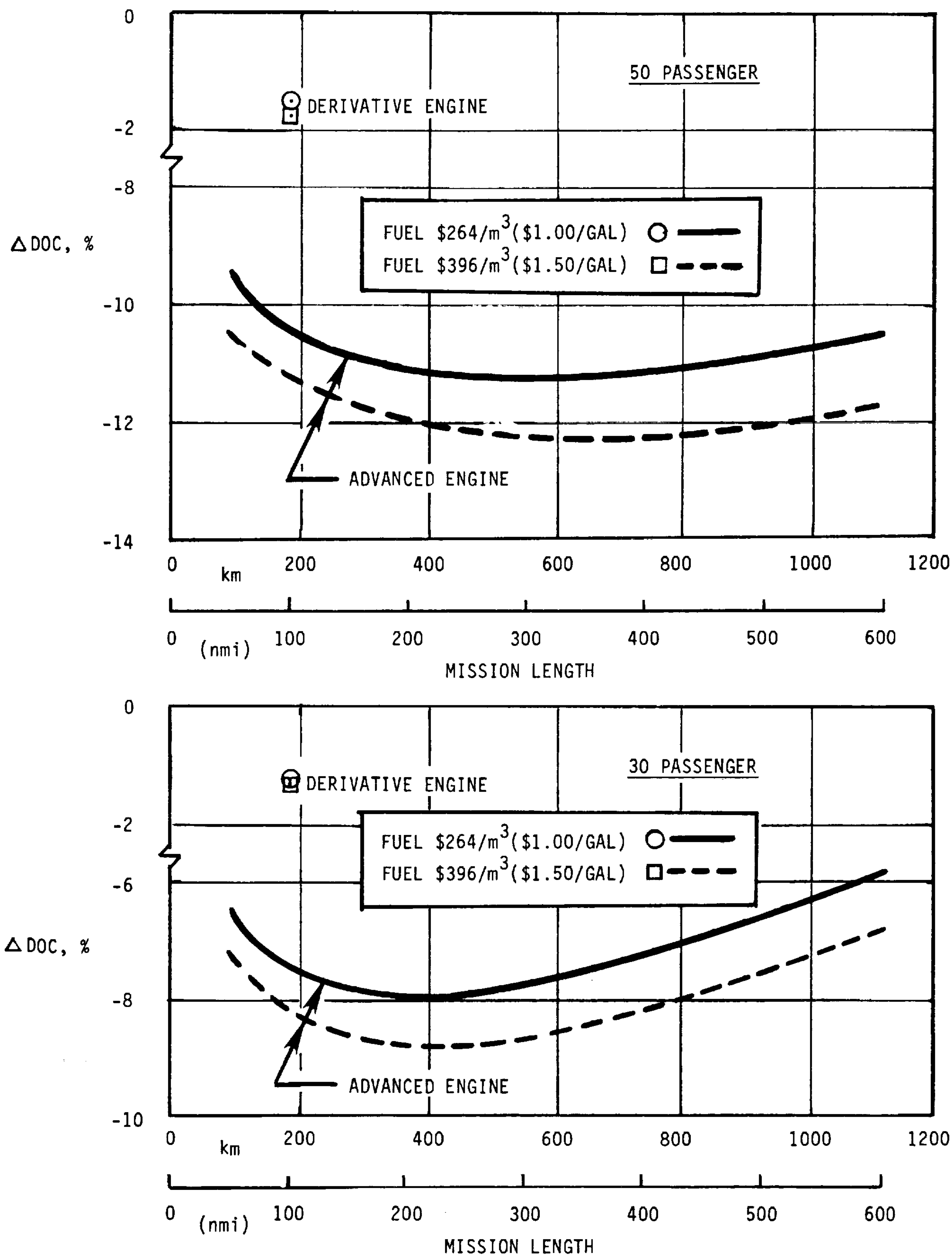
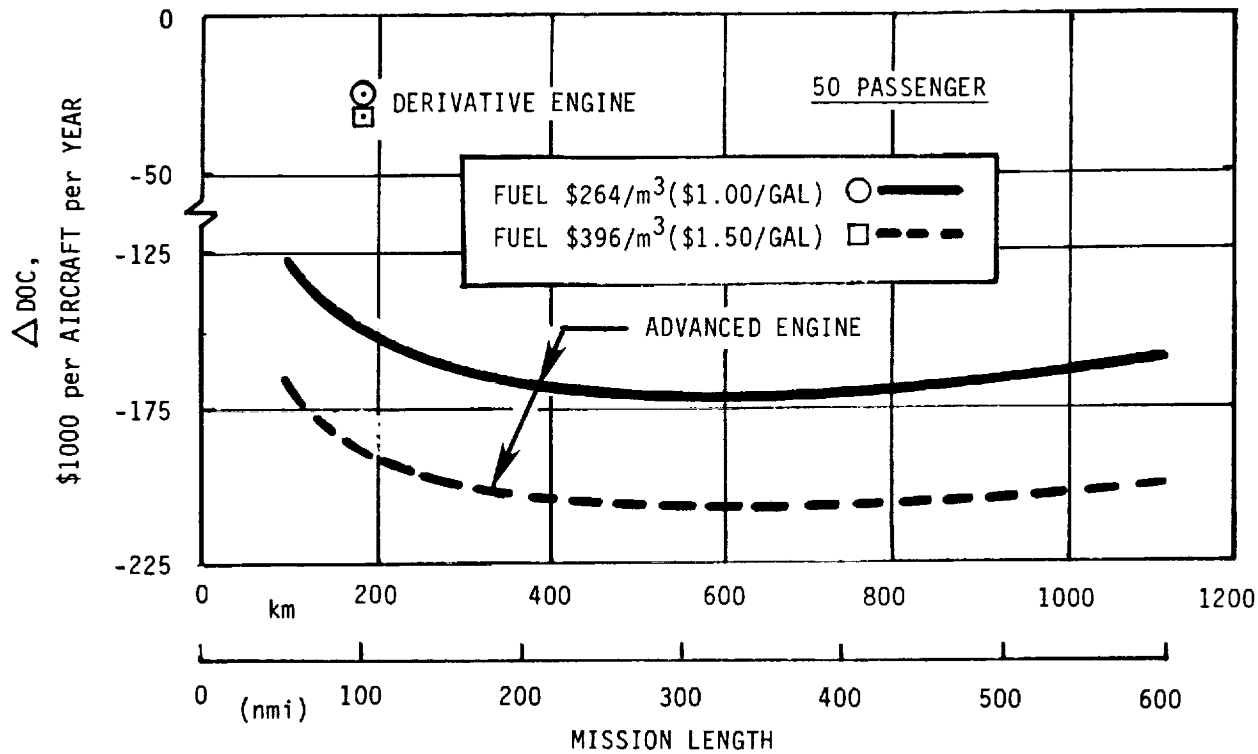


Figure 61. DOC Improvement vs CT7-5 Powered Baseline.



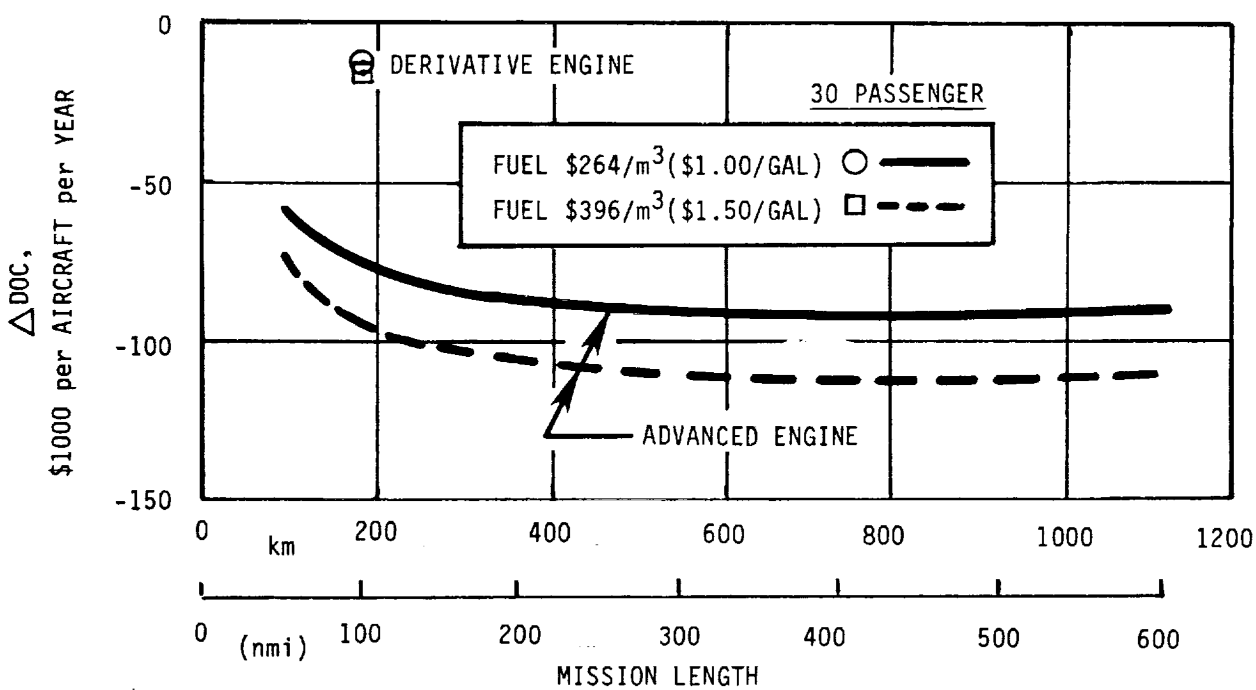


Figure 62. DOC Improvement vs CT7-5 Powered Baseline.

RECOMMENDATIONS FOR FUTURE RESEARCH

RANKING OF ADVANCED TECHNOLOGIES AND DESIGN FACTORS

For each of the advanced technologies recommended for inclusion in the commuter turboprop designs presented above, a development cost has been estimated. A probability of successfully achieving the stated improvements in performance, weight, and cost has also been estimated considering four factors:

1. Availability of analytical design techniques (e.g. computer programs for 3-D flow analysis and airfoil design).

2. Availability of required materials with targeted properties.

3. Availability of new manufacturing techniques.

4. Given the above, the probability of achieving the stated performance goals.

A relative value (RV) has been calculated for each item as

$$RV = (-1)\,\frac{(\Delta DOC)\ (\text{Probability of Success})}{(\text{Development Cost})}$$

These values have then been normalized such that the "best" item has a value of 100, and the items ranked by their average "score" for the two sizes and two fuel costs. Table 70 summarizes the results. It is clear from the results that those items significantly affecting performance (axial compressor, impeller, diffuser items) or life (combustor cooling) have the largest potential payoff in the STAT mission. Those items which are primarily targeted to weight and/or cost savings have a relatively minor benefit. Note also that one item, the HP turbine blade, shows no payoff in DOC. It was included in the 50-passenger design because it saves 1% in fuel for the 185.2 km (100 nmi) mission with no DOC penalty at $\$396/m^3$ (\$1.50/gal) fuel.

The design factor options are ranked in Table 71 in terms of their average predicted DOC savings for the two sizes and two fuel costs. These are options which may be incorporated in the engine without any associated development programs or technical risks. As such, no development costs or proabilities are involved in the ranking. (Where more than one option was investigated in a category, only the best is ranked.)

OTHER APPLICATIONS OF ADVANCED TECHNOLOGY

The technology items which were examined for applicability to the commuter turboprop had varying degrees of payoff in DOC. For each of the other applications considered in Table 72, there is some payoff as well. The magnitude of the payoff will depend upon time at part cruise, size and other factors which will place different relative values on SFC, weight and cost for each application.

The cores developed for the 30- or 50-passenger turboprops have applicability in the range of engines shown on Table 73. The only one that is questionable is a Bizjet derived from the 3.86 kg/sec (8.5 lb/sec) core which would be less than 8896 N (2000 lb) thrust.

TABLE 70
RELATIVE VALUE CALCULATIONS - ADVANCED TECHNOLOGIES

	Development Cost	Probability of Success	Change in DOC				Relative Value				Rank
			30-Passenger		50-Passenger		30-Passenger		50-Passenger		
			*A	**B	*A	**B	*A	**B	*A	**B	
Axial Compressor	1.9M	80	-.89	-.96	-.95	-1.03	56	72	68	84	3
Multi-Blade Impeller	2.0M	50	-.50	-.60	-.58	-.68	19	27	25	33	4
Advanced Diffuser	1.3M	80	-.63	-.74	-.71	-.82	57	81	75	97	2
Combustor Cooling	0.4M	90	-.30	-.25	-.26	-.23	100	100	100	100	1
Clearance Control	1.5M	80	-.01	-.08	-.05	-.12	1	8	5	11	8
HP Turbine Blade	0.7M	75	-	-	+.19	0	-	-	-35	0	9
LP Turbine Blisk	1.6M	75	-.08	-.07	-.08	-.07	6	6	6	6	7
Composite Shaft	0.4M	50	-.03	-.04	-.04	-.05	6	9	9	12	6
Closed-Loop Accel Control	1.7M	50	-.13	-.20	-.19	-.26	6	10	10	15	5

*A = $264/m^3$ ($1.00/Gal)
**B = $396/m^3$ ($1.50/Gal)

TABLE 71
DESIGN FACTOR RANKING

Item	Change in DOC				Rank
	30-Passenger		50-Passenger		
	$264/m^3$ ($1.00/Gal)	$396/m^3$ ($1.50/Gal)	$264/m^3$ ($1.00/Gal)	$396/m^3$ ($1.50/Gal)	
Modular Construction	+.41	+.46	+.45	+.50	4
Vaneless FOP	+.39	+.44	+.46	+.52	3
Diagnostic Data Recording	-.89	-.77	-1.01	-.85	2
10% Derate	-1.58	-1.41	-1.37	-1.22	1

TABLE 72
TECHNOLOGY APPLICABILITY

Application Technology	Commuter Turboprop	Business Turboprop	Commercial Helicopter Turboshaft	Military Helicopter Turboshaft	High Speed Rotocraft Convertible Engine	Bizjet Turbofan	Trainer Turbofan	Cruise Missiles
Axial and Centrifugal Compressor Aerodynamics	✓	✓	✓	✓	✓	✓	✓	✓
HP Turbine Blade Cooling Technology	✓	✓	✓	✓	✓	✓	✓	✓
Active Turbine Clearance Control	✓	✓	✓	✓	✓	✓	✓	
Combustor Material	✓	✓	✓	✓	✓	✓	✓	
LP Turbine Disk with Cast Blades	✓	✓	✓	✓	✓	✓	✓	✓
High Modulus Shaft	✓	✓	✓	✓	✓	✓	✓	✓
Inlet Particle Separator	✓	✓	✓	✓	✓			
Diagnostic System	✓	✓	✓	✓	✓	✓	✓	

Payoff of technology will vary between applications depending upon such factors as engine size, utilization and emphasis upon part power cruise or loiter operation in the mission.

TABLE 73
CORE APPLICABILITY

Application	Business Turboprop	Commercial Helicopter Turboshaft	Military Helicopter Turboshaft	High Speed Rotocraft Convertible Engine	Bizjet Turbofan	Trainer Turbofan	Cruise Missiles
Advanced Commuter Turboprop Core							
30-Passenger	✓	✓	✓	✓	Size too small	✓(1)	Size too large
50-Passenger		✓	✓	✓	✓	✓	Size too large

(1) Core requires modification to provide capability for supercharge in turbofan cycles.

APPENDIX A

HAMILTON STANDARD DIVISION GEARBOX DATA

The following sections contain synopses of the gearbox reports written under subcontract by Hamilton Standard[6,8]. Material which is quoted verbatim is indicated as such. Other material is paraphrased.

STATE-OF-THE-ART GEARBOX

The material presented here is representative of current technology and suitable within the 1119 to 1491 kw (1500 to 2000 hp) range.

"The configuration selected as the state-of-the-art gearbox is the offset pinion-bull-star system illustrated in Figure 50 (pg 106). This configuration provides: 1) an offset between the input and output shafting to allow access for propeller input signals, 2) a common direction of rotation for the input and output shafts as viewed from the rear of the gearbox, and 3) a self-contained, pressure fed lubrication system except for an airframe mounted heat exchanger. In addition, the gearbox includes an accessory drive gearbox with provisions to drive an AC generator and an aircraft hydraulic pump."

Weight Generalization

"In examining the factors affecting the weight of gearboxes, it becomes evident that by far the most predominant factor is the maximum continuous output torque of the gearbox. Accordingly, the generalized weight presentation in Figure 51 (pg 108) shows gearbox weight as a function of the maximum output torque and is based on the offset-star power gear reduction defined above. This relationship can be used to estimate the weight of offset-star gearboxes with reduction ratios of 14:1 to 16.5:1 over the output power range of 1119 to 1491 kW (1500 to 2000 shp). The estimated weight includes the main gearbox, accessory drive gearbox, and lube system pump. The gearbox weight generalization does not include accessories or special accessory drives, input drive shafting, propeller brake provisions, and the airframe mounted heat exchanger."

Efficiency

"At the maximum continuous power rating and 100% speed, the estimated efficiency of the gearbox including the accessory drive gearbox and lube pump is 97.8%. This value does not include the power extractions of the aircraft hydraulic pump, generator, and special accessories, i.e., tachometer, cabin supercharger, etc. This efficiency level is believed to be quite representative over the output power range of 1119 to 1491 kW (1500 to 2000 shp)."

Cost

"The cost per unit weight for offset-star gearboxes within the 1119 to 1491 kW (1500 to 2000 shp) output power range is approximately $507/kg ($230.00 per pound). This value is in terms of a 1979 economy and includes the main gearbox, accessory drive gearbox, and lube system pump."

Reliability and Maintainability

"The reliability prediction for the offset-star gearbox is 106.705 repair/replacement events per million hours giving a mean time between failures of 9372 hours. These values represent the repair/replacement events that arise, regardless of cause, for the main gearbox, accessory drive gearbox,

Preceding page blank

STATE-OF-THE-ART GEARBOX - Continued

and the lube system pump. Assuming a consistent design philosophy, these reliability values will be the same for gearboxes in the 1119 to 1491 kW (1500 to 2000 shp) range."

"Maintainability estimates for an offset-star gearbox sized for the 1119 kW (1500 shp) design power level are as follows:

Parts cost: $.37 per flight hour (1979 economy)

Labor: .021 manhours per flight hour

Over the output power range of 1119 to 1491 kW (1500 to 2000 shp), these maintainability costs will vary directly with the maximum continuous output torque of the gearbox."

This maintenance estimate assumes a fixed TBO of 7000 hours.

Scaling Factors

The baseline gearbox is sized for a torque of 8508 N·m (6275 ft·lb) and a gear ratio of 15.2:1. Gearbox parameters may be scaled as follows:

Parameter	Scales As
Weight	$\left(\frac{\text{Torque}}{6275}\right) \times \left(\frac{\text{Gear Ratio}}{15.2}\right)^{1/2}$
Cost/lb	Constant
Maintenance	$\frac{\text{Torque}}{6275}$
Linear Dimensions	$\left(\frac{\text{Torque}}{6275}\right)^{1/3}$

At 8508 N·m (6275 ft-lb) and 15.2:1 gear ratio, the important gearbox parameters are:

Wt, kg (lb)	102	(225)
Cost, k$	51.8	
Maintenance Cost, $/h	.38	
Frontal Area m^2 (in^2)	.197	(306)
Height, m (in)	.541	(21.3)
Width, m (in)	.493	(19.4)
Offset, m (in)	.216	(8.5)

ADVANCED TECHNOLOGY GEARBOX

Advanced Technology features are offered ".....that could conceivably be in service in the 1985 to 1990 time period."

Advanced Technology Features -- Identification and Screening

"The increased concern with reliability factors and maintenance costs on the part of commercial airline operators has caused a revitalization in design concepting and operating philosophies. In order to remain competitive in a

ADVANCED TECHNOLOGY GEARBOX - Continued

market that is faced with numerous constraints as well as soaring fuel costs, it has become increasingly necessary to direct attention toward the selection of reliable, low cost commercial products that are easy to maintain. To this end, the advanced technology items shown have been found to contribute to one or more of the following objectives:

1. Increased reliability.

2. Improved maintainability.

3. Reduced acquistion and/or operating costs."

Split Power Gear Train

"In this portion of the study, several different gear train configurations were examined including offset-starts, differential, and split power gear reductions. As a result, a split power, compound idler gear reduction was identified as offereing the best balance between weight, cost, maintainability and reliability. Compared to an offset-star design of equal reliability, the split power compound idler gear train (see Figure 50, pg 106) provides a major reduction in the number of gears and bearings and hence offers a significant cost and weight advantage. An added feature of the compound idler design is that it offers an attractive gear ratio arrangement for accessory drives. Unlike the offset-star gearbox, the compound idler gearbox can accommodate four accessory drive pads without additional gears and bearings since the arrangement of the idlers permits direct access to their respective centerlines."

"As with any split power train, the key to a successful arrangement is the the matching of the power split. After assessing the various concepts, a floating pinion design was selected to achieve the split power match. This approach provides essentially equal idler torque even with the offsets due to tolerance buildup and/or load deflections of the idlers. To accomplish this, the pinion is flexibly mounted in the direction of the gear line of action which allows the pinion to move until the load share is equal and the pinion loads are balanced. Furthermore, the pinion is stiffly mounted perpendicular to the gear line of action to provide stability for the in-and-out of mesh direction."

Modular Construction

"Replacement of the main gearbox because of an accessory failure imposes an unnecessary penalty on maintainability factors due to the increased manpower requirements, special ground support equipment, and spare parts costs. In order to reduce aircraft downtime and its associated high costs, it is desirable, if not imperative, to modularize all the accessories that are not indigenous to the basic gearbox and locate them such that their removal or replacement can be accomplished without removing the main propulsion components (i.e., propulsor, gearbox, or engine). Hence the following items have been identified as practical and significant contributors toward improved gearbox maintainability:

1. Externally mount all propeller accessories, including the overspeed governor, propeller control, auxiliary pump and motor, and the propeller brake.

ADVANCED TECHNOLOGY GEARBOX - Continued

2. Provide a modular, bolt-on accessory drive gearbox for the aircraft hydraulic pump and generator for easy field replacement and improved maintainability.

3. Externally mount the gearbox lube system components including the lube pump with attendant screens and relief valves, oil filter, chip detectors, and magnetic plugs.

4. Construct all of the accessories such that their removal and replacement can be performed with a small number of standard tools."

Advanced Lubricants

"Dramatic improvements in bearing life could be achieved by using lubricants that exhibit high film strength and flat viscosity characteristics. The high film strength not only spreads the bearing contact pattern, thereby reducing stress, but also prevents small particles from inflicting the surface distress that forms the focal point for material failures. Both of these factors have a direct impact on bearing life. Flat viscosity characteristics, on the other hand, help ensure the same quality of lubrication throughout the normal thermal environment of aircraft components."

High Filtration

"Marked improvement in bearing life can also be achieved by reducing the debris (i.e., wear particles) in the gearbox. However, simply installing finer filters within the same envelope would only serve to overburden the filter system and shorten the maintenance interval. The remedy for this is to approach the gearbox with a new philosophy. In the past, changes within a gearbox have generally been made to meet a specific objective or design requirement. By extending this philosophy a gearbox could be approached as a debris generator whereby the sources would be identified and appropriate changes made in those areas that need it to reduce the debris generation. For instance, if it were found that a certain bearing liner exhibited fretting at the housing interface, it would be appropriate to alter the hardness of the liner so as to stop the fretting. As more and more debris sources are treated in this fashion, the overall debris generated in the gearbox could be drastically reduced, thereby allowing the lubrication system to sustain a finer filtration level without penalizing the maintenance interval or the filter envelope."

High Contact Ratio Gearing

"High contact ratio gearing offers the advantage of reducing the dynamic load that the gear tooth carries thereby producing a smooth load transmission with less noise and vibration. The narrower teeth and reduced pressure angles typical of high contact ratio gears provide the basis for distributing the load among a larger number of teeth than is possible with conventional tooth profiles. A result of this gearing concept is that it offers reductions in face width approaching 15% with attendant reductions in gear weight."

Lightweight Housing Materials

"The use of lightweight materials in the gearbox housings can offer significant weight reduction. The candidates include materials such as

ADVANCED TECHNOLOGY GEARBOX - Continued

magnesium, titanium, and composite structures. The weight advantages for magnesium have been well established; however, in order to take full advantage of these benefits, better surface treatments should be developed that will provide the necessary corrosion protection as well as good resistance to handling damage. Titanium and composite structures offer weight savings comparable or better than those for magnesium. However, it was judged that their use was economically impractical for incorporation by the 1985 to 1990 time period."

Bearing Material Properties

"The advent of vacuum melt, high purity steels offers dramatic improvements in bearing material properties. However, the extent of the potential benefits has not yet been realized due to the lack of up-to-date material allowables. In fact, the current published material allowables are, for the most part, based on data developed many years ago for airmelt steels. Hence the need exists to realign the real material capabilities for today's high purity steels to take full advantage of the potential weight savings and extended bearing lives."

On-Condition Maintenance

"Fixed time maintenance permits a part or unit to be operated for a prescribed time before discard or overhaul. Although the overhaul period is subject to change in service, useful life is frequently forsaken to assure high reliability and safety. On-condition maintenance, on the other hand, relies on the functional and physical inspections of fleet leader units to provide the basis for extending the inspection period for all service units. Reliability is achieved through the detection of impending problems so that repair or replacement of the part can be accomplished before failure occurs in service units. An on-condition maintenance philosophy offers a substantial potential cost savings over fixed time overhaul periods."

Selected Gearbox

"The configuration selected as the advanced technology gearbox is the split power compound idler system illustrated in Figure 50 (pg 106). This gear reduction provides a major reduction in the number of gears and bearings, improved efficiency because of the fewer gear meshes, and a significant weight advantage compared to the offset-star design of equal reliability. In addition, the compound idler gear is a modular design. A bolt-on accessory drive gearbox and provisions for the propeller control and auxialiary pump/motor are incorporated on the aft side of the main housing. The lube pump mounts on the front housing while provisions for the propeller brake and propeller overspeed governor are also included on the front housing."

"The compound idler design is intended for on-condition maintenance. This design allows for routine maintenance to be performed with a small number of standard tools and includes features such as lubricant sight gauge, chip detectors, lube pressure monitoring, and filters with impending bypass indicators. The lubrication system is self-contained except for an airframe mounted heat exchanger. The major characteristics of this two-stage power gear reduction are shown in Table A-1 along with the offset-star characteristics."

APPENDIX A

TABLE A-1.
DESIGN CHARACTERISTICS COMPARISON

	Offset-Star		Compound Idler	
Weight	102 kg	(225 lbm)	89 kg	(196 lbm)
No. of gears	9		6	
No. of bearings	17		10	
Frontal area	.197 m^2	(306 $in.^2$)	.236 m^2	(366 $in.^2$)
Overall height	.541 m	(21.3 in.)	.602 m	(23.7 in.)
Overall width	.493 m	(19.4 in.)	.467 m	(18.4 in.)
Offset	.216 m	(8.5 in.)	.191 m	(7.5 in.)

Weight Generalization

"The generalized weight presentation in Figure 51 (pg 108) shows gearbox weight as a function of the maximum output torque and is based on the compound idler power gear reduction. The estimated weight includes the main gearbox with a magnesium housing, accessory drive gearbox, and lube system pump. Compared to an aluminum housing, the magnesium housing with the advanced treatment offers a net potential weight savings of 5 kg (11 pounds)."

Efficiency

"At the maximum continuous power rating and 100% speed, the estimated efficiency of the gearbox including the accessory drive gearbox and lube pump is 98.3%. This value does not include the power extractions of the aircraft hydraulic pump, generator, and special accessories, i.e., tachometer, cabin supercharger, etc. The increased efficiency of the compound idler design over the current technology gearboxes is primarily a result of the reduced number of gear meshes."

Cost Data

"The cost per unit weight for compound idler gearboxes within the 1119 to 1491 kW (1500 to 2000 shp) output power range is approximately $397/kg ($180.00 per pound). This value is in terms of the 1979 economy and reflects production rates of 30 units per month. It includes the main gearbox, accessory drive gearbox, lube system pump, and the advanced technology features described herein."

Reliability and Maintainability

"The impact on potential gains offered by both the split power and modular construction concepts is evident from the reliability prediction comparison in Table IV. These values represent the repair/replacement events that arise, regardless of cause, for the main gearbox, lube system pump, and accessory drive system. Assuming a consistent design philosophy, these reliability values will be the same for gearboxes in the 1119 to 1491 kW (1500 to 2000 shp) range."

HAMILTON STANDARD DIVISION GEARBOX DATA - Continued

ADVANCED TECHNOLOGY GEARBOX - Continued

"Maintainability estimates for an advanced technology gearbox sized for the 1119 kW (1500 shp) design power level are as follows:

Parts cost: $.077 per gearbox flight hour (1979 economy)

Labor: .0057 manhours per gearbox flight hour"

Recommendations for Further Work

"Certain technology items discussed herein require continued development before they become economically attractive. Specifically, the following areas should be further developed."

Bearing Material Properties

"As mentioned earlier in this report, existing material allowables for bearing steels are, for the most part, based on data obtained many years ago for air-melt steels. The high purity steels available today potentially offer dramatic improvement in material allowables. Furthermore, today's computer capabilities have greatly enhanced the designer's analytical tools and design methods but the advertised material properties do not appear to have kept up to date. Therefore, in order to fully exploit the potential weight, cost and reliability benefits, it is necessary to quantify the actual material allowables for today's high purity vacuum melt bearing steels."

High Contact Ratio Gearing

"Many of the high contact ratio gear applications found today have failed to take full advantage of the benefits offered by this type of gearing. The physical geometry of the gears in these applications has qualified them as high contact ratio gears; however, the design analysis employed was characteristic of that used for conventional spur gears. This has resulted in conservative designs that are heavier than necessary. Hence the advantages that ensue from the reduction in dynamic load are lost to an outdated analysis. Two areas of further attention are recommended: First, update the design methods and analyses to specifically address high contact ratio gears; and second, institute a test program to verify the design methods."

Lightweight Housings

"Magnesium housings have offered a distinct weight advantage in aircraft components for several years. One drawback to its use has been the need to provide protective surface treatments to control corrosion. As with most surface coatings, the susceptibility to handling damage is high and special care and repair procedures are often required to preserve the integrity of the coating. It is recommended, therefore, that a program be undertaken to develop a tough, lightweight coating for magnesium that will survive the rigors of a typical maintenance shop."

Advanced Lubricants

"Advanced lubricants appear to offer drastic improvements in component life and reliability. Hence, it is recommended that lubricants be developed that possess the characteristics found most suitable for highly loaded power gear applications, i.e., high film strength and flat viscosity characteristics."

APPENDIX A

TABLE A-2.
RELIABILITY PREDICTION COMPARISON

Main Drive Configuration	Repair/Replacement: Frequency, events per million hours	Repair/Replacement: Mean time between occurrence, hours
Offset-star, integral accessory drive system	106.705	9,372
Compound idler, integral accessory drive system	63.183	15,827
Compound idler, modular accessory drive system	41.266	24,233

APPENDIX B

HAMILTON STANDARD DIVISION PROPELLER DATA

The following sections summarize the material provided by Hamilton Standard under contract to NASA and used to establish the characteristics of the propellers in this study.

STATE-OF-THE-ART PROPELLER

"The baseline configuration which has been selected is a single acting, aluminum bladed propeller such as has been manufactured by several propeller suppliers and is currently in service on such commuter aircraft as the DeHavilland Twin Otter, the Beech 99, and the Swearingen Metro."

Aerodynamic Performance

"Tabulated performance data is provided for current technology propellers in non-dimensionsal coefficients of net thrust coefficient (C_{TNET}) versus power coefficient (C_P) for a range of advance ratios (J) from zero to 3.0 for 3 and 4-bladed propellers of the following blade activity factors (AF) and integrated design lift coefficients (C_{Li}) of 0.40, 0.55, and 0.70. Table B-1 is typical of the data provided."

No. of Blades	AF
3	100, 130, and 160
4	80, 100, and 120

"A compressibility correction factor (F_T) is supplied for use with the current technology propellers. Figure B-1 indicates the maximum free stream Mach number (M) to avoid compressibility as a function of advance ratio (J) for the three selected C_{Li} values. Figure B-2 depicts a delta Mach number (ΔM) correction as a function of C_{Li}. Figure B-3 allows for the estimation of the F_T factor."

HAMILTON STANDARD DIVISION PROPELLER DATA - Continued

TABLE B-1

4-BLADED, 100 ACTIVITY FACTOR, 0.55 INTEGRATED DESIGN C_L

PROPELLER PERFORMANCE

J	C_P	$C_{T_{Net}}$
0	0.0568	0.1456
	0.0737	0.1732
	0.0926	0.1965
	0.1170	0.2179
	0.1484	0.2327
	0.1866	0.2456
	0.2287	0.2531
	0.2746	0.2559
	0.3192	0.2565
	0.3558	0.2541
0.2	0.0499	0.1084
	0.0655	0.1354
	0.0841	0.1626
	0.1058	0.1890
	0.1299	0.2083
	0.1614	0.2300
	0.1999	0.2480
	0.2406	0.2580
	0.2818	0.2605
	0.3200	0.2600
0.4	0.0406	0.0622
	0.0564	0.0931
	0.0769	0.1237
	0.1001	0.1532
	0.1253	0.1812
	0.1547	0.2075
	0.1885	0.2290
	0.2234	0.2371
	0.2673	0.2470
	0.2840	0.2620
	0.3200	0.2640
0.6	0.0369	0.0362
	0.0564	0.0712
	0.0819	0.1051
	0.1110	0.1376
	0.1421	0.1685
	0.1758	0.1972
	0.2133	0.2229
	0.2561	0.2439
	0.3007	0.2551
	0.3200	0.2600

J	C_P	$C_{T_{Net}}$
0.8	0.0482	0.0447
	0.0797	0.0828
	0.1156	0.1186
	0.1541	0.1525
	0.1940	0.1844
	0.2378	0.2136
	0.2850	0.2389
	0.3347	0.2572
	0.3857	0.2649
1.0	0.0323	0.0158
	0.0697	0.0585
	0.1141	0.0985
	0.1607	0.1355
	0.2093	0.1706
	0.2597	0.2025
	0.3149	0.2321
	0.3722	0.2561
	0.4264	0.2694
	0.4821	0.2696
1.2	0.0536	0.0341
	0.1070	0.0785
	0.1639	0.1194
	0.2222	0.1527
	0.2821	0.1930
	0.4117	0.2533
	0.4777	0.2740
	0.5345	0.2782
1.4	0.0337	0.0108
	0.0965	0.0600
	0.1654	0.1052
	0.2346	0.1462
	0.3055	0.1850
	0.3768	0.2188
	0.4542	0.2505
	0.5307	0.2754
	0.5997	0.2883

J	C_P	$C_{T_{Net}}$
1.6	0.0695	0.0339
	0.1337	0.0744
	0.2001	0.1121
	0.2657	0.1466
	0.3323	0.1796
	0.4006	0.2105
	0.4667	0.2364
	0.5395	0.2624
	0.6084	0.2823
1.8	0.0407	0.0094
	0.1134	0.0543
	0.1913	0.0957
	0.2692	0.1338
	0.3464	0.1691
	0.4246	0.2026
	0.5015	0.2318
	0.5815	0.2588
2.0	0.0937	0.0368
	0.1836	0.0821
	0.2749	0.1238
	0.3643	0.1617
	0.4542	0.1976
	0.5855	0.2308
2.2	0.0773	0.0227
	0.1797	0.0720
	0.2853	0.1170
	0.3891	0.1578
	0.4916	0.1958
	0.5951	0.2312
2.4	0.0675	0.0130
	0.1531	0.0532
	0.2433	0.0905
	0.3341	0.1254
	0.4231	0.1576
	0.5103	0.1878
	0.5980	0.2167

APPENDIX B

HAMILTON STANDARD DIVISION PROPELLER DATA - Continued

TABLE B-1 - Continued

4-BLADED, 100 ACTIVITY FACTOR, 0.55 INTEGRATED DESIGN C_L

PROPELLER PERFORMANCE

J	C_P	$C_{T_{Net}}$
2.6	0.0968	0.0223
	0.1794	0.0576
	0.2649	0.0904
	0.3510	0.1213
	0.4361	0.1503
	0.5188	0.1773
	0.6010	0.2031
2.8	0.0759	0.0080
	0.1473	0.0387
	0.2230	0.0674
	0.3005	0.0947
	0.3784	0.1209
	0.4556	0.1457
	0.5312	0.1689
	0.6046	0.1909
3.0	0.0996	0.0132
	0.1810	0.0451
	0.2666	0.0754
	0.3537	0.1039
	0.4410	0.1309
	0.5272	0.1565
	0.6112	0.1804

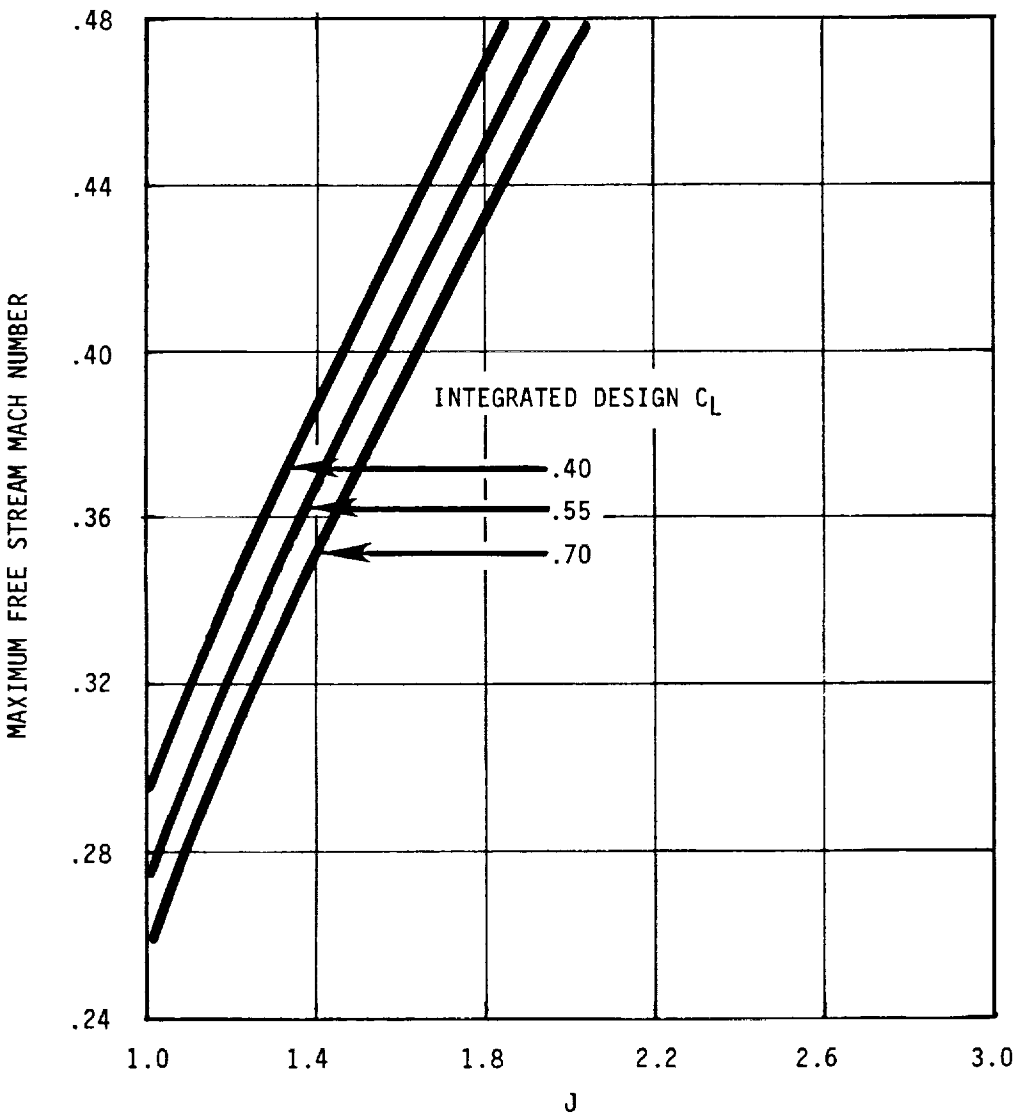


Figure B-1. Maximum Free Stream Mach Number to Avoid Compatibility Losses as Function of Advance Ratio and Integrated Design C_L.

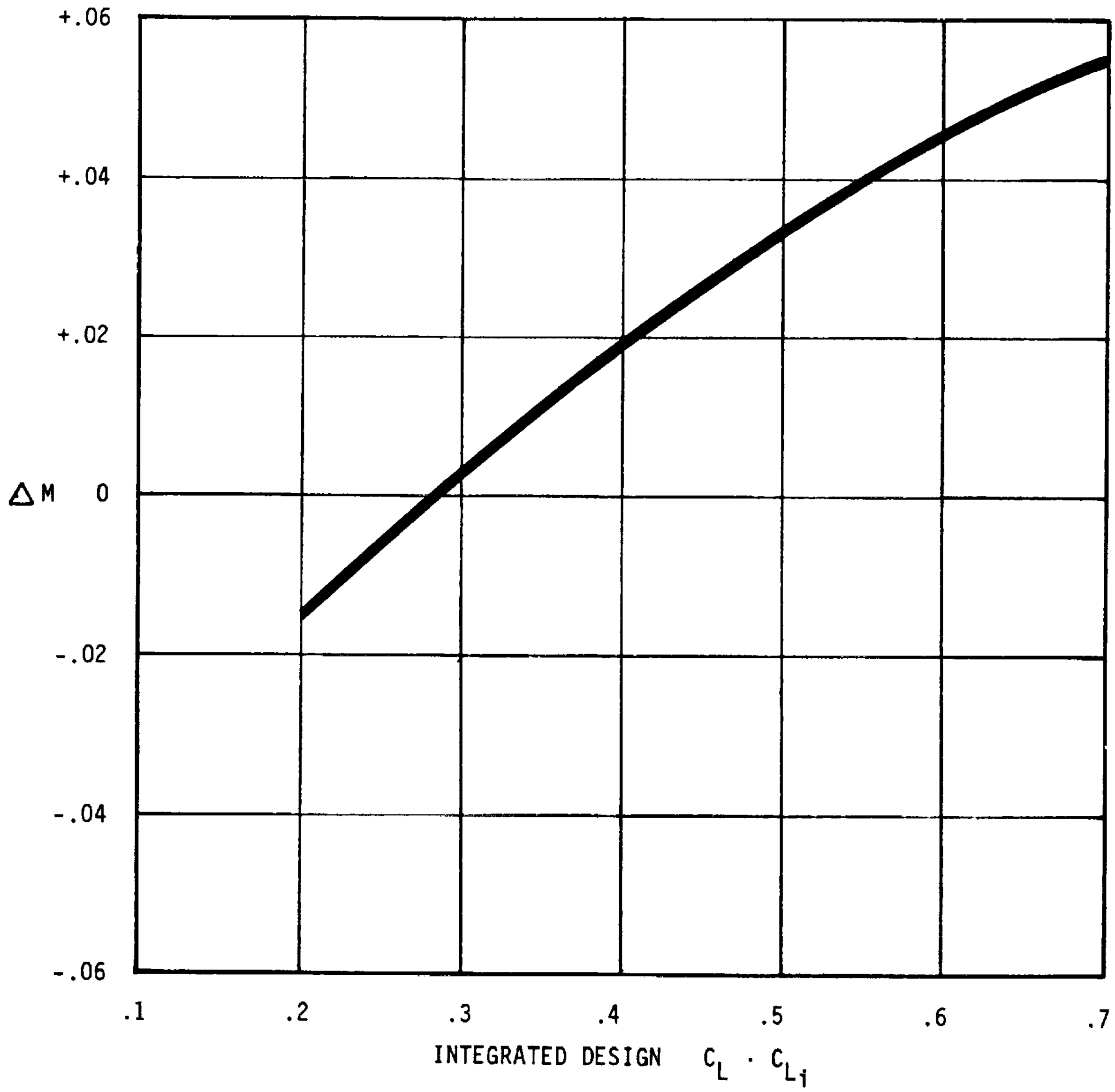


Figure B-2. Mach Number Adjustment for Effect of Blade Camber.

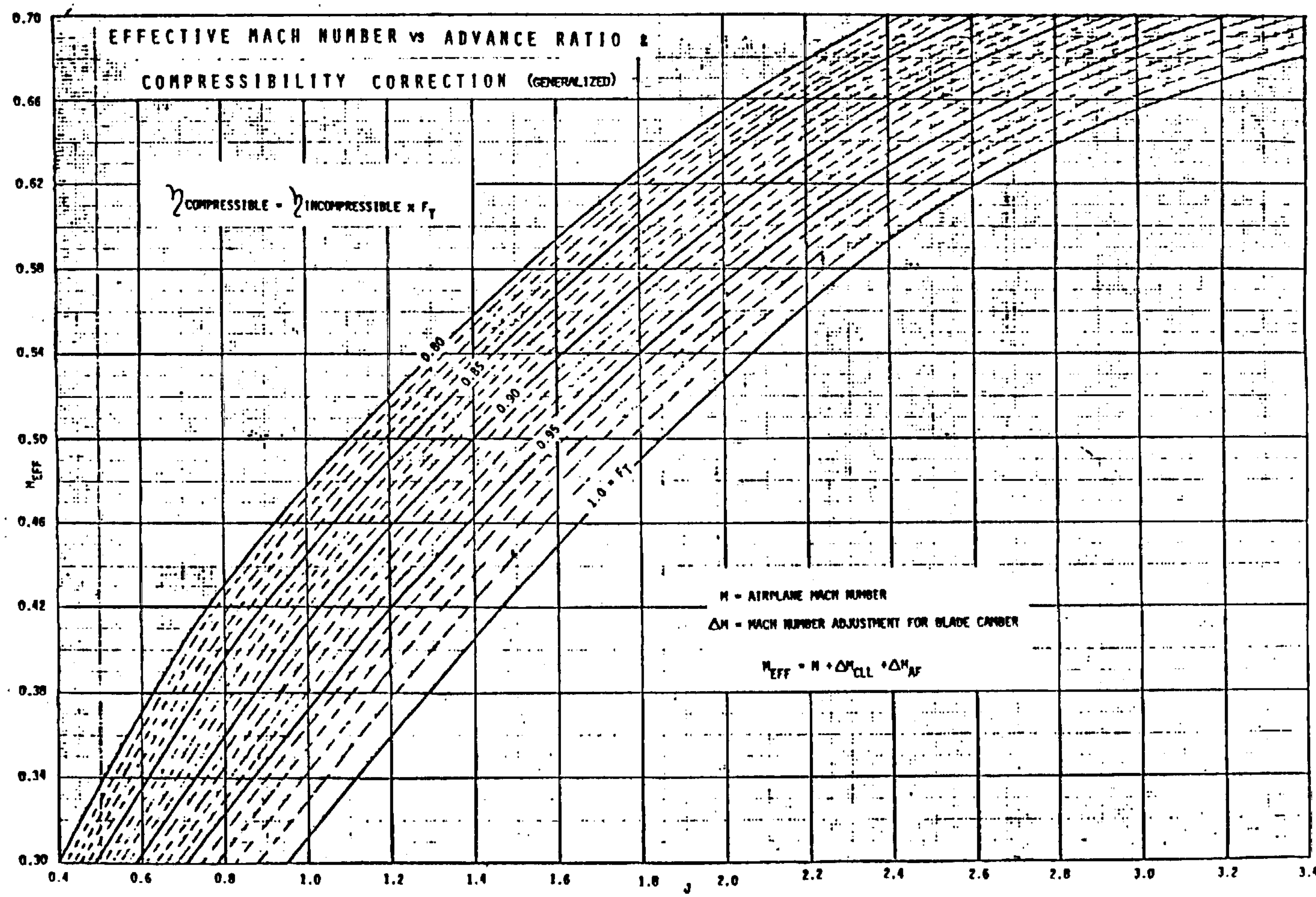


Figure B-3. Effective Mach Number vs Advance Ratio and Compressibility Correction.

ORIGINAL PAGE IS
OF POOR QUALITY

STATE-OF-THE-ART PROPELLER - Continued

Weight and Cost Generalizations

The formulae used to calculate propeller weight and cost were provided in the Propeller Characteristics section (pgs 110-112). Figure B-4 is the learning curve applied to cost.

Reliability and Maintainability

"The current technology propeller system has been analyzed to develop maintenance cost relationships. For this analysis, the current technology propeller system is a single-acting system consisting of a hub, pitch change mechanism, and blade assembly, including deicing hardware. The blades are solid aluminum. Results of the analysis are presented in Figure B-5. The cost relationship was developed utilizing frequencies of unscheduled maintenance actions derived from reliability studies as discussed below."

"Reliability predictions were prepared for the current technology propeller system. The predictions include both inherent failure causes (those primarily caused by propeller equipment failure) and non-inherent failure causes (those caused by other than propeller equipment failure such as FOD, and accident damage)."

ADVANCED TECHNOLOGY PROPELLER

"Propellers for the new and emerging advanced commuter aircraft included in this study, must meet stringent performance and low cabin and far field noise requirements with minimum weight and cost. High thrust levels for takeoff and climb conditions are essential while maintaining near optimum efficiency at the cruise conditions. The tip speeds need to be low and special attention must be paid to the propeller geometry to achieve the low noise requirements called out in the work statement. Moreover, the propeller solidity must be minimal to assure minimum weight. These stringent requirements are unique to the new commuter aircraft propellers and, to meet them, lead to the exploration of advanced technologies as well as the existing technologies not now being incorporated in propellers on today's commuter aircraft."

"In undertaking the task of establishing those advanced technologies with the greatest payoff, it is important to first determine the sources of efficiency losses, noise generation, weight and cost sensitive components. Then a list of potential remedies and new technologies to alleviate these sources and to improve performance, noise, weight and cost can be compiled."

"Thus, performance losses associated with round or thick blade roots can be improved by incorporating reasonably thin airfoils from the tip to the root. Also the spinner blade juncture should be configured to minimize the spinner-to-blade gap. Profile losses may be reduced by utilizing airfoils designed for high critical Mach numbers. In many applications, new airfoils designed to meet special requirements appear to offer improved performance. Compressibility losses may be alleviated by utilizing thinner airfoils along the blade, the use of sweep and reduced tip speed. Induced losses may be reduced by use of many blades and by end plates or proplets (akin to winglets on high-speed wings). For high-speed aircraft, Prop-Fans with thin, swept blades and possibly counter-rotation tandem propellers may permit improved performance at reduced size and/or tip speed possibly with correspondingly reduced noise."

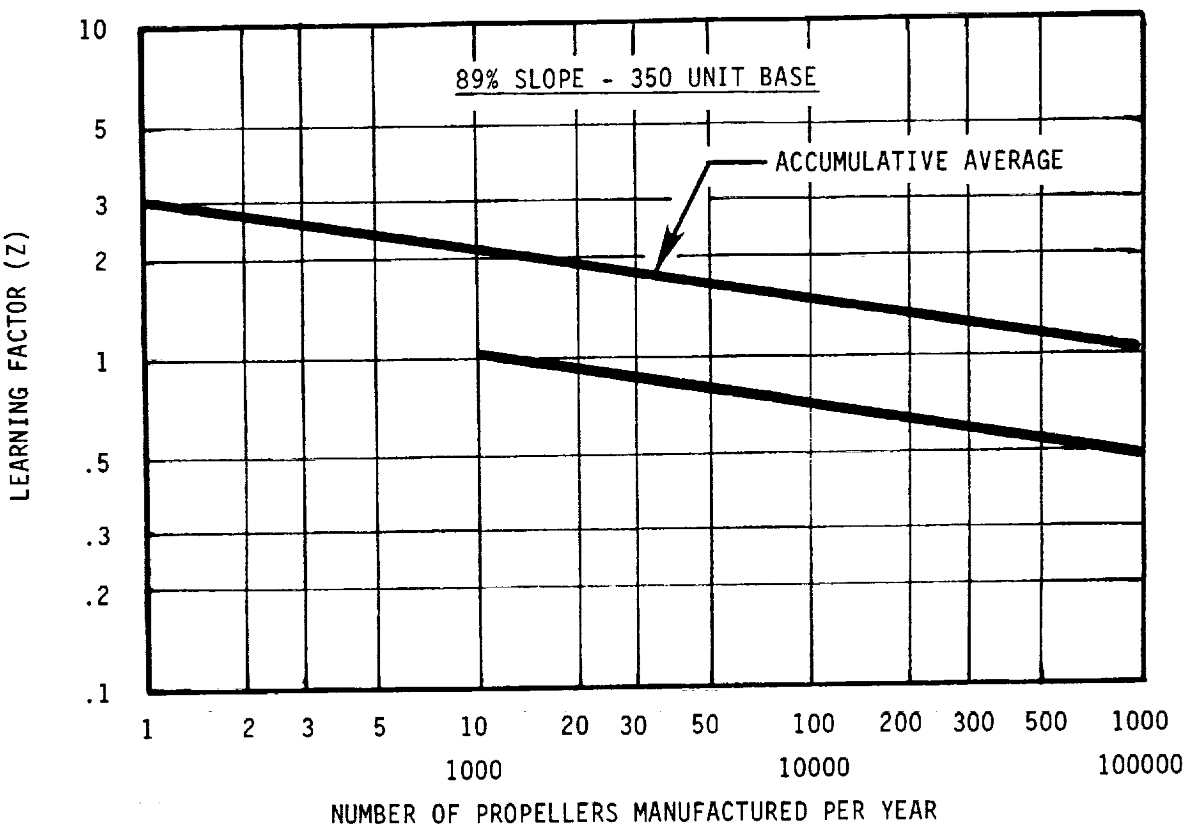


Figure B-4. Learning Curve.

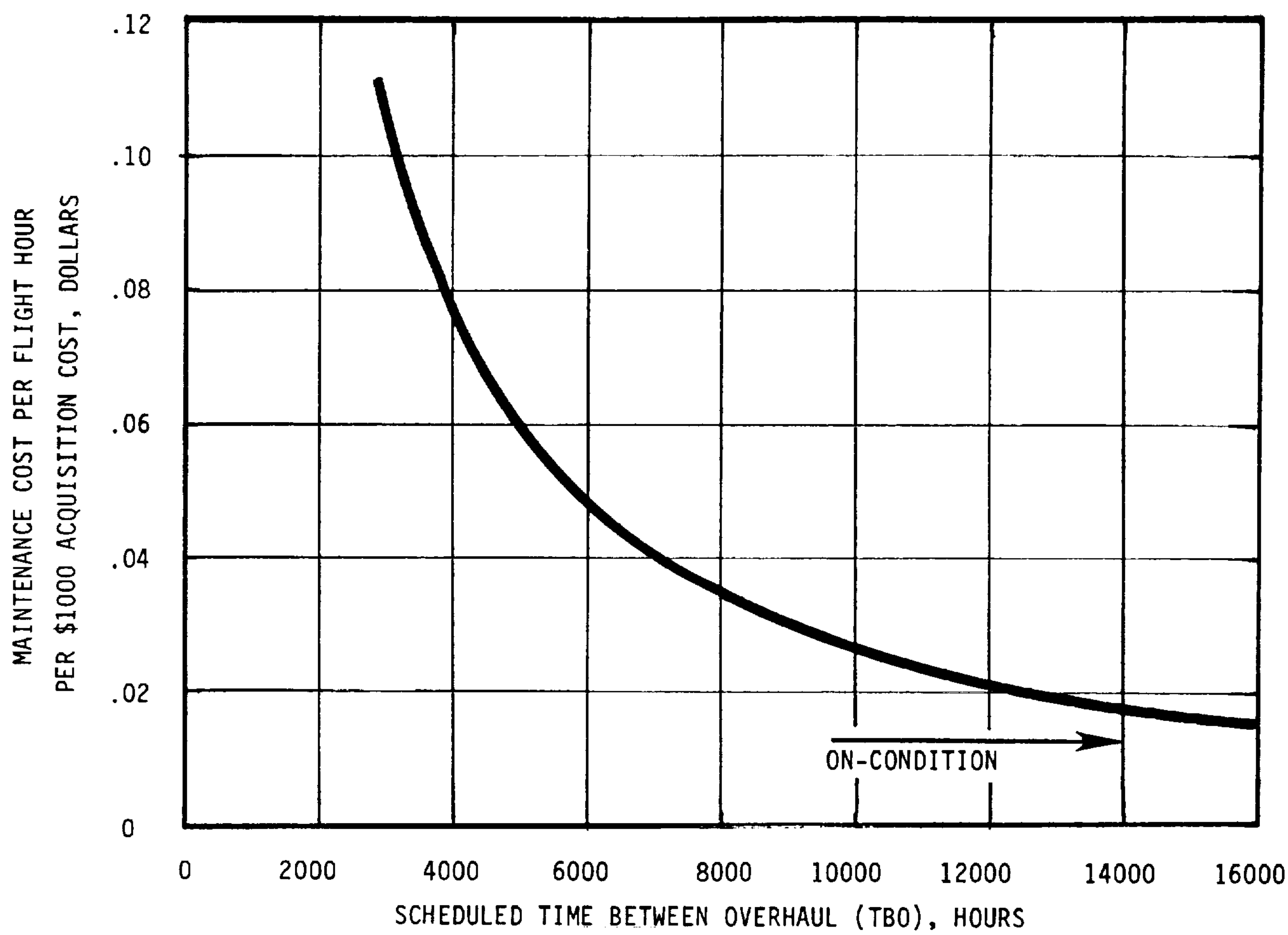


Figure B-5. Maintenance Cost per Flight Hour per $1000 Acquisition Cost vs Scheduled Time Between Overhaul for Current Technology Propeller

HAMILTON STANDARD DIVISION PROPELLER DATA - Continued

ADVANCED TECHNOLOGY PROPELLER - Continued

"Noise reduction may be achieved with increased number of blades, sweep, proplets, reduced tip speeds, and in some cases, thinner airfoil sections. Advanced precision synchrophasers may significantly reduce the cabin noise of multi-engine aircraft."

"Advanced composites offer reduced blade weight, narrower blades required with increased blade number, maintenance of smooth surfaces to alleviate performance losses with time."

"Moreover, the concepts mentioned above may be combined in some cases to produce additional effects as well as to improve performance, noise and weight simultaneously."

"A number of these propeller geometric and aerodynamic parameters and new concepts could be included in a list of advanced technologies for commuter aircraft propellers. A list of the more promising parameters and concepts is presented below. Performance, noise, weight, and cost parametric data are presented herein.

1. Blade sweep.
2. Advanced aerodynamic/acoustic airfoils.
3. Blade tip proplets.
4. Multibladed propellers.
5. Narrow blades (low activity factor).
6. Thin blades.
7. Advanced composite structures.
8. Precision synchrophasers."

"Each of the above technologies have been considered in the study. The state-of-the-art of several of these are only at the initial stages of development. In some cases, the concepts look promising on the basis of rather crude aerodynamic and/or acoustic analyses. Some are still being investigated under this program. Moreover, the advanced technology which have been included in this report are not in all cases based on firm analyses or on experimental data. Yet in all cases, the concepts look attractive enough for consideration and further evaluation."

HAMILTON STANDARD DIVISION PROPELLER DATA - Continued

ADVANCED TECHNOLOGY PROPELLER - Continued

Aerodynamic Performance

Performance data tabulations are provided for the same combinations of blade number, activity factor (AF) and integrated design lift coefficient (C_{L_i}), as for the current technology propellers*, with the addition of one 6-bladed, 75 AF, .55 C_{L_i} propeller. "The data represents the imcompressible performance. Corrections are presented to modify the performance data for compressiblity and for advanced technology features."

"To achieve the low activity factor of the six-bladed propeller, it was necessary to increase the airfoil thickness ratios in relation to the higher AF propellers. Thicker airfoils were incorporated directly in the performance predictions for this propeller, but not for the other propellers which are affected. The thicker airfoils lower the propeller imcompressible performance and reduce the airfoil critical Mach numbers. The first of these effects is shown on Figure B-6 as a small correction, $(\Delta C_{T_{Net}})$ AF to the incompressible net thrust coefficient. This increment is subtracted from the tabulated $C_{T_{Net}}$'s for the propellers which require thicker airfoils." This correction applies to both adfanced and conventional technology propellers.

"A compressibility correction (F_T) is provided for use with the tabulated performance. This correction is obtained from Figures B-7 and B-8 and Figure B-3 of the preceding section for propellers without blade tip sweep. No correction is required for blades with the 45° of tip sweep that was incorporated in this study."

"The precedure for calculating the compressible propeller performance is:

1. Incompressible $C_{T_{Net}}$ from Tables.
2. $(\Delta C_{T_{Net}})_{AF} = f(V\sqrt{\theta}$, AF) from Figure B-6.
3. Corrected Incom. $C_{T_{Net}}$ = Incomp. $C_{T_{Net}} + (\Delta C_{T_{Net}})_{AF}$.
4. $\Delta MC_{L_i} = f(C_{L_i})$ from Figure B-7.
5. $\Delta M_{AF} = F(AF, J)$ from Figure B-8.
6. M_{EFF} = Flight Mn + $\Delta MC_{L_i} + \Delta M_{AF}$.
7. $F_T = f(J, M_{EFF})$ from Figure B-3.
8. Compressible $C_{T_{Net}} = F_T$ (Corrected Inc. $C_{T_{Net}}$)."

* NOTE: Tabulated performance data provided by Hamilton Standard to General Electric is identical for conventional and advanced technology propellers.

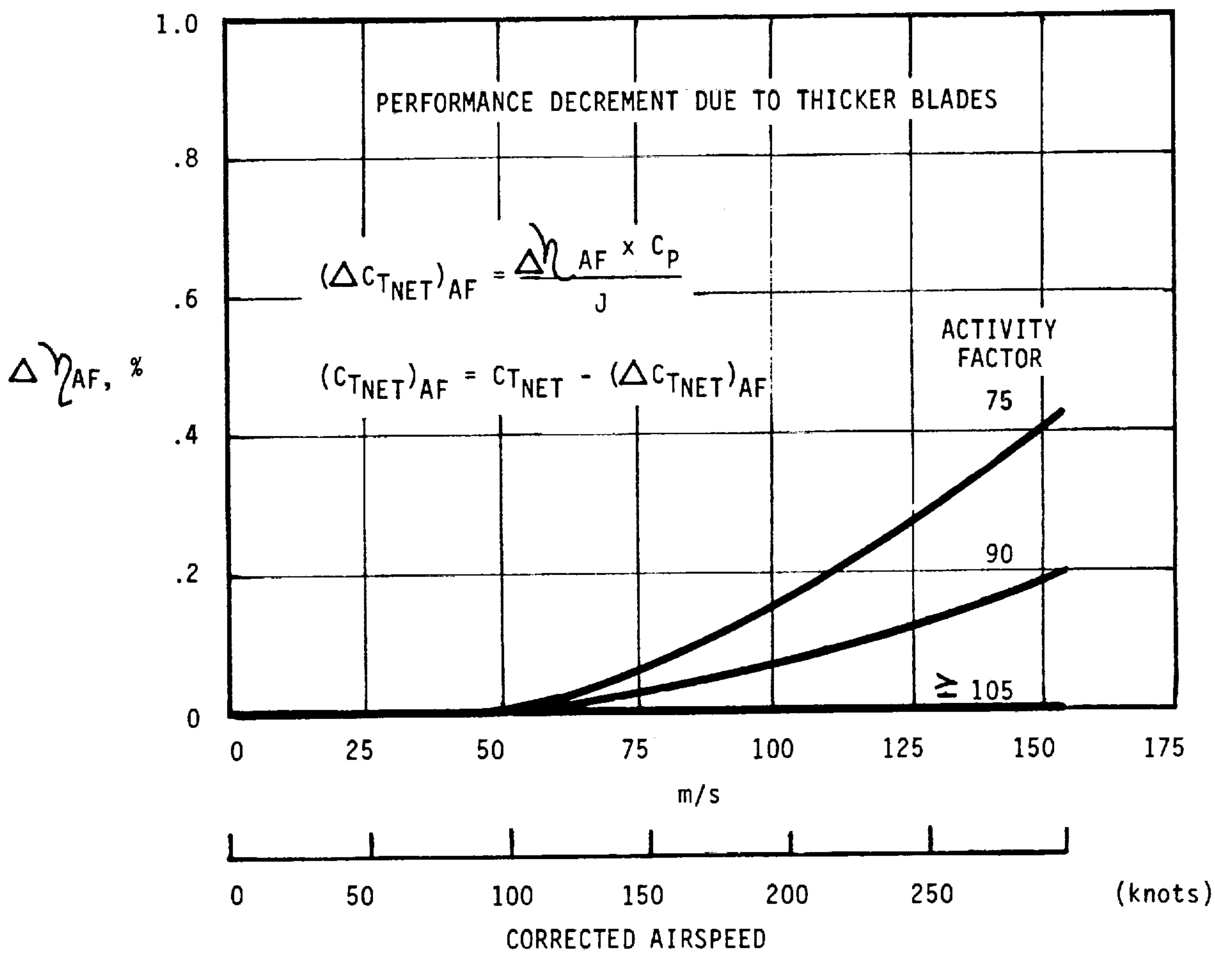


Figure B-6. Performance Decrement Due to Activity Factor for Subcritical Operation.

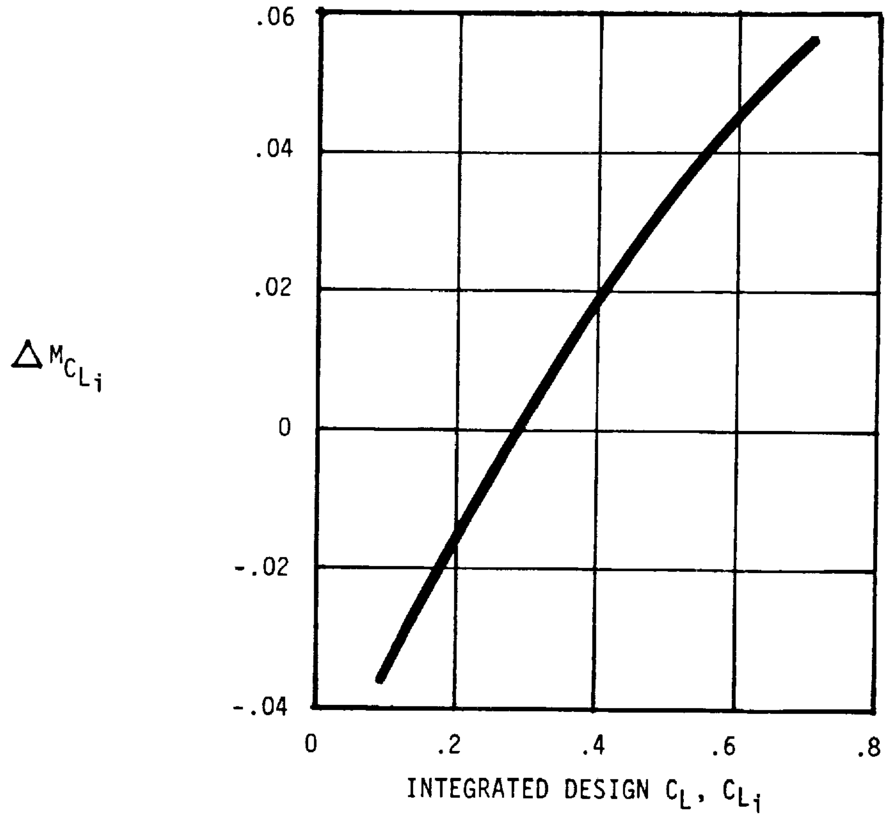


Figure B-7. Mach Number Adjustment for Effect of Blade Camber.

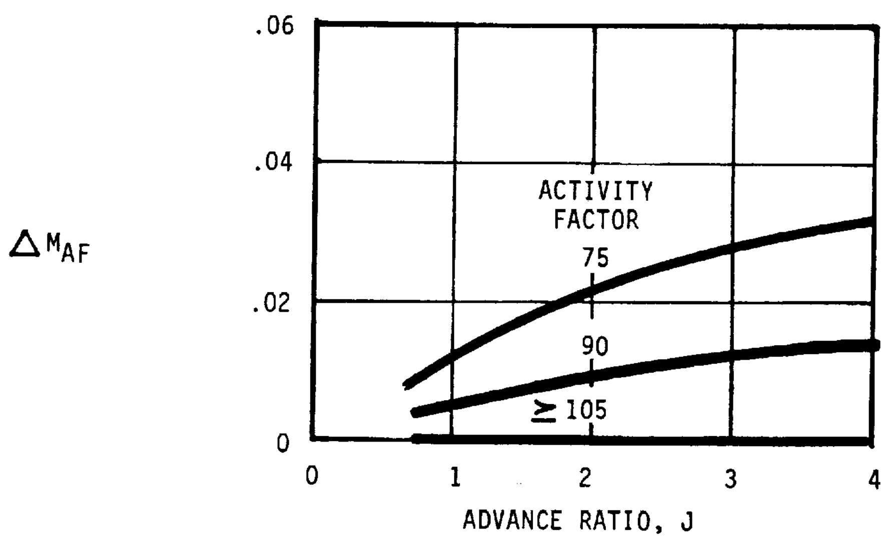


Figure B-8. Mach Number Adjustment for Effects of Activity Factor.

HAMILTON STANDARD DIVISION PROPELLER DATA - Continued

ADVANCED TECHNOLOGY PROPELLER - Continued

Aerodynamic Performance Correction for the Addition of Blade Tip Proplets

"The propeller performance can be modified for the addtion of blade tip proplets. The proplet corrections, $\Delta C_{T_{Net}}$, is shown in Figure B-9 and was calculated from vortex drag reduction data measured for wings with wing tip sails. The compressible performance of an advanced technology propeller with proplets is obtained from:

1. Compressible $C_{T_{Net}}$ = Incomp. $C_{T_{Net}} \times F_T$, as shown above.
2. Read $\Delta C_{T_{Net}} = f(J, C_P, TAF)$ from Figure B-9.

   Where TAF = Total Activity Factor = AF x No. of Blades.
3. Compressible $C_{T_{Net}}$ with proplets = Compressible $C_{T_{Net}} + \Delta C_{T_{Net}}$."

Aerodynamic Performance Correction for the Addition of Propeller Tip Sweep

"The performance tabulations are for propellers with straight or unswept blades. Tip sweep is generally not necessary to improve the propeller performance for the low speed airplanes. The major benefit of sweep is to effect relative Mach numbers which are below the critical Mach numbers of the airfoil sections. Therefore, the tabulated data including the low activity factor correction in Figure B-6 can be used to represent the compressible performance of propellers with tip sweep for the low speed airplanes."

Weight and Cost Generalizations

See the Propeller Characteristics section (pgs 110-112) for the basic weight and cost calculations.

"Two parameters may be added to propeller design which are not reflected in the generalized weight formula. These are blade sweep and proplets. If sweep is used, add an additional 10% to the weight. If proplets are used, add an additional 5% to the weight."

"Three parameters may be added to the propeller design which will affect the cost and are not reflected in the generalized cost formula. These parameters are blade sweep, blade proplets, and advanced precision synchrophasing."

"If sweep is used, add 5% to the cost of a propeller."

"If proplets are used, add 10% to the cost of a propeller."

"If advanced precision synchrophasing is used, add $5000 to the cost of a propeller."

Reliability and Maintainability

"The advanced technology propeller system has been analyzed to develop maintenance cost relationships. For this analysis, a double-acting system consisting of a hub, pitch change mechanism, and blade assembly, including deicing hardware, has been assumed for the advanced technology propeller. The blades are fabricated with advanced composites for the airfoil. Results of the analysis are presented in Figure B-10. The cost relationship was developed utilizing frequencies of unscheduled maintenance actions derived from reliability studies as discussed below."

ADVANCED TECHNOLOGY PROPELLER - Continued

"Reliability predictions were prepared for the advanced technology propeller system. The predictions include both inherent failure caused (those primarily caused by equipment failure) and non-inherent failure causes (those primarily caused by other than propeller equipment failure such as FOD, and accident damage)."

Combining Various Advanced Technology Features

"It might appear that if a single advanced technology feature produces attractive results, combining two or more features would be even better. This is true in some instances, such as combining multi-blades, thin airfoils, sweep and advanced composite structures, for example. Caution should be exercised in other instances where the procedures that are presented would permit the superposition of effects. For example, the practicality of adding proplets to a swept propeller has not yet been established, and at this time does not appear to be practical. Only those effects for which procedures are actually described in the text are considered practical at this time."

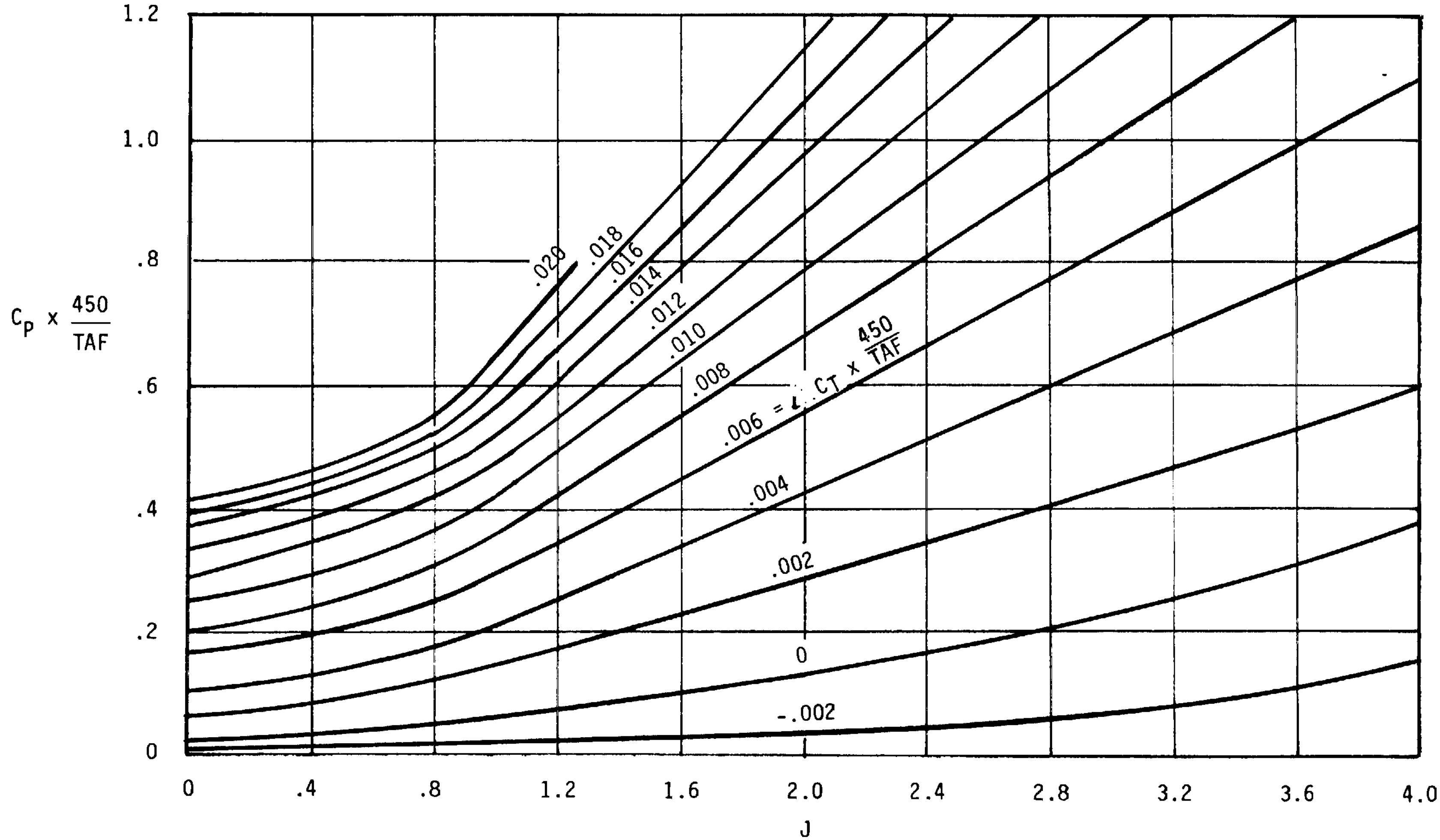


Figure B-9. Preliminary Effect of Proplets on Thrust Coefficient.

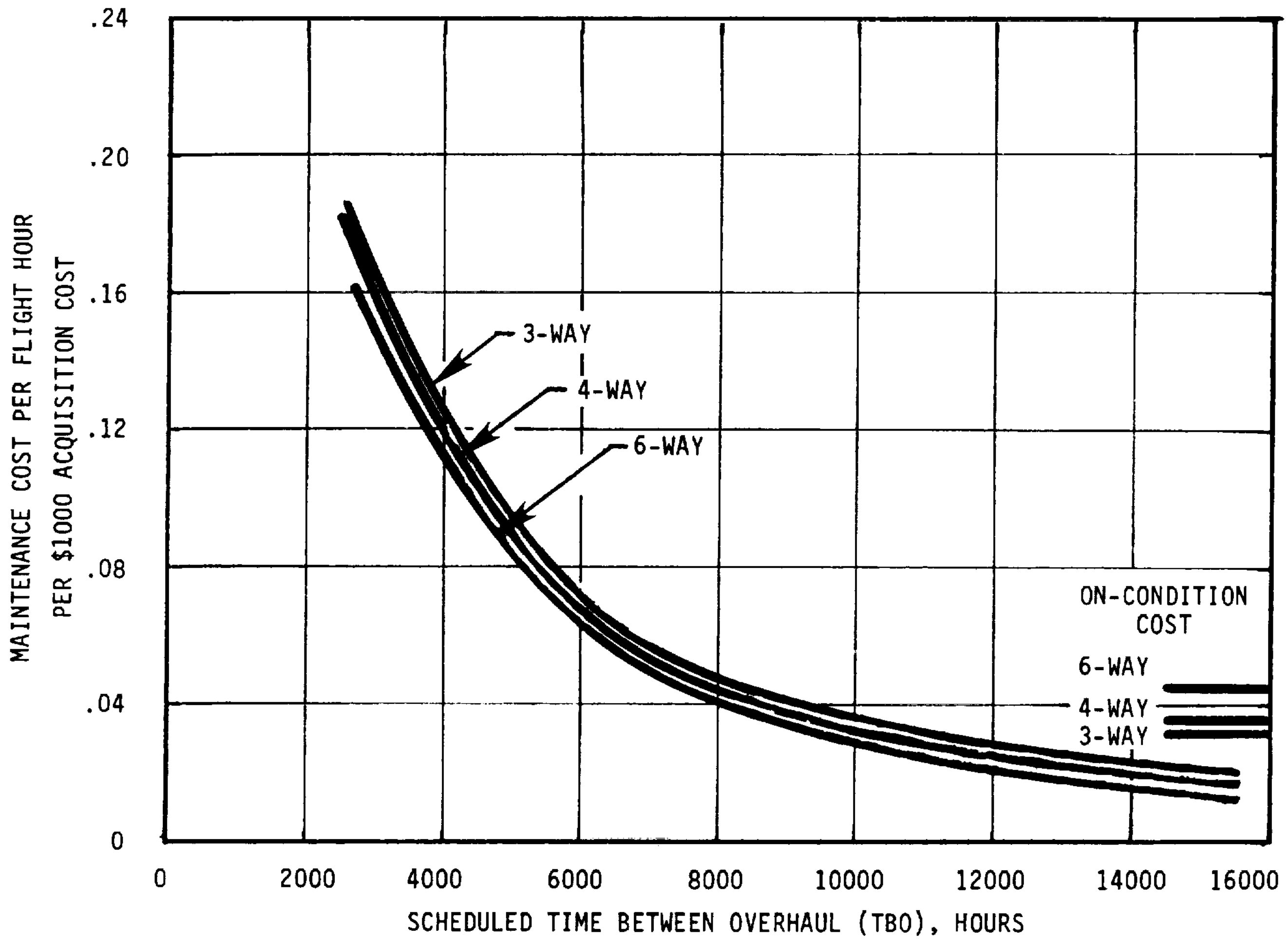
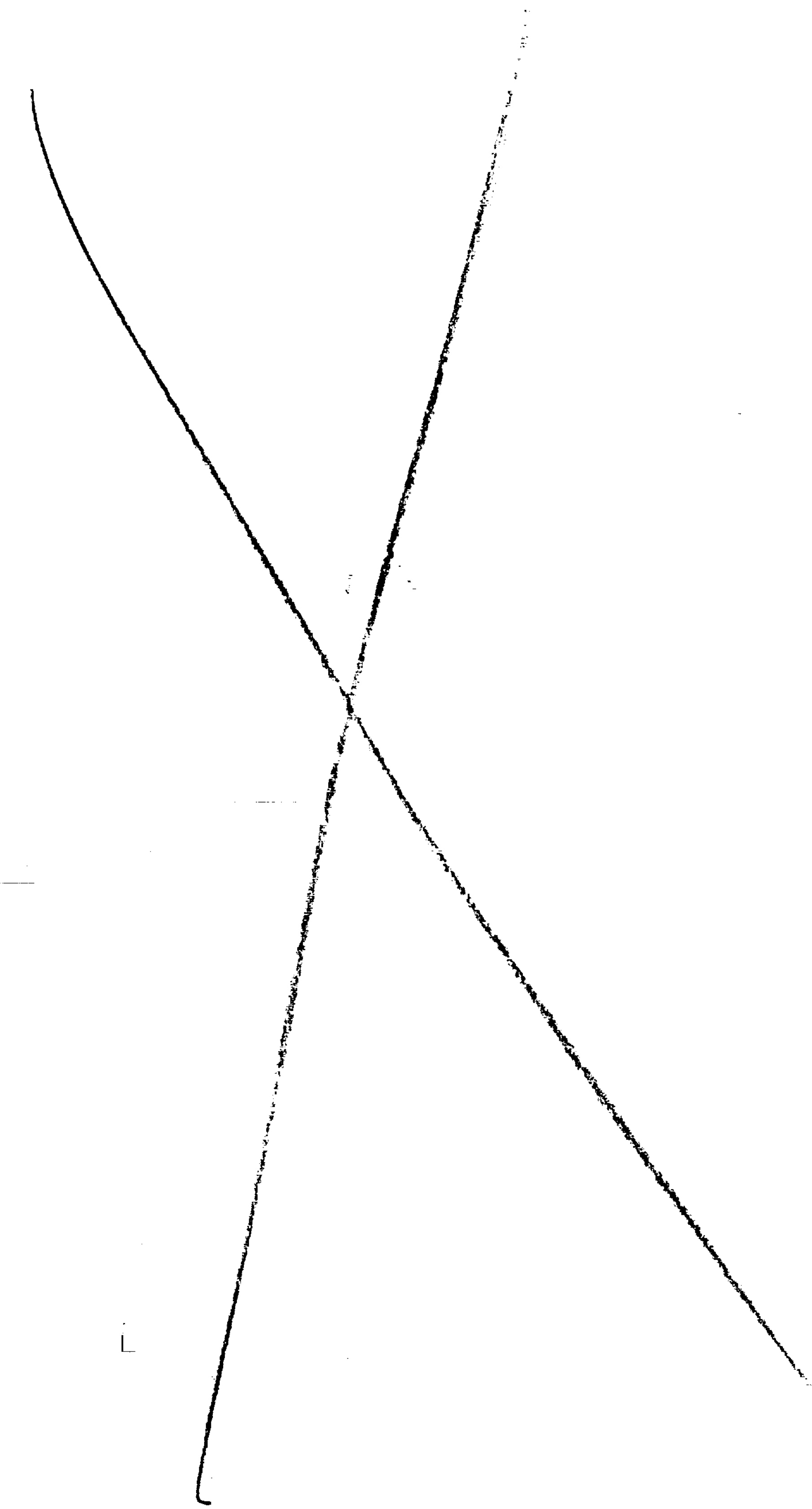


Figure B-10. Maintenance Cost per Flight Hour per $1000 Acquisition Cost vs Scheduled Time Between Overhaul for Advanced Technology Propeller.



APPENDIX C

ADVANCED ENGINE PERFORMANCE DATA

Table C-1 provides a detailed cycle definition of the two advanced engines in the final mission size. Figures C-1 through C-10 provide performance data for the 30-passenger advanced turboprop engine in terms of equivalent power and fuel flow versus altitude, mach number, ambient temperature, and turbine inlet temperature. Figures C-11 through C-20 provide the same information for the 50-passenger advanced turboprop engine. Note that data are provided in the design size. To obtain values in the mission size, scale uninstalled equivalent power and fuel flow by 0.916 for the 30-passenger size and by 0.935 for the 50-passenger size.

Preceding page blank

TABLE C1

ADVANCED ENGINE CYCLE DEFINITIONS

MISSION SIZE

Sea Level, Static, Std. Day except as noted

	30-Passenger Size Advanced Engine	50-Passenger Size Advanced Engine
Turbine Inlet Temp °C (°F)	1260 (2300)	1316 (2400)
Cycle Pressure Ratio	17.0	20.2
Output Power - kW (hp)		
15°C (59°F)	1107 (1485)	1831 (2455)
32.2°C (90°F)	943 (1265)	1510 (2025)
Specific Power - kW/kg/S (hp/lbm/sec)	312 (190)	342 (208)
SFC - kg/kW·h (lbm/hp·h)	.267 (.439)	.252 (.415)
Net Thrust - N (lb)	765 (172)	1156 (260)
Fuel Flow - kg/h (lbm/h)	296 (652)	381 (1019)
Booster		
Number of Stages	None	1 Axial
Inlet Flow - kg/s (lbm/sec)		5.4 (11.8)
Inlet Corrected Flow - kg/s (lbm/sec)		5.4 (11.8
Inlet Corrected Tip Speed m/s (ft/sec)		335.3 (1100)
Pressure Ratio		1.35
Adiabatic Efficiency		.872
Rotational Speed, rad/s (rpm)	2885 (27560)	2325 (22190)
Compressor		
Number of Stages	3 Ax. + 1 Cent.	3 Ax. + 1 Cent.
Inlet Flow - kg/s (lbm/sec)	3.5 (7.8)	5.4 (11.8)
Inlet Corrected Flow - kg/s (lbm/sec)	3.5 (7.8)	4.2 (9.3)
Inlet Corrected Tip Speed m/s (ft/sec)	472 (1550)	459 (1505)
Centrifugal Impeller Corr. Tip Speed m/s (ft/sec)	640 (2100)	652 (2140)
Pressure Ratio	17.0	15.2
Adiabatic Efficiency	.840	.845
Rotational Speed, rad/s (rpm)	5350 (51075)	4780 (45650)

TABLE C1 - Continued

	30-Passenger Size Advanced Engine	50-Passenger Size Advanced Engine
Discharge Pressure-kN/m^2(lbf/in^2)	1724 (250)	2041 (296)
Discharge Temperature-°C (°F)	430 (806)	470 (878)
Combustor		
Pressure Loss - %	4.2	4.2
Efficiency	.995	.995
Fuel Lower Heating Value kJ/kg (BTU/lbm)	42800 (18400)	42800 (18400)
HP Turbine		
Number of Stages	1	1
Flow Function (W$\sqrt{T}$/P) - kg °K$^{.5}$ m^2/(kN·S) [lbm °R$^{.5}$ in^2/(lbf·sec)]	.078 [1.59]	.102 [2.07]
Specific Work (Δh) - kJ/kg (BTU/lbm)	460 (198)	472 (203)
Mean Pitch Line Wheel Speed - m/s (ft/sec)	527 (1730)	540 (1772)
Loading ($\overline{\Psi}$p)	.83	.81
Pressure Ratio	4.1	4.0
Adiabatic Efficiency	.866	.868
LP Turbine		
Number of Stages	2	3
Flow Function (W$\sqrt{T}$/P) - kg °K$^{.5}$ m^2/(kN·s) [lbm °R$^{.5}$ in^2/(lbf·sec)]	.3 [6.12]	.381 [7.78]
Specific Work (Δh) - kJ/kg (BTU/lbm)	321 (138)	381 (164)
Inlet Temperature - °C (°F)	866 (1590)	916 (1680)
Mean Pitch Line Wheel Speed - m/s (ft/sec)	309 (1015)	271 (890)
Loading ($\overline{\Psi}$p)	.84	.86
Pressure Ratio	3.5	4.2
Adiabatic Efficiency	.915	.916
Exit Mach No.	.5	.5
Exit Swirl, - deg.	15	8

TABLE C1 - Continued

	30-Passenger Size Advanced Engine	50-Passenger Size Advanced Engine
Exhaust Nozzle		
Pressure Loss, %	1.9	1.2
Pressure Ratio (P_8/P_{Amb})	1.10	1.10
Exhaust Temperature - °C (°F)	586 (1087)	588 (1090)
Secondary Flows*		
Axial Compressor Disch. Bleed		
Returned Post LPT	1.4	1.4
Vented Overboard	0.5	0.5
Total	1.9	1.9
Centrifugal Comp. Disch. Bleed		
Returned Post HPT	6.2	5.75
Returned Post LPT	1.2	1.2
Overboard Leakage	0.25	0.25
Total	7.65	7.20

*Expressed as percent of HP compressor inlet flow.

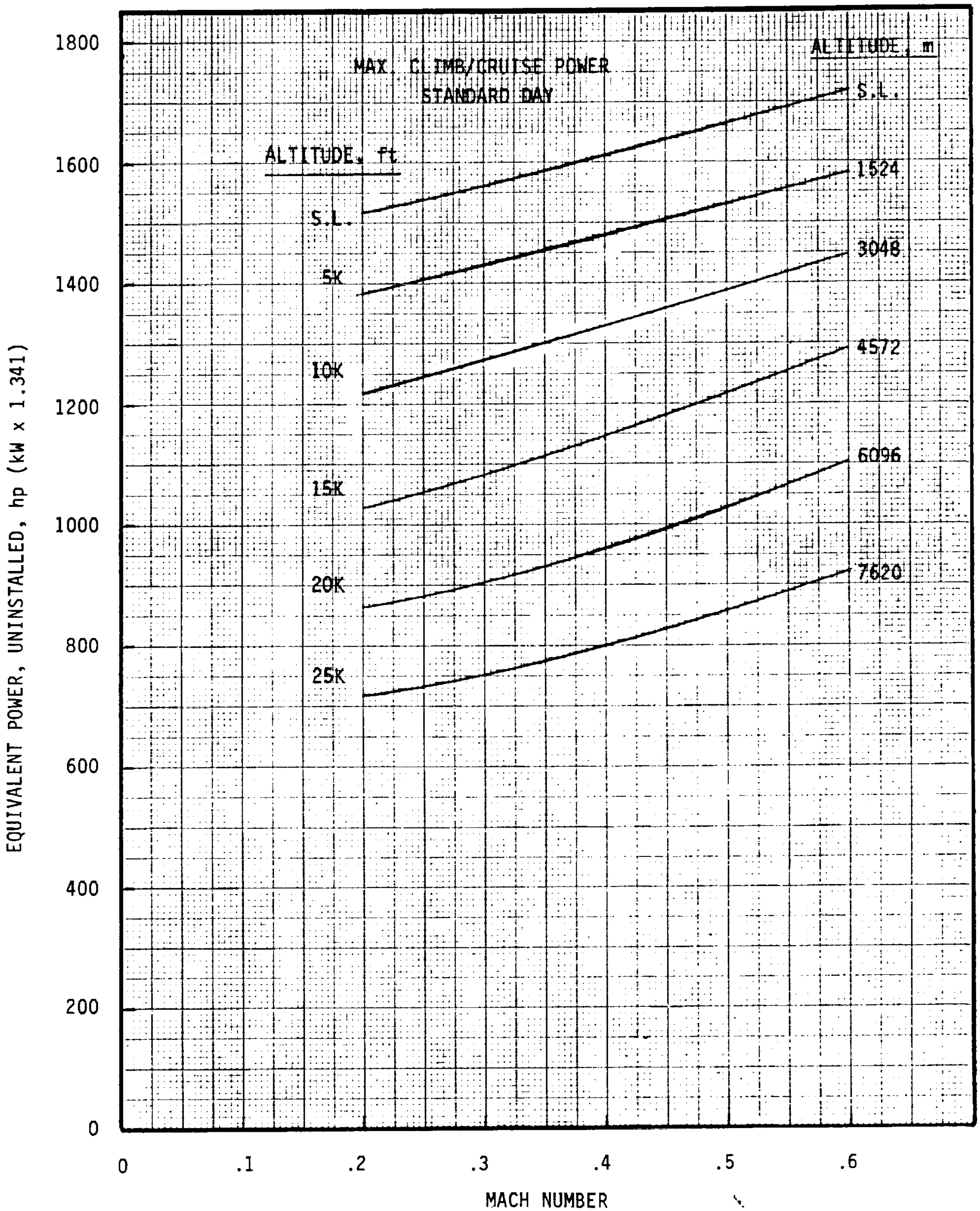


Figure C-1. 30-Passenger Size Advanced Engine - Equivalent Power vs Altitude and Mach Number.

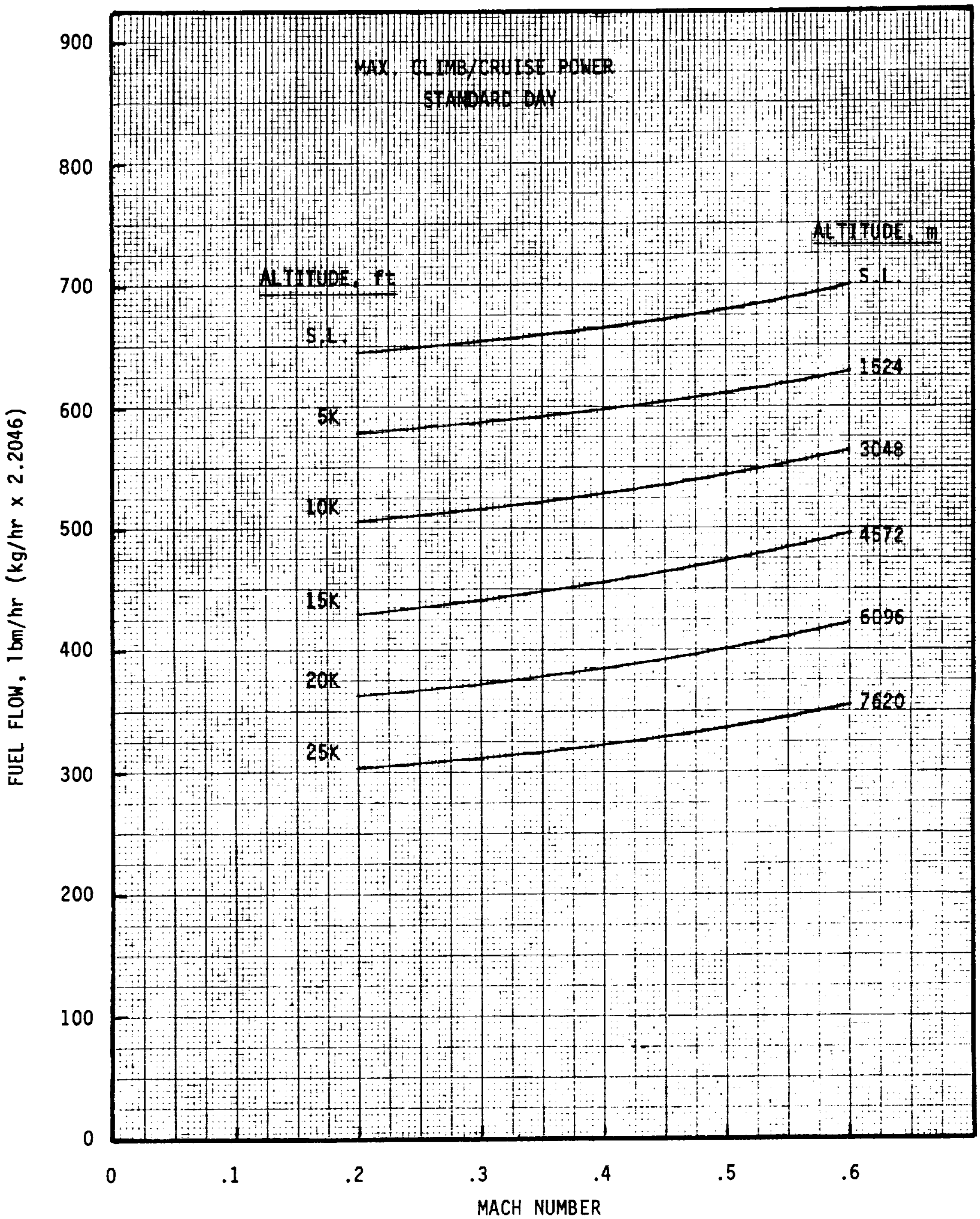


Figure C-2. 30-Passenger Size Advanced Engine - Fuel Flow vs Altitude and Mach Number.

ORIGINAL PAGE IS
OF POOR QUALITY

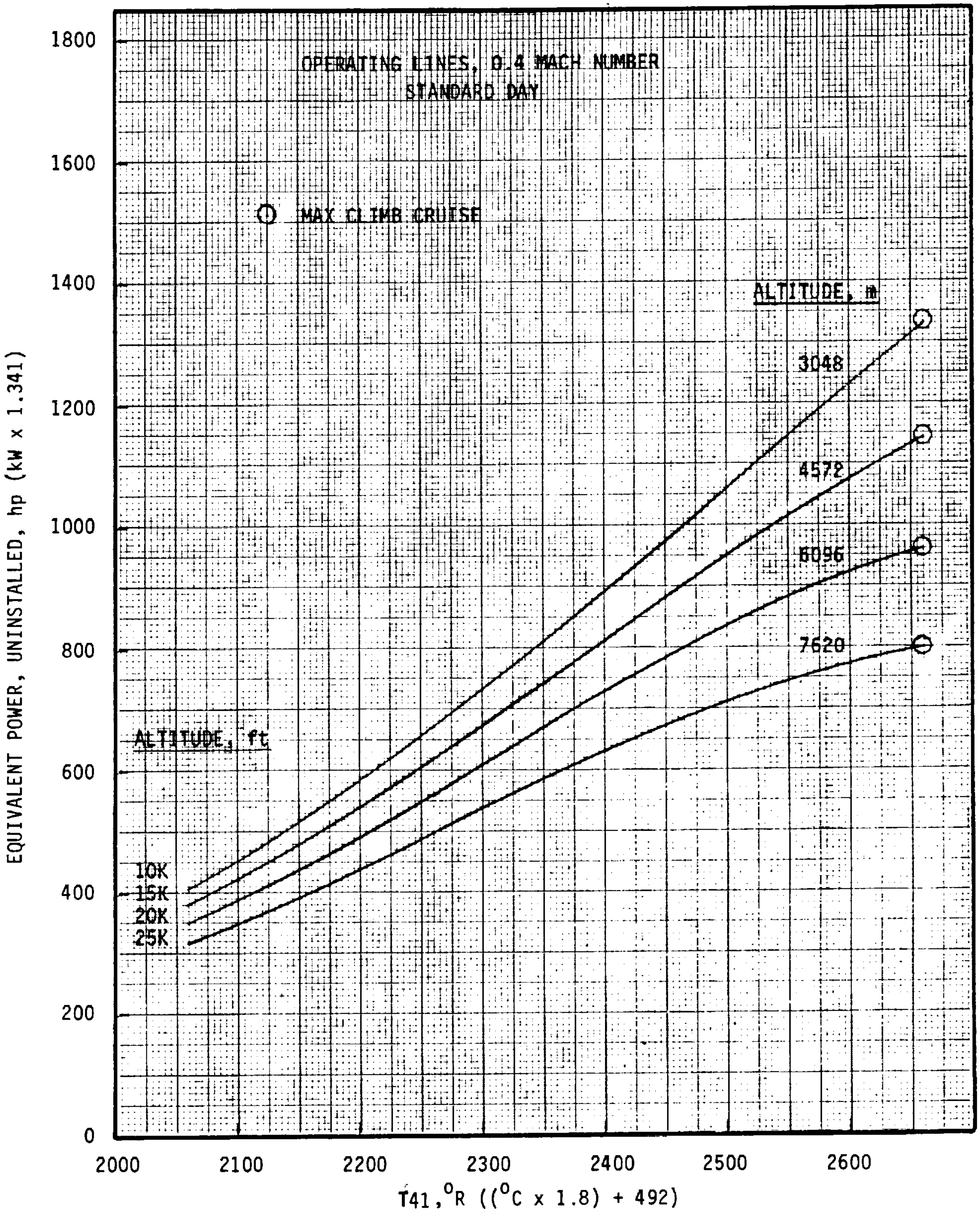


Figure C-3. 30-Passenger Size Advanced Engine - Equivalent Power vs Altitude and T41.

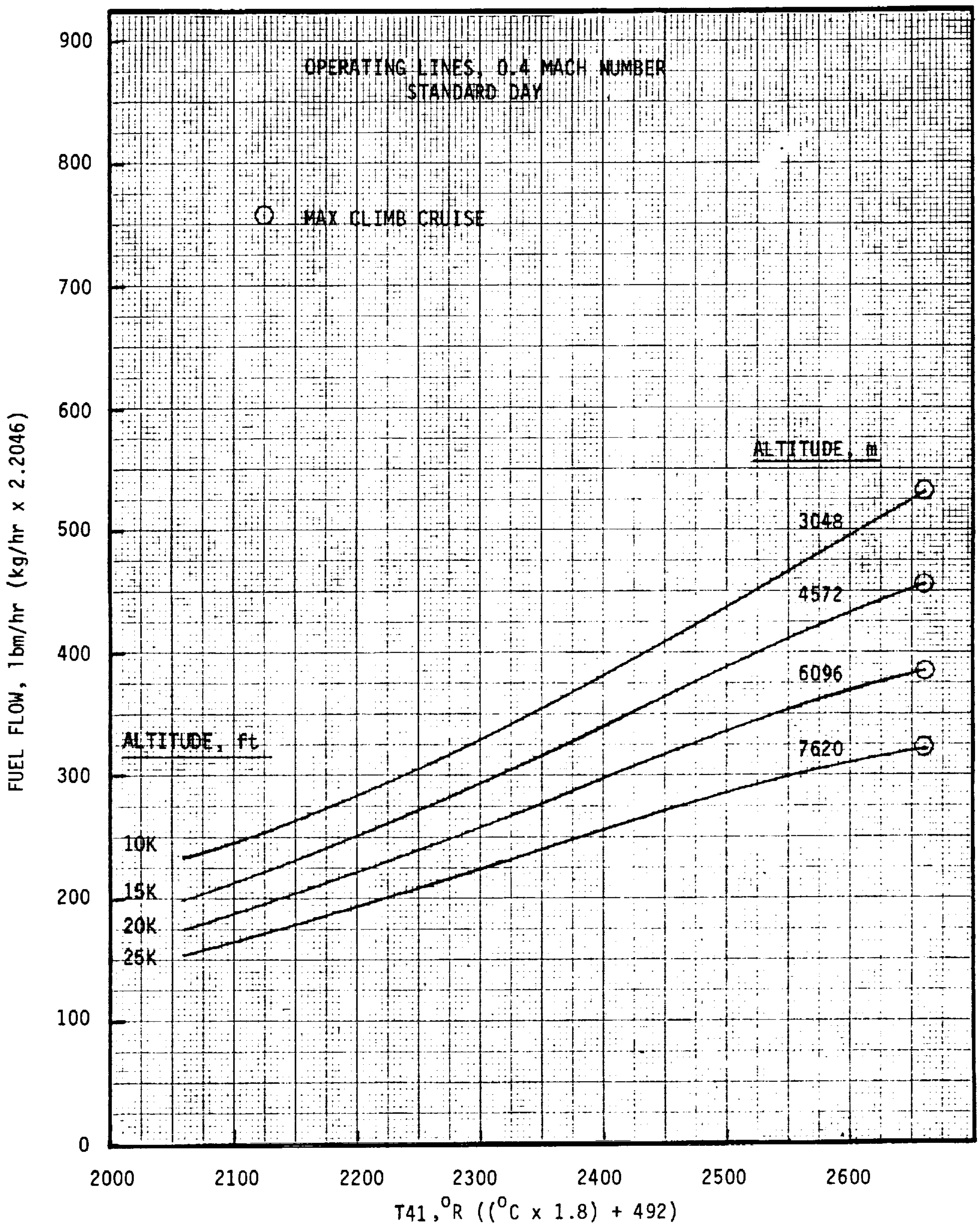


Figure C-4. 30-Passenger Size Advanced Engine - Fuel Flow vs Altitude and T41

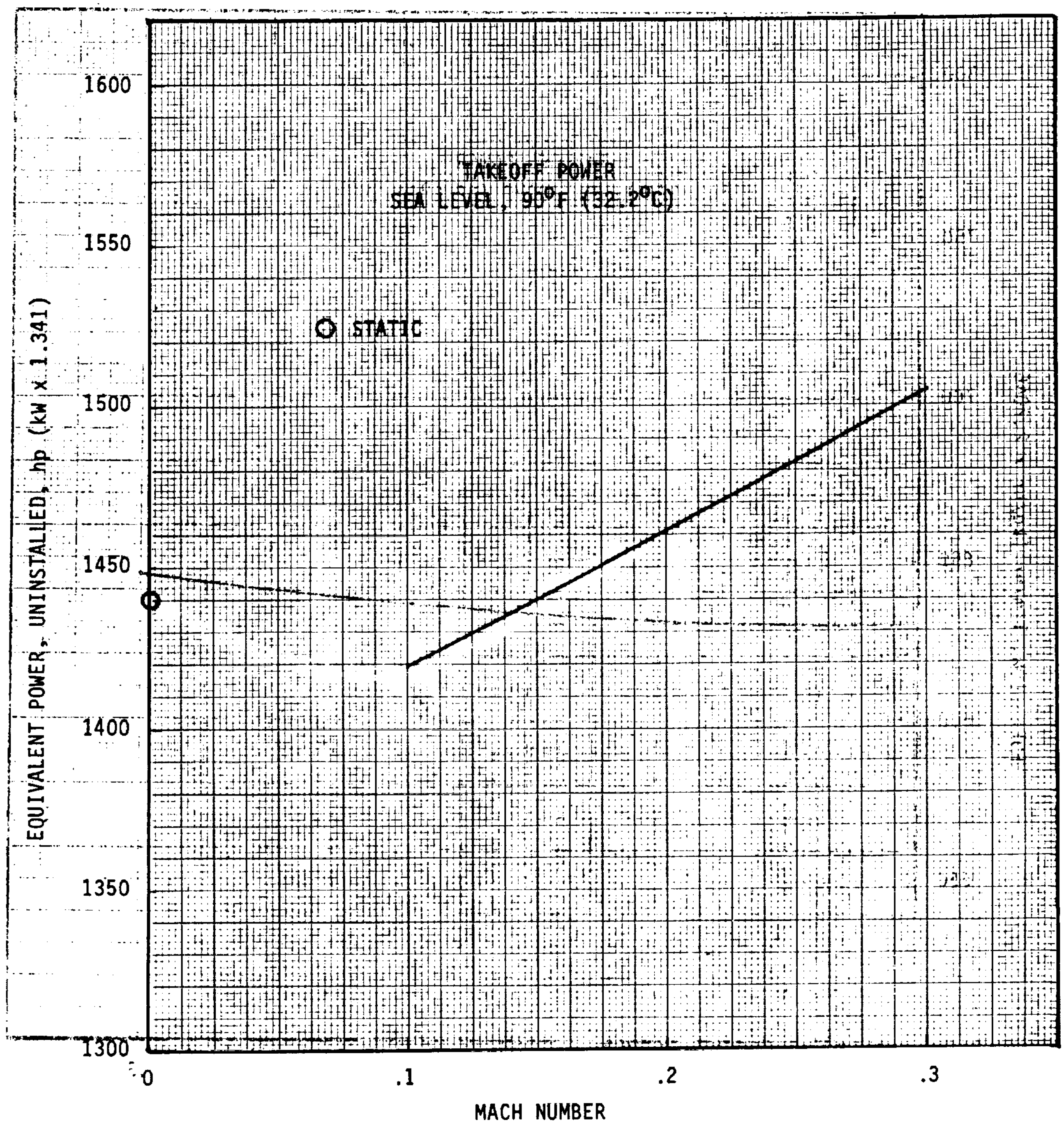


Figure C-5. 30-Passenger Size Advanced Engine - Takeoff Equivalent Power vs Mach Number.

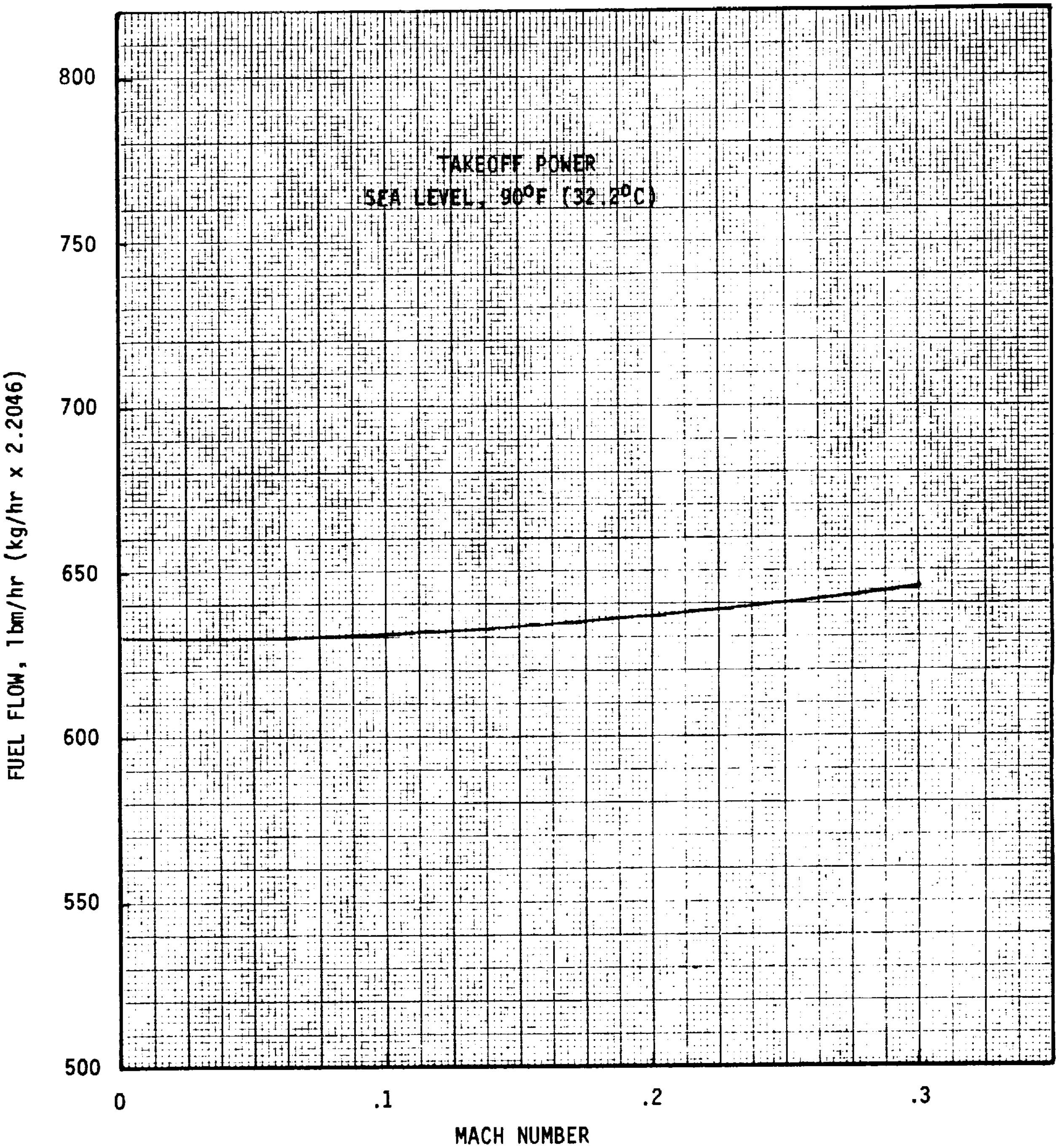


Figure C-6. 30-Passenger Size Advanced Engine - Takeoff Fuel Flow vs Mach Number.

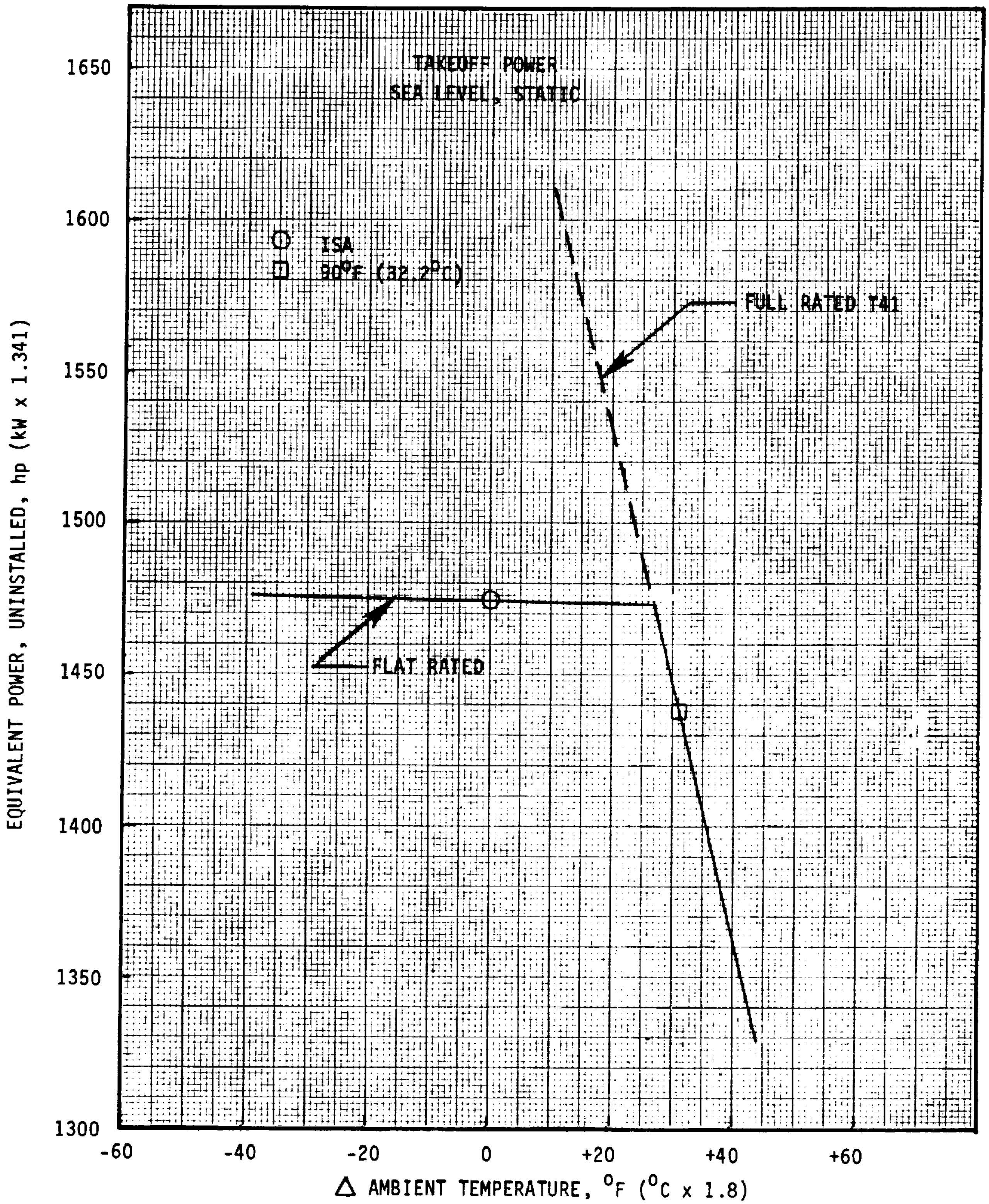


Figure C-7. 30-Passenger Size Advanced Engine - Takeoff Equivalent Power vs Ambient Temperature.

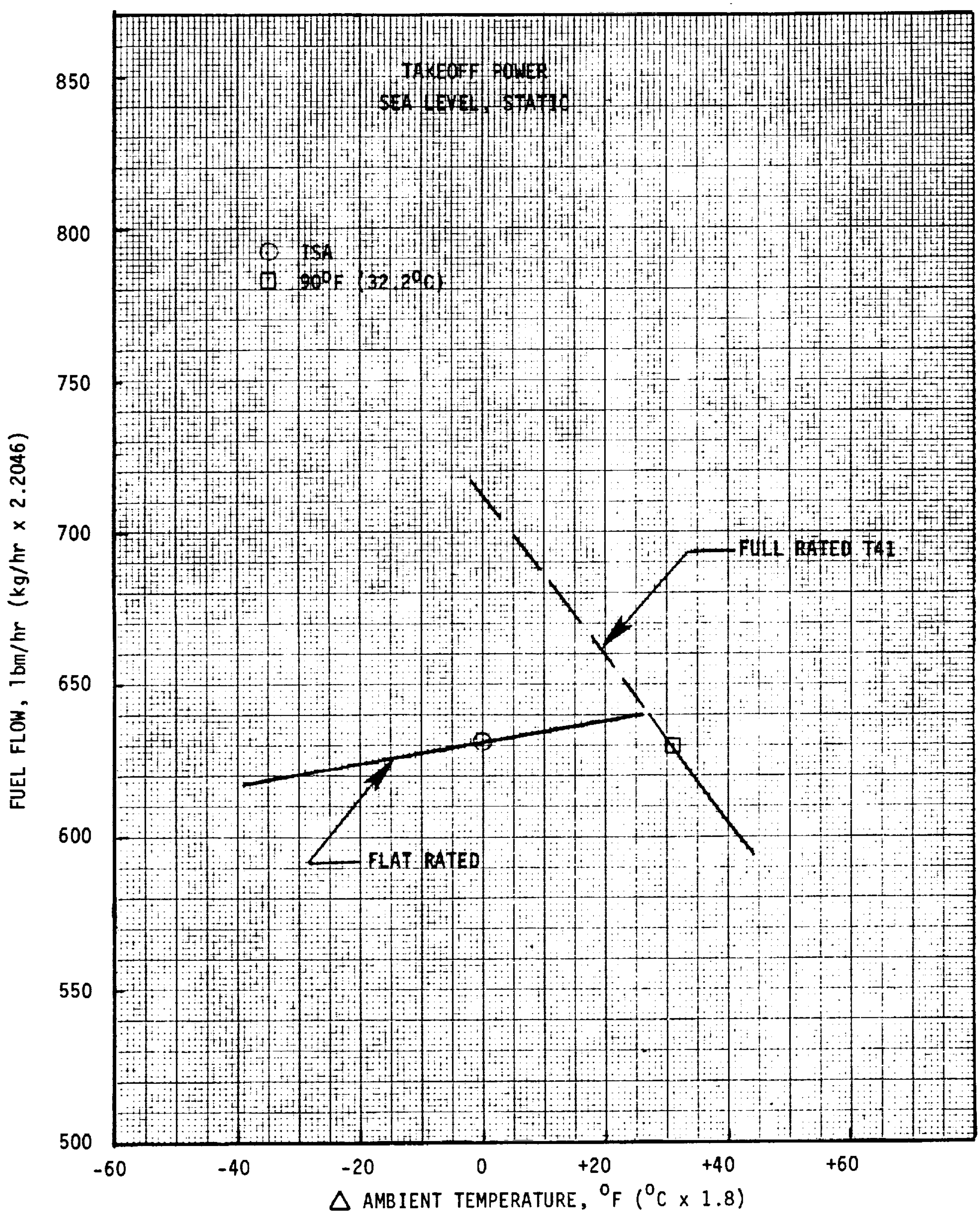


Figure C-8. 30-Passenger Size Advanced Engine - Takeoff Fuel Flow vs Ambient Temperature.

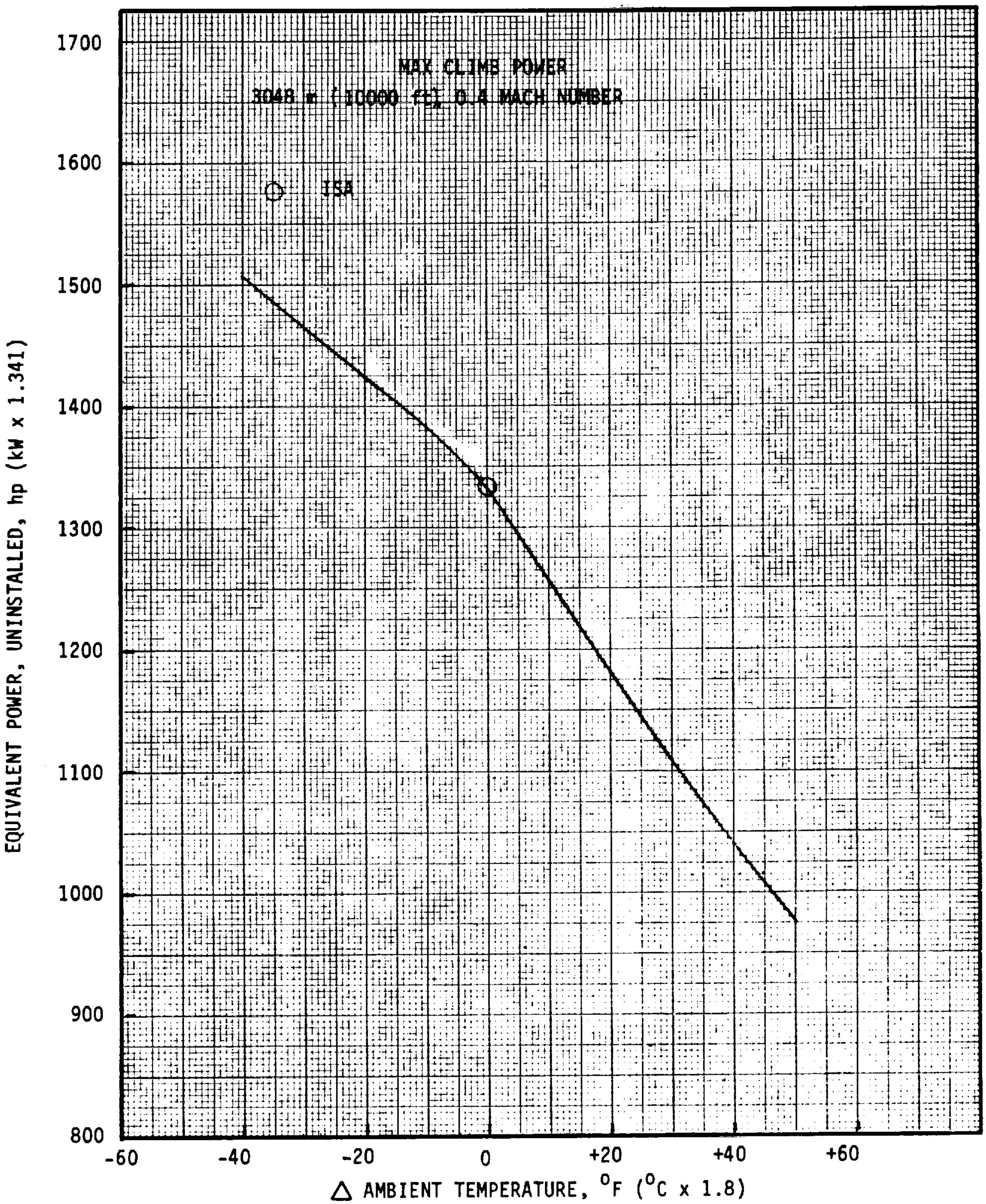


Figure C-9. 30-Passenger Size Advanced Engine - Climb Equivalent Power vs Ambient Temperature.

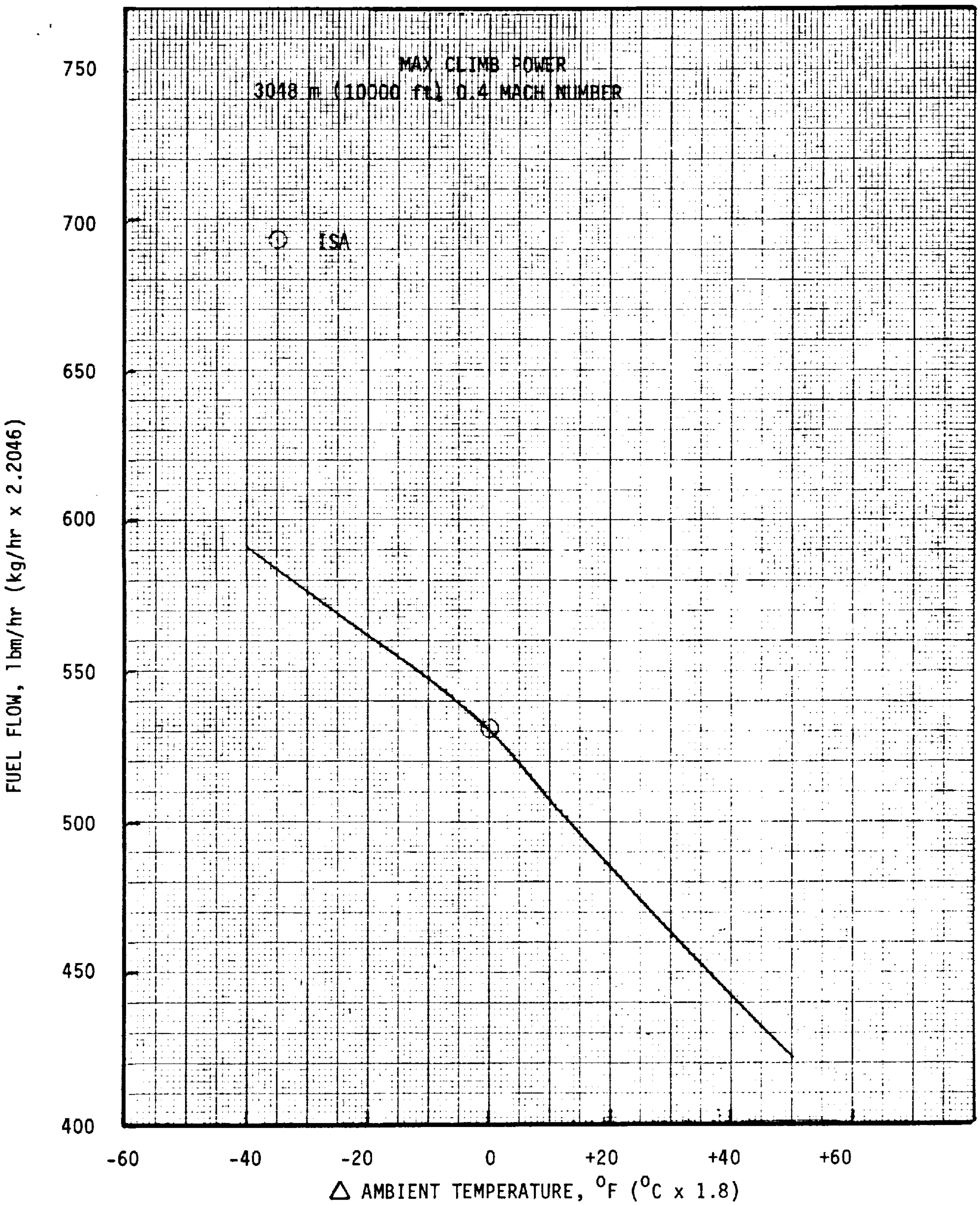


Figure C-10. 30-Passenger Size Advanced Engine - Climb Fuel Flow vs Ambient Temperature.

C-3

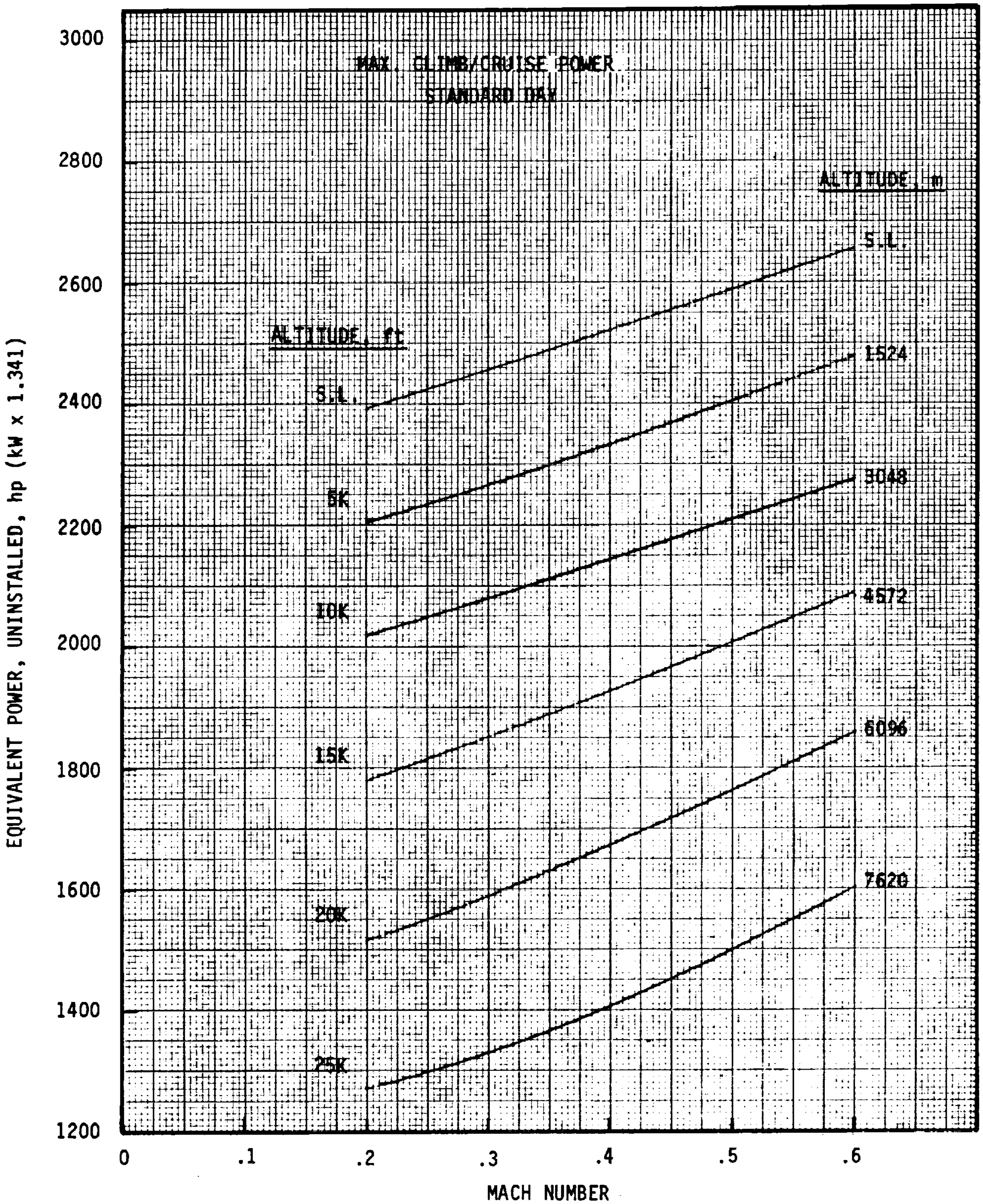


Figure C-11. 50-Passenger Size Advanced Engine - Equivalent Power vs Altitude and Mach Number.

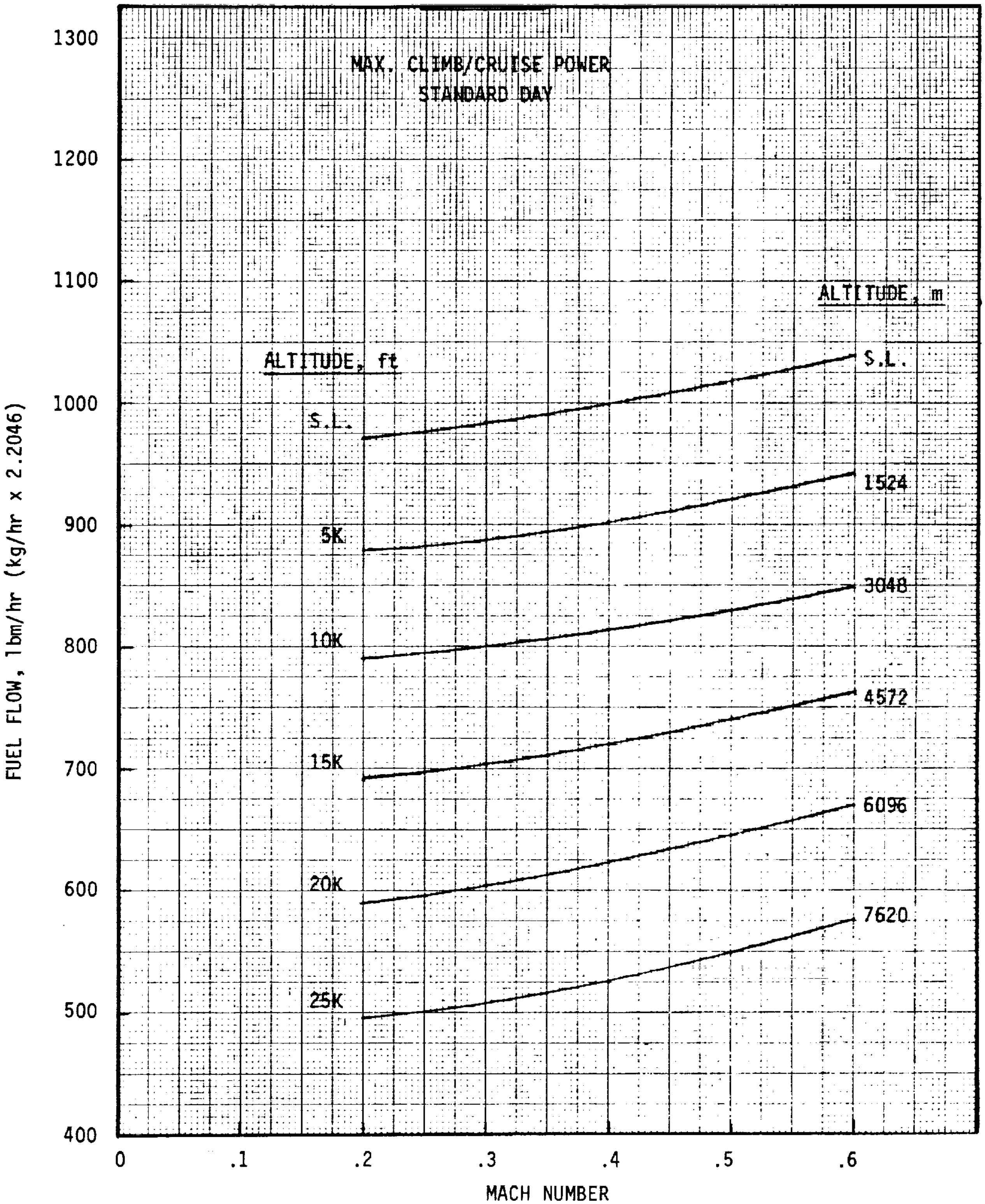


Figure C-12. 50-Passenger Size Advanced Engine - Fuel Flow vs Altitude and Mach Number.

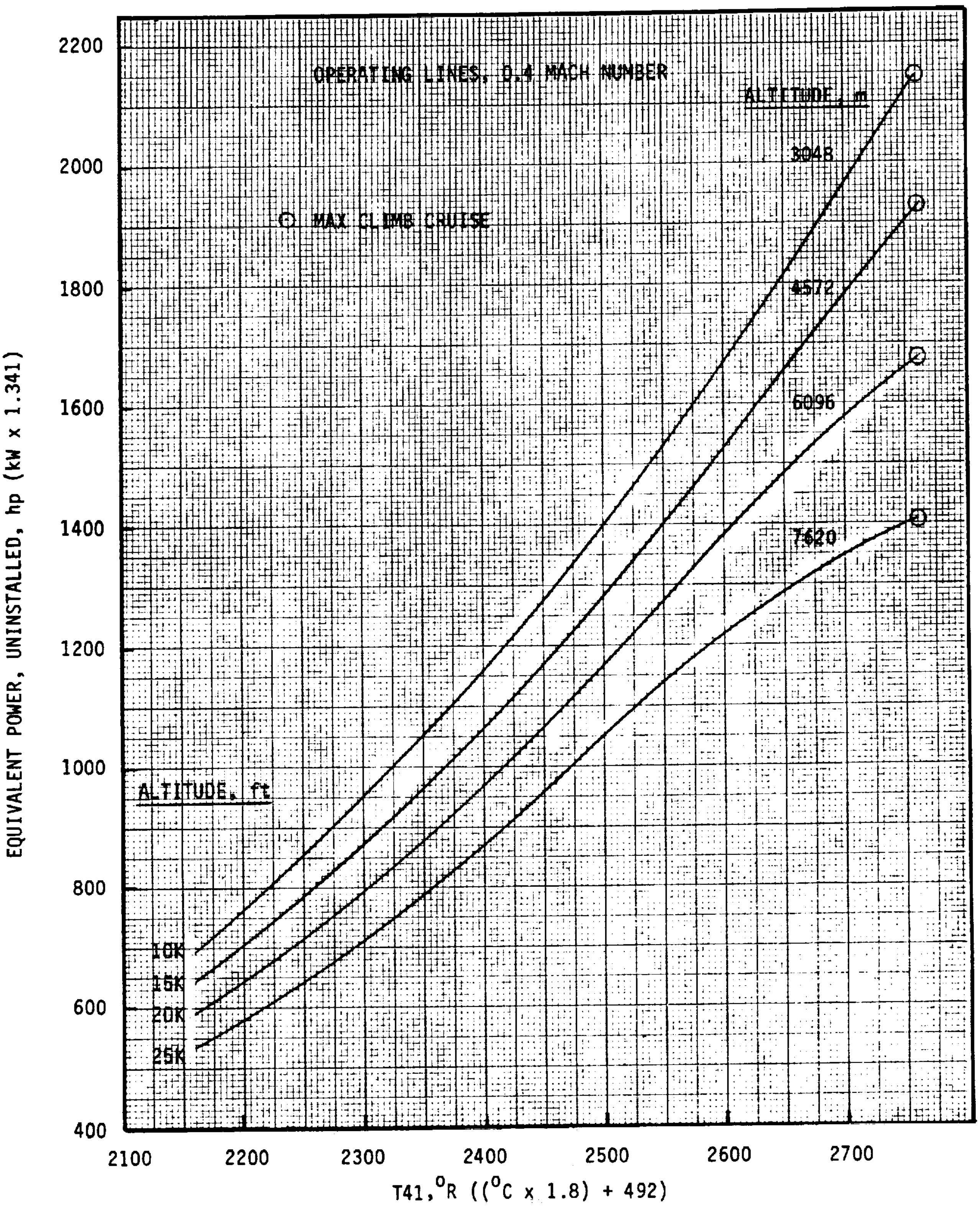


Figure C-13. 50-Passenger Size Advanced Engine - Equivalent Power vs Altitude and T41.

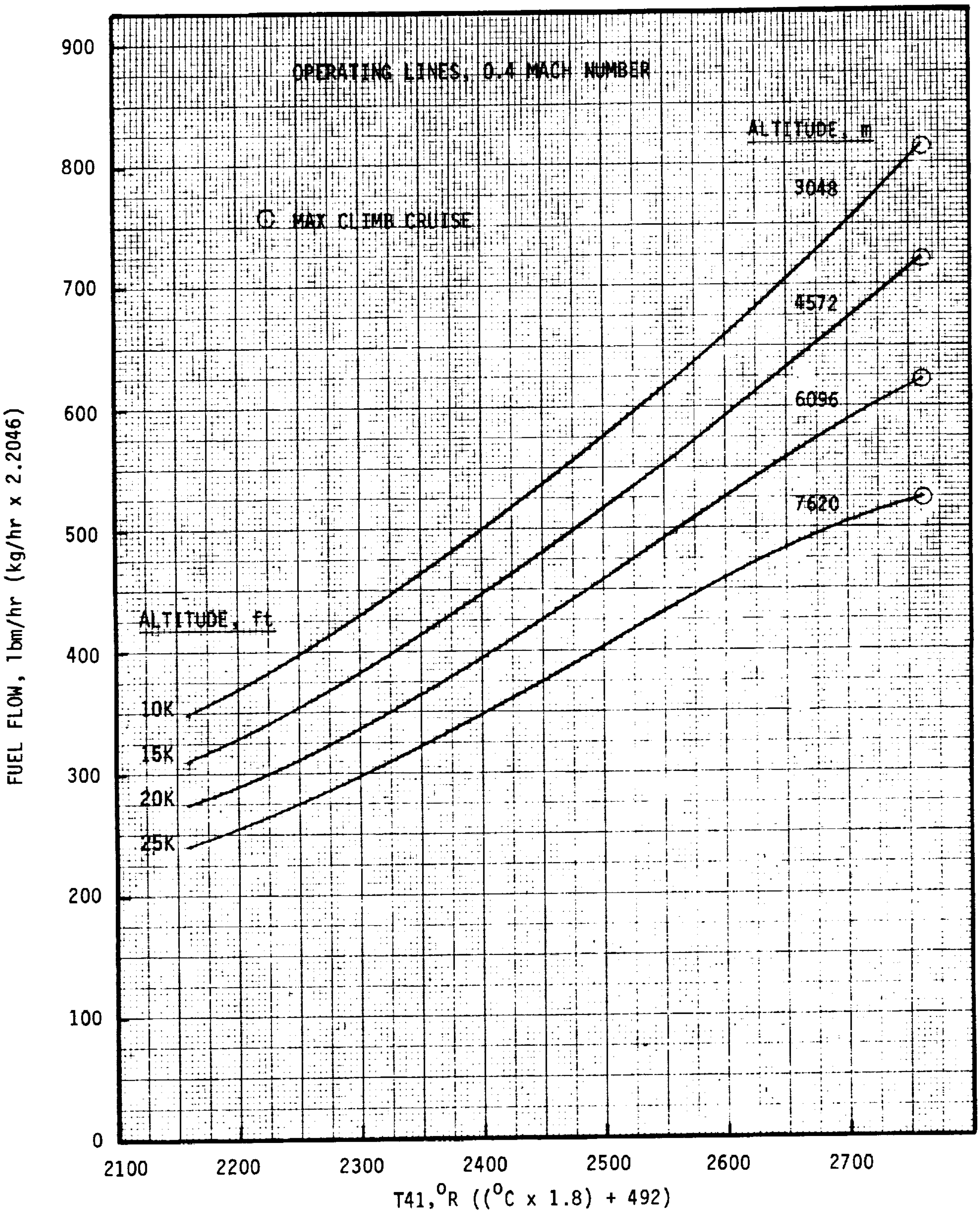


Figure C-14. 50-Passenger Size Advanced Engine - Fuel Flow vs Altitude and T41.

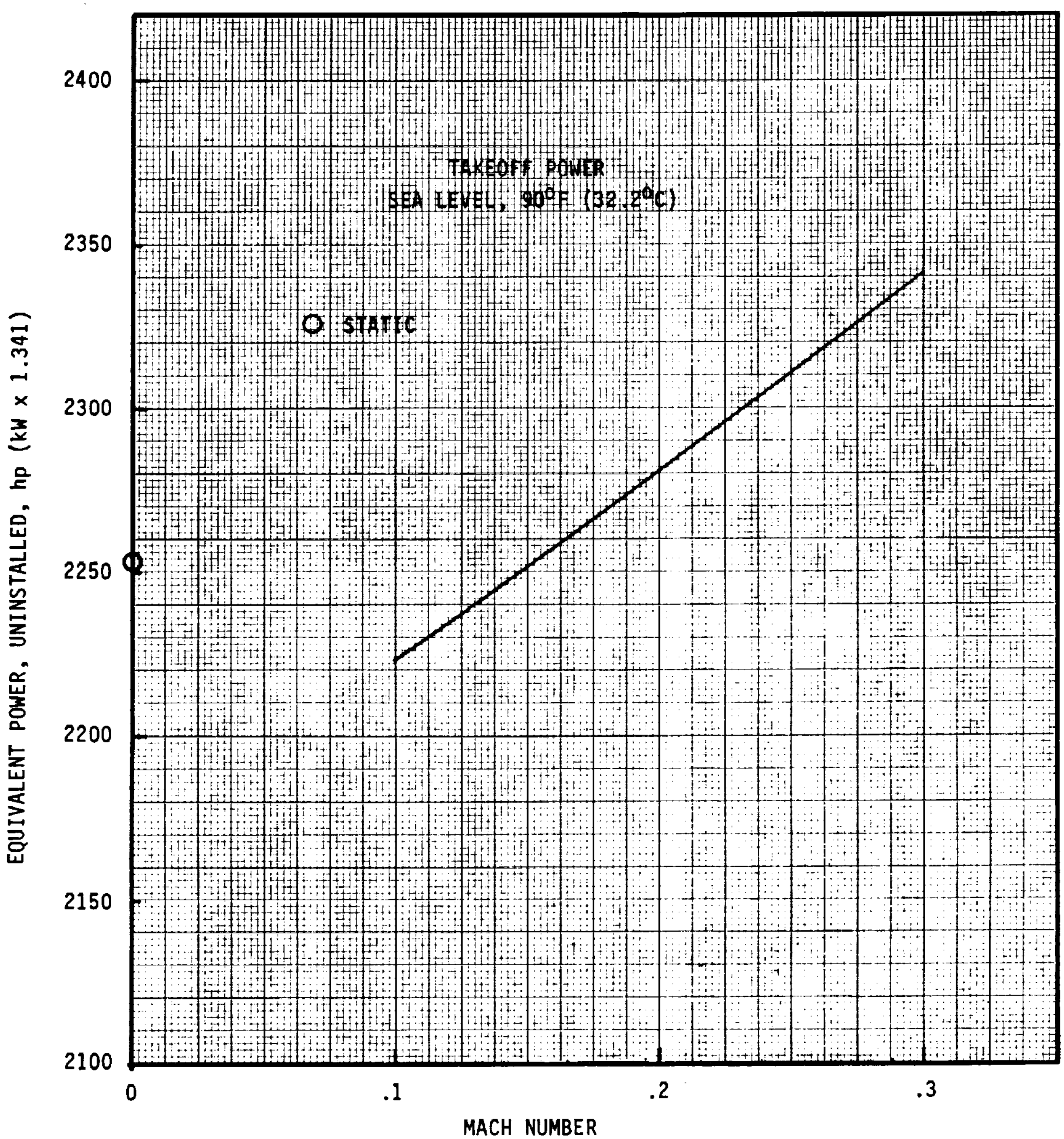


Figure C-15. 50-Passenger Size Advanced Engine - Takeoff Equivalent Power vs Mach Number.

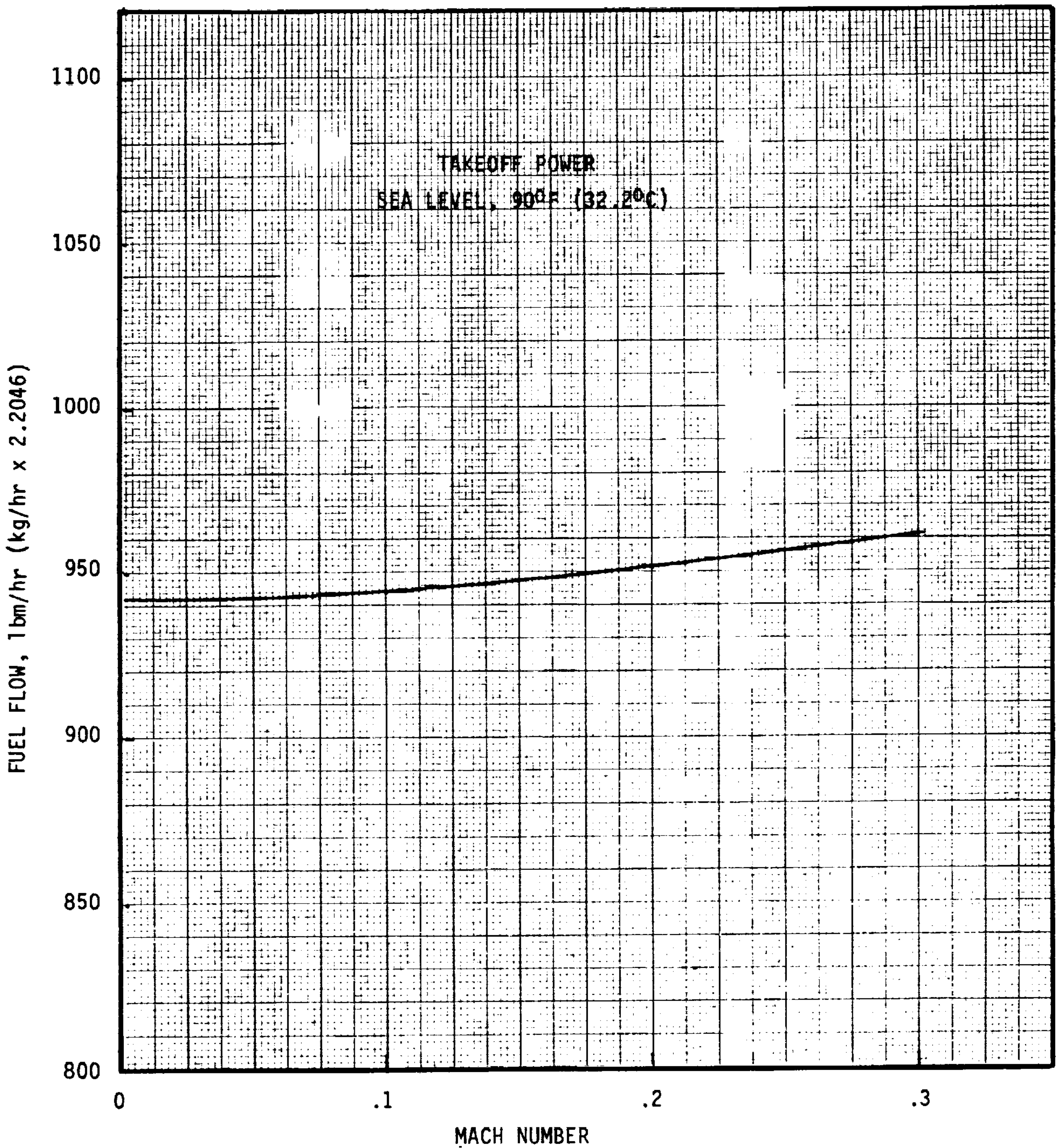


Figure C-16. 50-Passenger Size Advanced Engine - Takeoff Fuel Flow vs Mach Number.

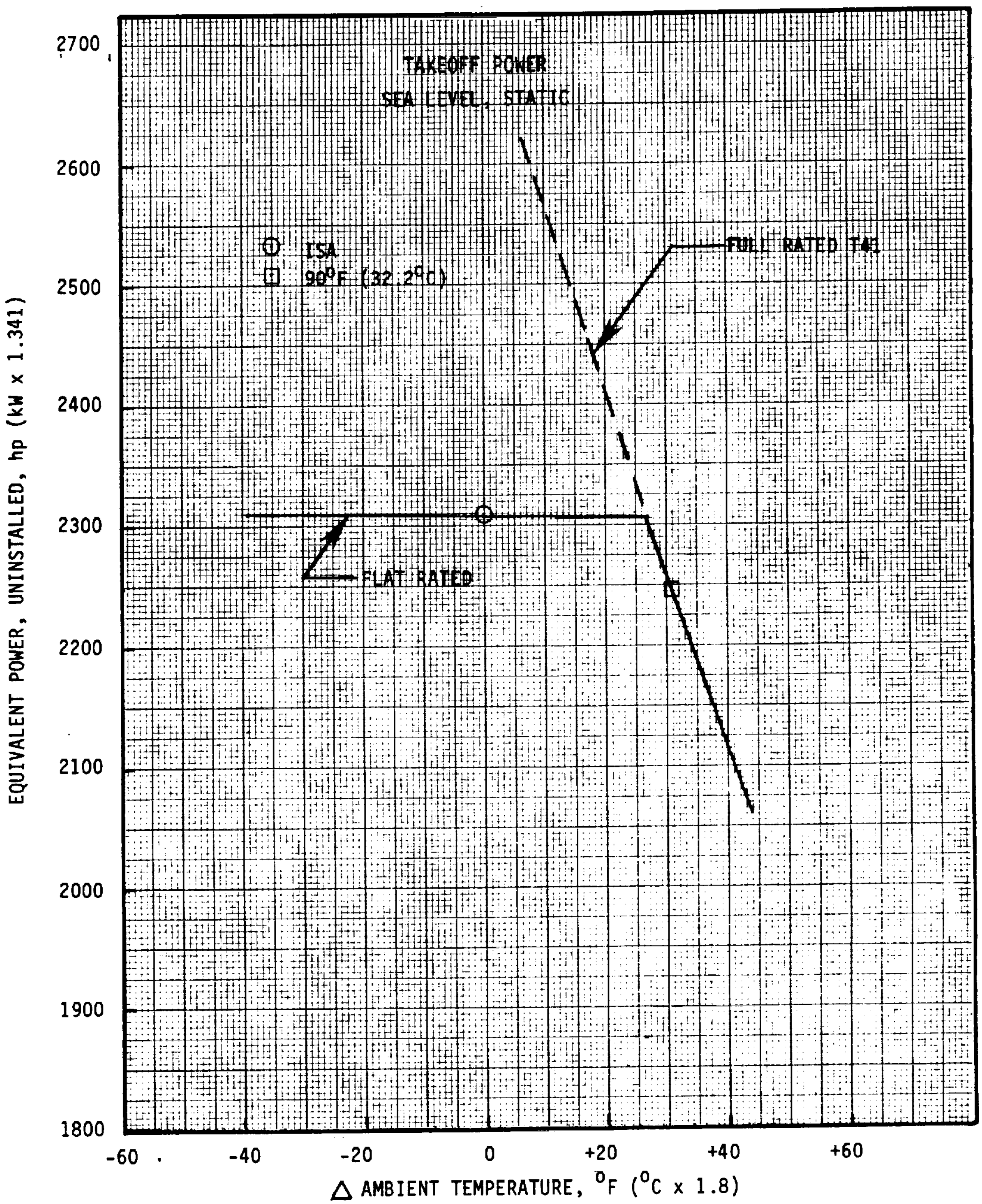


Figure C-17. 50-Passenger Size Advanced Engine - Takeoff Equivalent Power vs Ambient Temperature.

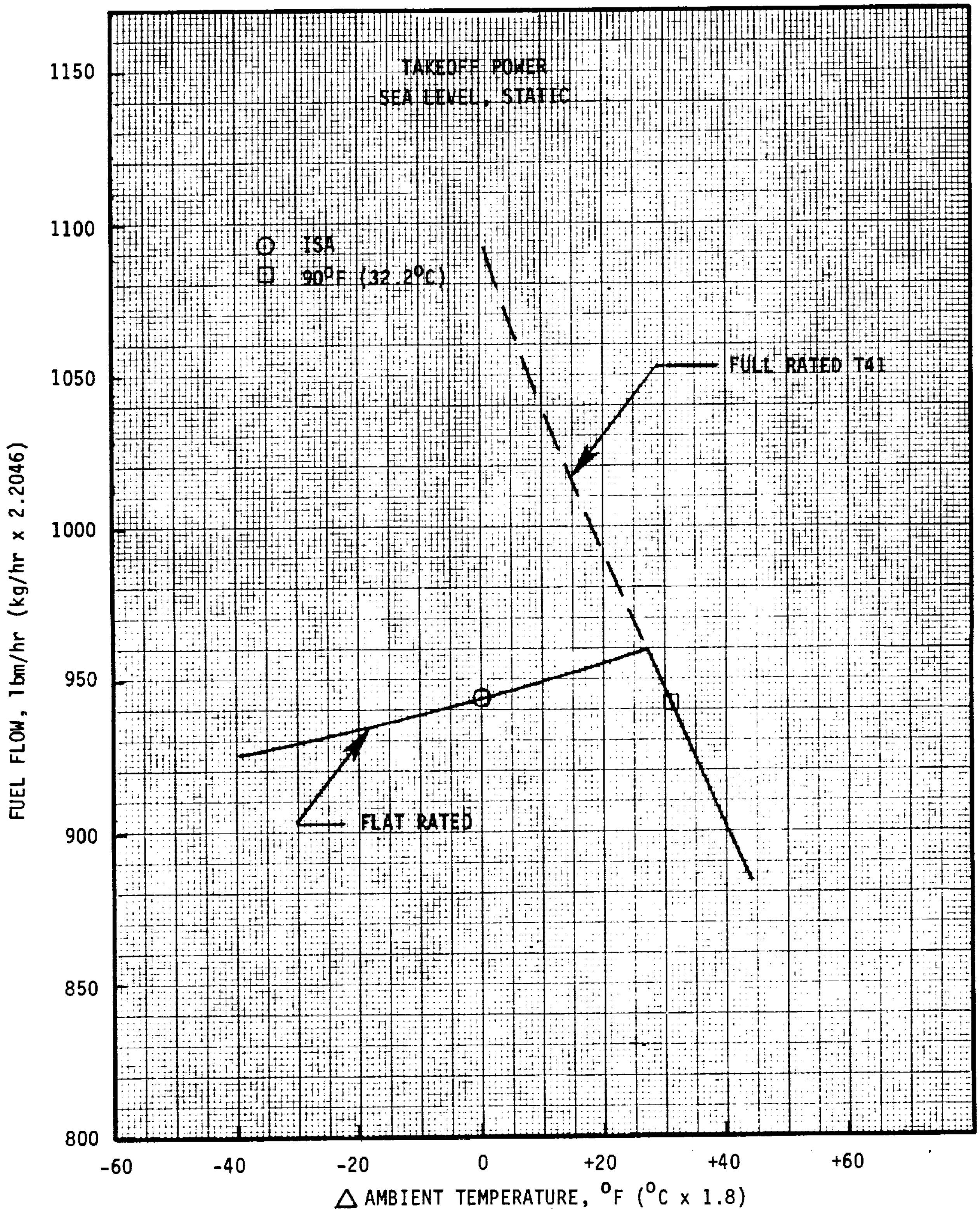


Figure C-18. 50-Passenger Size Advanced Engine - Takeoff Fuel Flow vs Ambient Temperature.

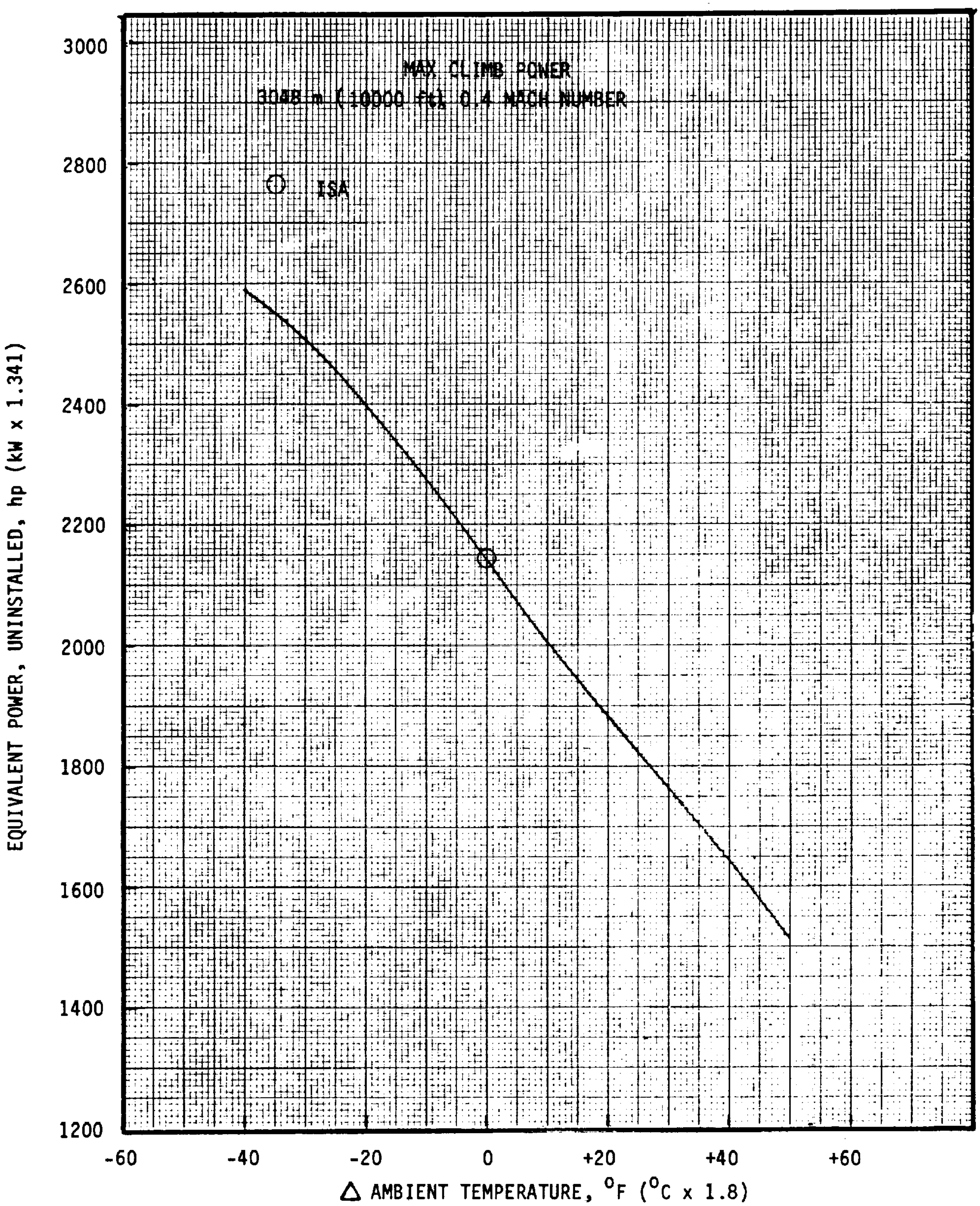


Figure C-19. 50-Passenger Size Advanced Engine - Climb Equivalent Power vs Ambient Temperature.

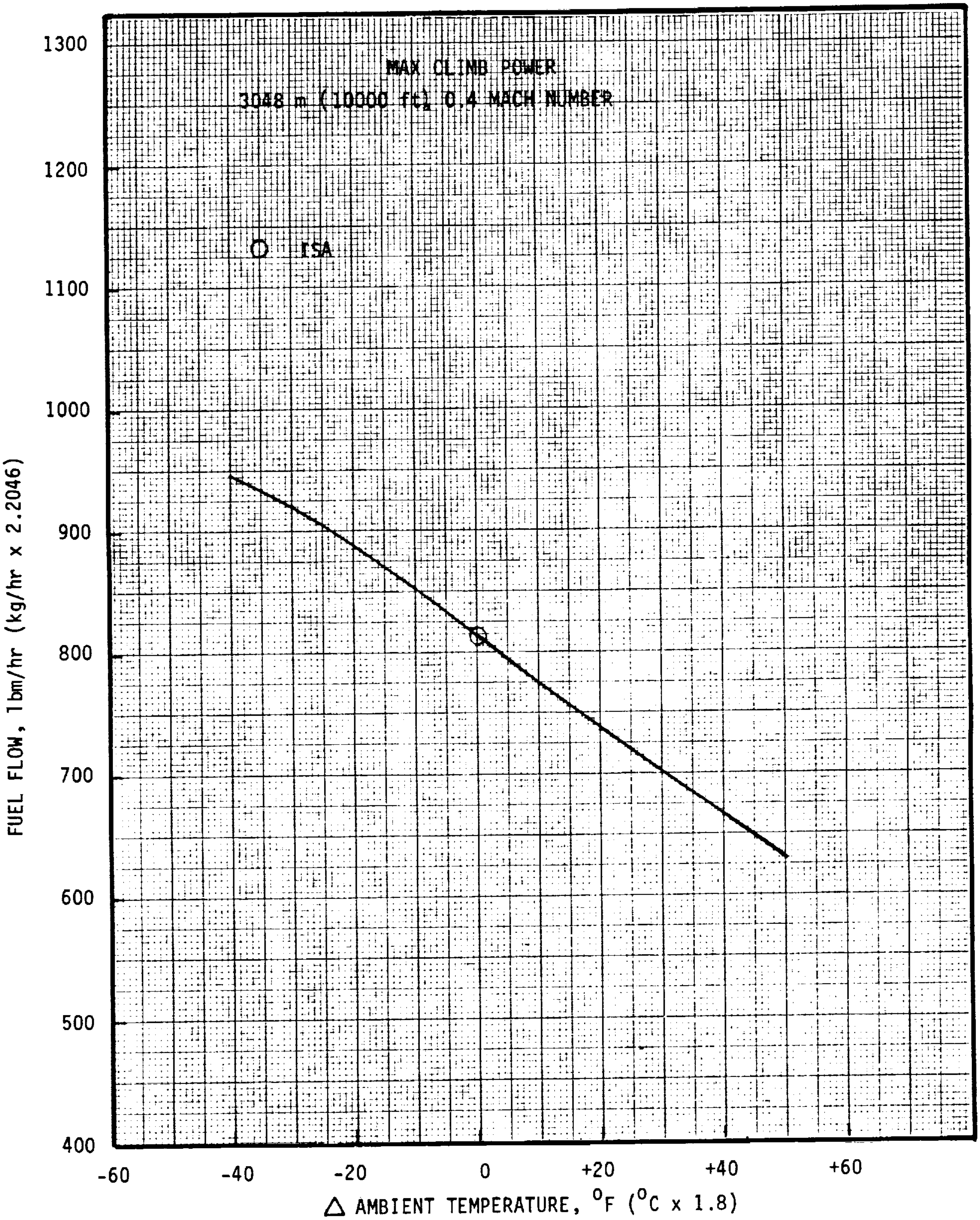


Figure C-20. 50-Passenger Size Advanced Engine - Climb Fuel Flow vs Ambient Temperature.

ORIGINAL PAGE IS OF POOR QUALITY

APPENDIX D

HAMILTON STANDARD DIVISION STUDY RESULTS

Hamilton Standard's results, as provided to General Electric by NASA after completion of the contract effort show significantly greater DOC benefits due to the propeller alone than do General Electric's results (6% versus 1.0 to 1.3%). A large part of the difference can be ascribed to the selection of the baseline level of technology.

Table D-1 compares the baseline selected by General Electric (GE) from data provided by Hamilton Standard (HS) during the contract period with two baselines used by HS in its own studies. Table D-2 compares the GE and HS advanced technology propeller selections. Note here that the basic efficiency data (i.e., exclusive of proplets and tip sweep) provided to GE were identical for current and advanced technology propellers.

The impact on DOC of Hamilton Standard's results in terms of efficiency, weight, price, and maintenance cost changes has been estimated using GE's mission merit factor sensitivities. The HS propellers were scaled into the proper mission size for the GE aircraft. The results shown in Table D-3 indicate that the reasons for the difference with the GE contract results lie in the input, not the evaluation procedure.

TABLE D-1
BASELINE PROPELLER COMPARISON

	General Electric* Baseline Propeller	Hamilton Standard Baseline Propellers General Aviation	Improved Commuter
Construction	Solid Aluminum	Solid Aluminum	Spar-Shell
Pitch Control	Single Acting	Single Acting	Single Acting
Blade Shank Shape	Airfoil	Circular	Airfoil
Cruise Efficiency, %	88-89	84.5	87.5
Number of Blades	4	3	3
Activity Factor Per Blade	100	100	100
Tip Speed, m/s (ft/sec) TO	228.6 (750)	256.3 (841)	256.3 (841)
Tip Speed, m/s (ft/sec) CR	228.6 (750)	205.1 (673)	205.1 (673)
Fuselage Accoustic Treatment Weight, kg (lbm)	272.2 (600)	382.8 (844)	382.8 (844)

*Selected from material supplied by Hamilton Standard.

TABLE D-2
ADVANCED PROPELLER COMPARISON

	General Electric** Advanced Propeller	Hamilton Standard Advanced Propeller
Construction	Composite With Proplets	Composite With Proplets
Pitch Control	Double Acting	Double Acting
Blade Shank Shape	Airfoil	Airfoil
Cruise Efficiency, %	89-90	92.3
Number of Blades	4	6
Activity Factor Per Blade	100	75
Tip Speed, m/s (ft/sec) TO	228.6 (750)	227.1 (745)
Tip Speed, m/s (ft/sec) CR	228.6 (750)	221.0 (725)
Fuselage Accoustic Treatment Weight*, kg (lb)		
Without Synchrophasing	182.9 (600)	---
With Synchrophasing	163.3 (360)	0

*163.3 kg (360 lb) accoustic treatment weight is GE estimate of result of 10 dB source noise reduction.
**Selected from material supplied by Hamilton Standard.

TABLE D-3
ADVANCED PROPELLER - MISSION MERIT FACTOR RESULTS
30- Passenger Aircraft, 185.2 km (100 nmi) Mission

Hamilton Standard Assumptions
(Improved Commuter Baseline)

Parameter	Change	% Change in DOC $264/m³ ($1.00/Gal)	% Change in DOC $396/m³ ($1.50/Gal)
Propeller Weight, kg (lbm)	+18.1 (+40)	+.25	+.28
Propeller Price, $1000	+17.9	+.36	+.30
Propeller Maintenance, $/h	+.17	+.06	+.05
Propeller Efficiency*, %	+5.9	-4.4	-4.9
Fuselage Treatment Weight, lb	-321.6 (-709)	-4.5	-5.0
Total		-8.2	-9.3

*Mission weighted. Includes performance and scaling effects.

SYMBOLS, ABBREVIATIONS, AND ACRONYMS

AC	Aircraft
AF	Propeller Blade Activity Factor
APR	Automatic Provisional Rating
B	Number of Propeller Blades
C	Propeller Pricing Constant
C_D	Drag Coefficient
CL	Climb
C_L	Lift Coefficient
C_{L_i}	Propeller Integrated Design Lift Coefficient
C_P	Propeller Power Coefficient
CR	Cruise
$C_{T_{Net}}$	Propeller Net Thrust Coefficient
CTOL	Conventional Takeoff and Landing
CW	Counterweights Weight, kg (lbm)
D	Diameter, m (ft)
DOC	Direct Operating Cost, \$/seat·km (\$/seat·nmi)
DS	Directionally Solidified
E	Youngs Modulus, GN/m^2 (lb/in^2)
ESFC	Equivalent Specific Fuel Consumption, kg/kW·h (lbm/hp·h)
FAA	Federal Aviation Administration
FADEC	Full Authority Digital Electronic Control
FN	Net Thrust, N (lb)
FOD	Foreign Object Damage
FOP	Foreign Object Protector
F_T	Propeller Compressibility Correction Factor
h	Specific Enthalpy, kJ/kg (Btu/lbm)
HP	High Pressure
HPC	High-Pressure Compressor
HPT	High-Pressure Turbine

ID	Idle
IGV	Inlet Guide Vane(s)
IPS	Inlet Particle Separator
IRP	Intermediate Rated Power
J	Propeller Advance Ratio
KW	Propeller Weight Constant
L	Length, m (ft)
LP	Low Pressure
LPC	Low-Pressure Compressor
LPT	Low-Pressure Turbine
M	Mach number
$\dot{m}$	Mass Flow Rate, kg/s (lbm/sec)
M3	Compressor Discharge Mach number
ODS	Oxide Dispersion Strengthened
OEI	One Engine Inoperative
OEM	Original Equipment Manufacturer
P	Pressure, kn/m^2 (lb/in^2)
P3	Compressor Discharge Pressure
P8	Exhaust Nozzle Discharge Pressure
PAMB	Ambient Pressure
PAX	Passengers
P/P	Pressure Ratio
PR	Price, $
QCSEE	Quiet, Clean, Short-Haul Experimental Engine
RV	Relative Value
SFC	Specific Fuel Consumption, kg/kW·h (lbm/h_p.h)
SLS	Sea Level, Static
STAT	Small Transport Aircraft Technology
T	Temperature, °C (°F)
T3	Compressor Discharge Temperature

T41	HP Turbine Rotor Inlet Temperature, °C (°F)
TAF	Total Activity Factor, AF*B
TAMB	Ambient Temperature
TBO	Time Between Overhauls, h
TO	Takeoff
TOGW	Takeoff Gross Weight, kg (lbm)
TSFC	Thrust Specific Fuel Consumption, kg/N·h (lbm/lbf.h)
T/W	Engine Thrust/Aircraft Weight, N/kg (lb/lbm)
Up	Pitch Line Wheel Speed, m/s (ft/sec)
Vo	Flight Velocity, m/s (ft/sec)
V_j	Exhaust Jet Velocity, m/s (ft/sec)
W	Weight or Airflow, kg (lbm) or kg/s (lbm/sec)
W2	Compressor Inlet Airflow, g/s (lbm/sec)
WA	Airflow, kg/s (lbm/sec)
WF	Engine Fuel Flow or Mission Fuel Burned, kg/h, (lbm/h) or kg (lbm)
W/S	Wing Loading; Aircraft Weight/Wing Area, N/m^2 (lbm/ft^2)
Z	Propeller Price Learning Curve Factor
Δ	Difference, Change
δ	P (lb/in^2)/14.696
η	Efficiency
θ	T (°F)/518.67
ρ	Density, kg/m^3 (lbm/ft^3)
$\overline{\Psi}$	Turbine Loading $= \dfrac{gJ\Delta h}{2\overline{U}_p^{\,2}}$