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Rotorcraft Convertible Engine Study

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16. Abstract

The objective of the Rotorcraft Convertible Engine Study was to define future research and technology effort required for commercial development by 1988 of convertible fan/shaft gas turbine engines for unconventional rotorcraft transports.

Two rotorcraft and their respective missions were defined: a Fold Tilt Rotor aircraft and an Advancing Blade Concept (ABC) rotorcraft. Sensitivity studies were conducted with these rotorcraft to determine parametrically the influence of propulsion characteristics on aircraft size, mission fuel requirements, and direct operating costs (DOC).

The two rotorcraft were "flown" with conventional propulsion systems (separate lift/cruise engines) and with convertible propulsion systems to determine the benefits to be derived from convertible engines.

Trade-off studies were conducted to determine the optimum engine cycle and staging arrangement for a convertible engine. Advanced technology options applicable to convertible engines were studied. Research and technology programs were identified which would ensure technology readiness for commercial development of convertible engines by 1988.

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I. SUMMARY

Detroit Diesel Allison (DDA), Division of General Motors Corporation, completed the Rotorcraft Convertible Engine Study for the National Aeronautics and Space Administration (NASA), Lewis Research Center (LeRC), under Contract NAS3-22742.

This study identified future research and technology efforts applicable to convertible gas turbine engines for unconventional rotorcraft anticipated for the early 1990s. These aircraft are unconventional in that they combine the vertical flight capability of rotorcraft with the high-speed cruise capability of fixed wing aircraft.

DDA selected two airframe subcontractors to assist in the definition of the two baseline aircraft and their respective missions and to conduct mission studies with engine data furnished by DDA. Bell Helicopter Textron Division of Textron, Inc., provided technical assistance in the definition of a Fold Tilt Rotor Aircraft and Sikorsky Aircraft Division of United Technologies Corporation assisted in the definition of an Advancing Blade ConceptⓉ* (ABC) Rotorcraft.

The Fold Tilt Rotor Aircraft with conventional propulsion systems uses two turboshaft engines for vertical flight (they drive the proprotor at each wing tip) and two underwing, pod-mounted turbofan engines for cruise flight. The Fold Tilt Rotor Aircraft with convertible propulsion systems uses two underwing, pod-mounted convertible fan/shaft engines to drive the tip-mounted proprotors via driveshafts during takeoff, landing, and transition modes only.

The ABC Rotorcraft with conventional propulsion systems uses two turboshaft engines for rotor drive during vertical flight and two turboshaft engines driving tractor propellers on side-mounted pods via reduction gears for cruise flight. The ABC Rotorcraft with convertible propulsion systems uses two conventional turboshaft engines interconnected with the two propellers and the rotor system. The convertible features of this configuration are provided by the aircraft gearboxes and power transmission system.

The baseline aircraft were each designed for a payload of 30 passengers. Their size and significant features of their design missions are given below:

	Fold tilt wing	ABC
Takeoff gross weight--kg (lbm)	17,742.2 (39,115)	14,695.0 (32,397)
Design range--km (nmi)	1111.2 (600)	402.3 (217.2)
Design cruise velocity--km/h (kt)	852 (460)	463 (250)
Design cruise altitude--m (ft)	6096 (20,000)	3048 (10,000)

Sensitivity studies were conducted for both aircraft to determine the changes in certain aircraft characteristics resulting from changes in several engine parameters. The following aircraft changes, in percent, result from 10% changes in the specified engine parameters for the ABC Rotorcraft using convertible propulsion systems.

*Advancing Blade Concept is a trademark of Sikorsky Aircraft Division.

	Engine parameters		
	sfc	Weight	Diameter
Takeoff gross weight--%	2.44	0.64	0.17
Fuel required, design mission(1)--%	10.78	0.24	0.57
Fuel required, typical mission(2)--%	10.94	0.36	0.46
Acquisition cost--%	1.42	0.42	0.15
DOC, typical mission(3)--%	6.30	0.28	0.32

(1) Design mission = 402.3 km (217.2 nmi)
(2) Typical mission = 139.9 km (86.9 nmi)
(3) Fuel cost = \$0.528/1 (\$2.00/gal)

Sensitivity studies with the Fold Tilt Rotor Aircraft using convertible engines showed the following percentage changes in select aircraft characteristics as a result of 10% changes in the specified engine parameters:

	Engine parameters	
	sfc	Weight
Takeoff gross weight--%	2.69	1.50
Fuel required, design mission(1)--%	11.81	1.04
Fuel required, typical mission(2)--%	13.64	0.76
Acquisition cost--%	1.18	0.55
DOC, typical mission(3)--%	5.88	0.59

(1) Design mission = 1111.2 km (600 nmi)
(2) Typical mission = 370.4 km (200 nmi)
(3) Fuel cost = \$0.528/1 (\$2.00/gal)

The convertible engine cycle selected for the Fold Tilt Rotor Aircraft has a fan pressure ratio of 1.65:1, an overall pressure ratio of 30:1, and a turbine rotor inlet temperature of 1589 K (2400°F). This engine, in unity size, delivers 13500 N (3035 lbf) thrust at the design cruise conditions of 0.75 Mach at 6096 m (20,000 ft). This fan/shaft engine is 1.773 m (69.80 in.) long and weighs 615.1 kg (1356 lbm). This engine differs from a conventional high bypass turbofan in that it provides a full power takeoff drive from the power turbine and a torque converter between the power turbine output shaft and the fan. The torque converter permits selection of propulsive effort as fan thrust or mechanical drive for aircraft propulsors. This configuration permits the fan to be designed for maximum efficiency at its altitude cruise point and was selected from among several alternates, including those with variable pitch fans, wet disk clutches in the fan drive, fan variable inlet and exit guide vanes, partial-span fan inlet guide vanes, and remote or independent power turbines for auxiliary propulsion. The selection of the preferred convertible engine configuration was based on a ranking of the alternates in the areas of tsfc, weight, price, complexity, reliability, and noise.

The engine cycle for the ABC Rotorcraft convertible propulsion system has a pressure ratio of 24.2:1 and a turbine rotor inlet temperature of 1535 K (2300°F). The unity size version of this engine delivers 2733 kW (3665 shp) at the design cruise conditions of 0.38 Mach at 914.4 m (3000 ft). This turboshaft engine is 1.369 m (53.90 in.) long and weighs 251.7 kg (555 lbm).

The convertible propulsion systems provided the study aircraft with significant improvements when compared to conventionally powered aircraft, as shown below.

	Fold Tilt Rotorcraft-- % improvement	ABC Aircraft-- % improvement
Design gross weight	9.0	11.7
Design mission fuel	10.5	12.9
Acquisition cost	14.9	16.5
DOC, typical mission	14.7	12.0

During this study, the commonality between civil and military versions of the unconventional rotorcraft was assessed. Within the scope of this study, no specific feature of the convertible engines was determined to be applicable only to one of these versions. The convertible propulsion systems recommended in this study are equally applicable to both civil and military unconventional rotorcraft.

Several advanced technology options were studied to determine their potential merit for application to future convertible engines. Of these, the torque convertor showed the most promise and it was applied to the convertible engine for the Fold Tilt Rotor Aircraft.

A research and technology plan was prepared which identified several advanced engine features whose development would directly benefit convertible engines.

II. INTRODUCTION

Future unconventional rotorcraft are now in the planning and experimental development stages. These aircraft combine the vertical takeoff and landing capabilities of current rotorcraft with a high-speed cruise capability typical of fixed wing aircraft. Aircraft configurations studied are the folded tilt rotor and advancing blade concepts (ABC). These aircraft offer the possibility of substantial improvements in rotorcraft productivity and economics. Particularly suited to these unconventional rotorcraft are "convertible engines," which offer the advantage of providing cruise and vertical propulsion from a single engine.

NASA LeRC sponsored the Rotorcraft Convertible Engine Study under Contract No. NAS3-22742. The purpose of this study was to evaluate candidate concepts and technologies for convertible engines, define two such engines, assess their benefits and costs, and define R&T programs desired to establish technology readiness for commercial development of the engines by 1988, with commercial application in the early 1990s.

This study was divided into the following seven basic tasks:

- Task I--Definition of Baseline Aircraft and Missions
- Task II--Baseline Convertible Powerplant Selection
- Task III--Alternative Convertible Powerplant Configurations/Technologies
- Task IV--Engine Cycle and Staging Arrangements
- Task V--Definition of Preferred Powerplants
- Task VI--Benefit Assessment
- Task VII--Recommendations for Future Research

III. BASELINE AIRCRAFT AND MISSIONS

GENERAL

Two baseline aircraft and missions were defined to represent different propulsion system requirements for anticipated future unconventional civil rotorcraft. One baseline aircraft features the Fold Tilt Rotor; the other, the ABC.

The design of each baseline aircraft utilizes anticipated 1990 technology in structures, aerodynamics, systems, and propulsion. The aircraft and corresponding missions were defined on the basis of available study data for various rotorcraft applications.

Bell Helicopter Textron Division of Textron, Inc., provided the basic design and mission definition for the Fold Tilt Rotor Aircraft. This aircraft is a 30-passenger commercial transport capable of 852 km/h (460 kt) at 6096 m (20,000 ft). The design range at optimum airspeed is 1111.2 km (600 nmi).

Sikorsky Aircraft Division of United Technologies, Inc., provided the basic design and mission definition for the ABC Rotorcraft. This aircraft carries 30 passengers at 463 km/h (250 kt) at cruise altitudes up to 3048 m (10,000 ft). Design range is 402.3 km (250 mi).

Detroit Diesel Allison provided engine data for the baseline aircraft definitions. Anticipated 1990 levels of engine performance, weight, size, and costs were provided. These data were used for preliminary aircraft sizing and determination of aircraft system sensitivity to variations in propulsion parameters. For example, changes in aircraft gross weight and direct operating cost (DOC) resulting from variations in engine sfc, weight, diameter, acquisition cost, and maintenance cost were determined. Cost standards used in the study are shown in Table I.

Table I.
Standards and assumptions used for cost analysis.

January 1981 economics
Production quantity: 500 aircraft
Development cost amortized into price of aircraft
DOC includes direct cost of fuel, maintenance, crew, insurance, and depreciation
Insurance rate: 1.5% of aircraft price
Spares:

Engine	40%
Propeller	40%
Dynamic system	25%
Airframe	8%

Depreciation:
Aircraft plus spares depreciated straight line over 12 yr, 15% residual
Fuel: $0.528/L ($2/gal)
Maintenance labor: $12.50/hr
Annual utilization: 2800 flight hours

During preparation of the engine data packages, a sensitivity study was made to determine the impact of varying original equipment manufacturer (OEM) engine price and premature removal rate (PRR) upon engine maintenance cost per engine flight hour ($/EFH). Figure 1 shows the effects of varying OEM price while Figure 2 shows the results of variations in PRR.

ADVANCING BLADE CONCEPT ROTORCRAFT

Background

The principle of the ABC rotor was conceived during the early years of helicopter development as forward speed limitations became a serious problem (Ref. 1). Unlike conventional rotors, the ABC, which employs two coaxial, counterrotating rigid rotors, is not limited by retreating blade stall at high forward velocities. This is because the advancing blades of each rotor furnish the major lift with the rigid rotors counterbalancing each other's rolling moment. No wing is required and the transition between low speed and high speed flight modes is smooth and not complicated by the need to transfer lift from one device to another or to vary the basic orientation of the lift devices.

In the mid-sixties, advances in materials technology made the ABC practical. Development has progressed through small-scale model testing, flow visualization studies, and theoretical analyses to the design and fabrication of a full-scale, 12.2 m (40 ft) diameter rotor system. This system was successfully tested in the 12.2 x 24.4 m (40 x 80 ft) wind tunnel at NASA-Ames in 1970. This test provided valuable data for actual velocities up to 333.4 km/h (180 kt), the maximum capability of the wind tunnel, and simulated velocities up to 556 km/h (300 kt).

In December 1971, the U.S. Army awarded Sikorsky a contract to design, fabricate, and test an ABC Technology Flight Research aircraft to explore the capabilities and limitations of the ABC concept. The ABC research aircraft, the XH-59, was designed for exploration in the pure helicopter mode at velocities up to 314.8 km/h (170 kt) and in the auxiliary propulsion mode at velocities up to 556 km/h (300 kt) (Ref. 2).

Aircraft Description

Concept: The aircraft is a rotary wing aircraft employing Sikorsky's ABC and auxiliary cruise propulsion. The ABC rotor system consists of two counterrotating, three-bladed rotors providing 100% of the required lift throughout the flight envelope. At moderate speeds, the rotors may also provide all or part of the propulsive force; at higher speeds, forward flight propulsive force is provided by an auxiliary propulsion system while the rotors are partially powered to achieve a level aircraft cruise attitude. In the XH-59 flight demonstrator, auxiliary propulsion is provided by two side-mounted jet engines. For the civil commuter design of this study, two side-mounted tractor propellers are used in lieu of jet engines for improved cruise efficiency.

Operational Capabilities: Sikorsky considers its ABC suitable for cruise speeds in the range of 333.4 km/h (180 kt) up to 555.6 km/h (300 kt), the upper boundary generally established by economic considerations rather than technical limits (Ref. 3). Altitude capability has been demonstrated up to 7620 m (25,500 ft).

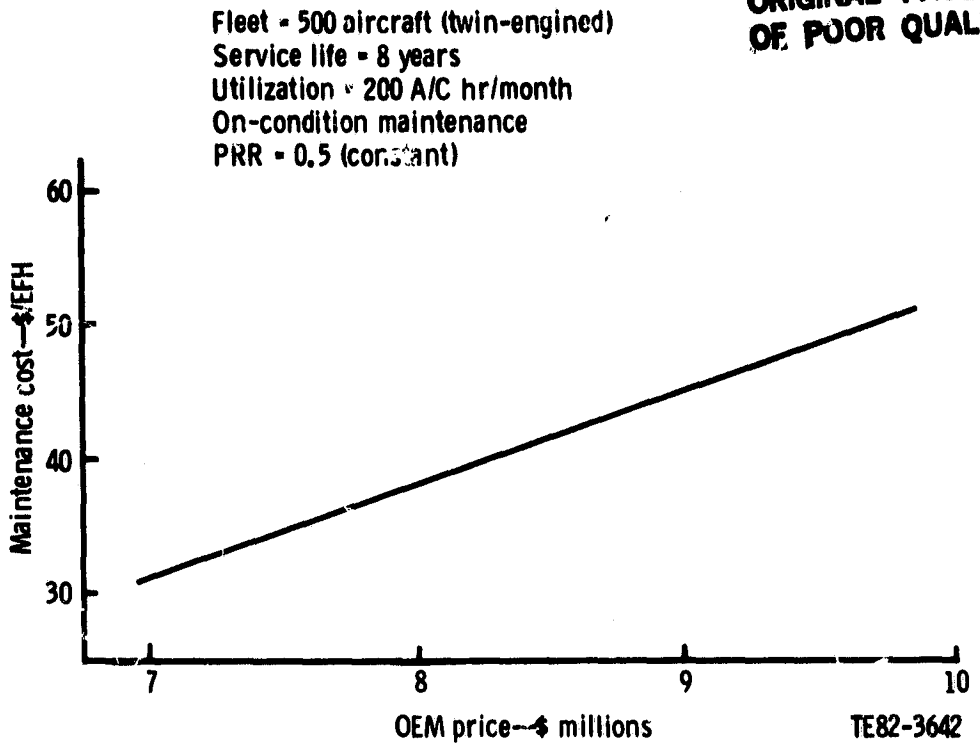

Figure 1. Price versus maintenance cost efficiency.

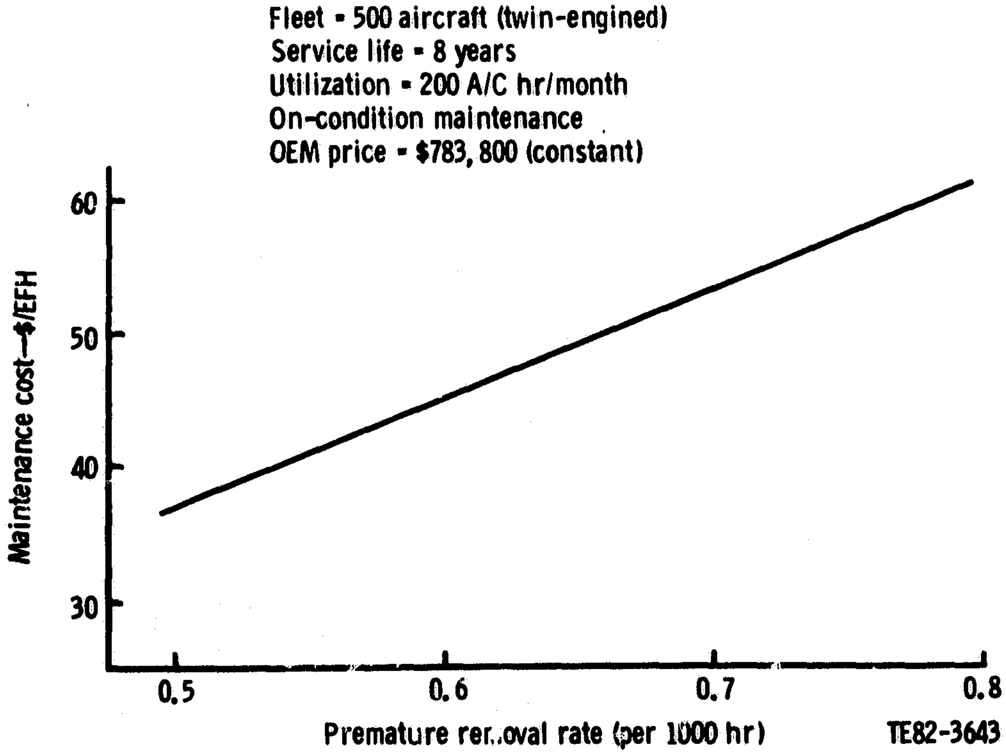

Figure 2. Premature removal rate versus maintenance cost sensitivity.

For short-range commuter-type operations in airspace with an indicated airspeed limitation of 463 km/h (250 kt) below 3048 m (10,000 ft) altitude (FAR Part 91.70A), it appears reasonable to design the aircraft with a 463 km/h (250 kt) cruise capability and to limit mission altitude to 3048 m (10,000 ft). This operating envelope avoids the need for cabin pressurization with the associated structural weight penalty and eliminates the need for a cabin emergency oxygen system.

Airframe: The fuselage provides accommodations for 30 passengers in a four-abreast cabin layout with a center aisle. The aircraft is sized to fulfill a need for a short-range commuter to heliports and airports. Two fuel tanks, one in front and one behind the passenger compartment, are provided. The cockpit accommodates two pilots. The landing gear is retractable and is of the tricycle type with a nose wheel. The empennage is a V-tail with moving trailing edge surfaces. The basic design characteristics of the aircraft are shown in Table II.

Table II.
Primary characteristics--ABC Rotorcraft.

Design cruise velocity	463 km/h (250 kt)
Disk loading	718.2 N/m^2 (15.0 lbf/ft^2)
Design limit load factor	2.59 gravity
Design mission payload (30 passengers)	2721.6 kg (6000 lbm)
Design mission range	402.3 km (250 mi)
Design cruise altitude	3048 m (10,000 ft)

Furnishings and Equipment: The cabin is furnished as appropriate for commuter-type operation. Heating, ventilating, and air conditioning are provided by an independent environmental control system (ECS) incorporating a compressor
driven by the main gearbox. The avionics complement offers full instrument flight rules (IFR) capability. The aircraft is equipped for operation in icing conditions. The crew consists of a pilot, a copilot, and a flight attendant.

Propulsion: For purposes of this study, the ABC Rotorcraft was analyzed with two different propulsion systems, one with two turboshaft lift engines and two turboshaft cruise engines and the other with two turboshaft engines in combination with convertible features in the aircraft power transmission system.

Separate lift/cruise system: The aircraft shown in Figure 3 employs two lift engines for the ABC rotor system and two cruise engines for the auxiliary propulsion system. The lift engines are installed on top of the fuselage deck and drive forward into the main combining gearbox which drives the rotors and all airframe accessories. The auxiliary propulsion cruise engines are installed on outriggers left and right of the fuselage, each independently controlled and driving, through a reduction gearbox, a 3.05 m (10 ft) diameter, four-bladed, constant-speed, governed propeller. There is no cross-shafting between the cruise engines nor is there a connection between the lift system and the auxiliary propulsion system.

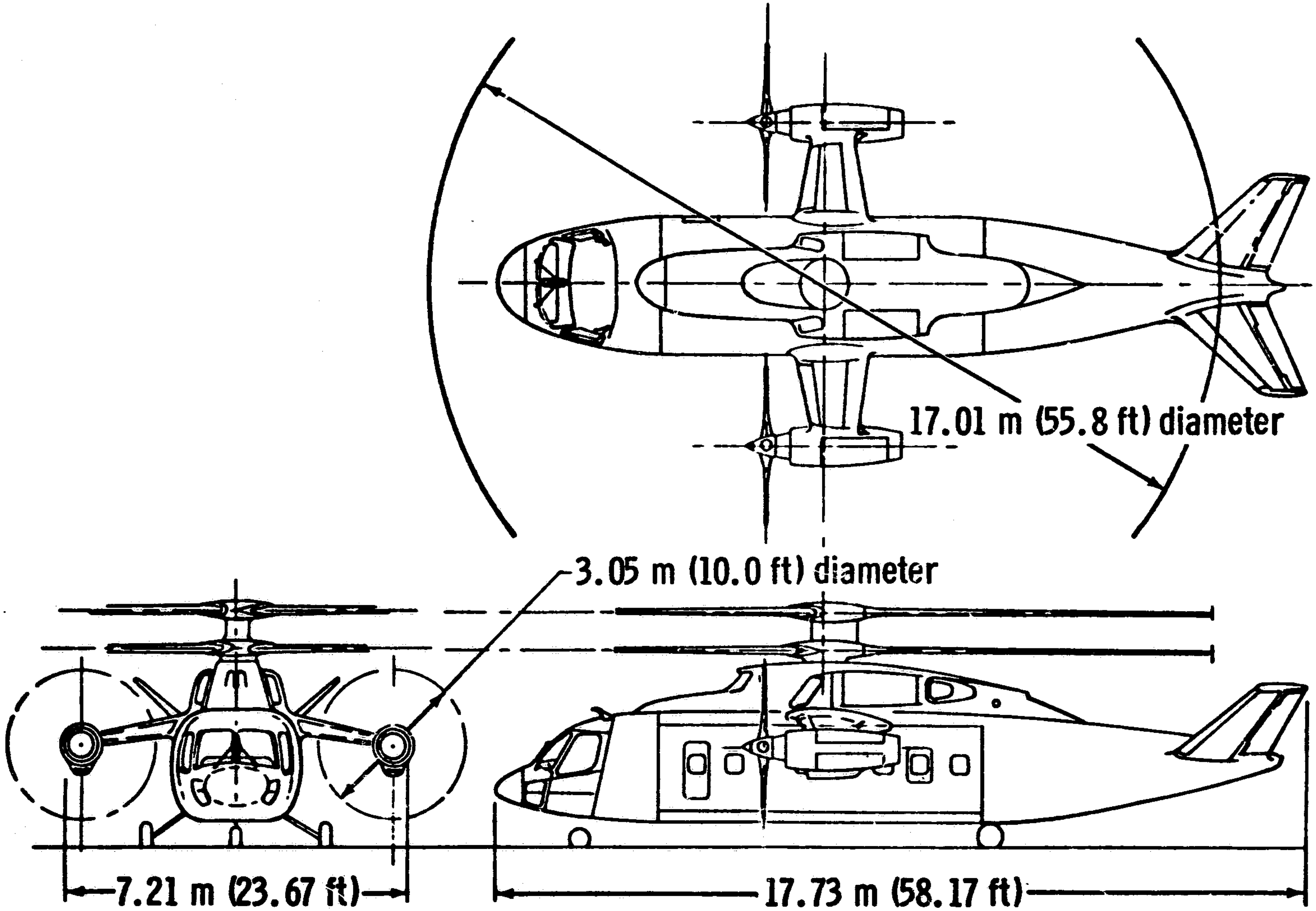

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Figure 3. Sikorsky ABC Rotorcraft with conventional separate engine propulsion system.

Rotor system rotational speed (N_R) varies from 100% in hover and the low flight speed regimes to 77% at design cruise speed to avoid high advancing blade tip Mach number. The auxiliary propulsion system operates only during the level flight cruise segments of the mission; the rotational speed of the auxiliary propulsion system is constant.

The lift engines are controlled by closed-loop power turbine governors incorporated into electronic engine fuel controls, permitting speed reset over the desired rotor range. The cruise engines are controlled by conventional open-loop, turboprop-type power controls in conjunction with conventional constant speed propeller controls and governors.

Convertible System: This aircraft, shown in Figure 4, employs two engines providing power for both the lift rotor system and the auxiliary cruise propulsion system as well as for aircraft accessories. The engines are installed on top of the fuselage deck and drive forward into the main combining gearbox which drives the rotor, the propellers, and the aircraft accessories. The two auxiliary propulsion 3.05 m (10 ft) diameter propellers are installed on outriggers left and right of the fuselage and are driven from the main gearbox by drive shafts via bevel gearboxes and clutches.

Engine output and rotor system rotational speed (N_R) varies from 100% in hover and the low flight speed regime to 77% at design cruise speed. The aircraft is operated in helicopter mode (100% N_R, propellers feathered) to about 259.3 km/h (140 kt) and until the noise sensitive takeoff area has been cleared; then the propellers are unfeathered and accelerated by windmilling. When propeller and drive shaft speeds match, the clutches engage. During subsequent further acceleration to cruise velocity, drive system speed is progressively reduced to 77% and power is diverted primarily to the propellers with the rotor absorbing only partial power. The variation of rotor system and propeller rotational speeds and propulsive thrust with airspeed is shown schematically on Figure 5. During deceleration, the procedure is reversed.

The engines are controlled by closed-loop power turbine governors incorporated into electronic engine fuel controls, permitting speed reset over the desired lift rotor range. When the propeller clutches are engaged, propeller speed is slaved to rotor drive system speed. Propeller blade pitch is set by an open-loop control.

Aircraft Design and Mission Rationale

The 402.3 km (250 mi) design mission depicted in Figure 6 is used to size the aircraft and its fuel system for both separate lift/cruise and convertible propulsion systems. The typical 160.9 km (100 mi) mission shown in Figure 7 represents more nearly day-to-day operations and is, consequently, used for estimating operating costs.

Separate Lift/Cruise System

Start and Ground Maneuvers: In the typical operational mission all ground operation, lift-off, and air maneuvers are represented by an allowance of 3.3 minutes engine operation at maximum continuous power.

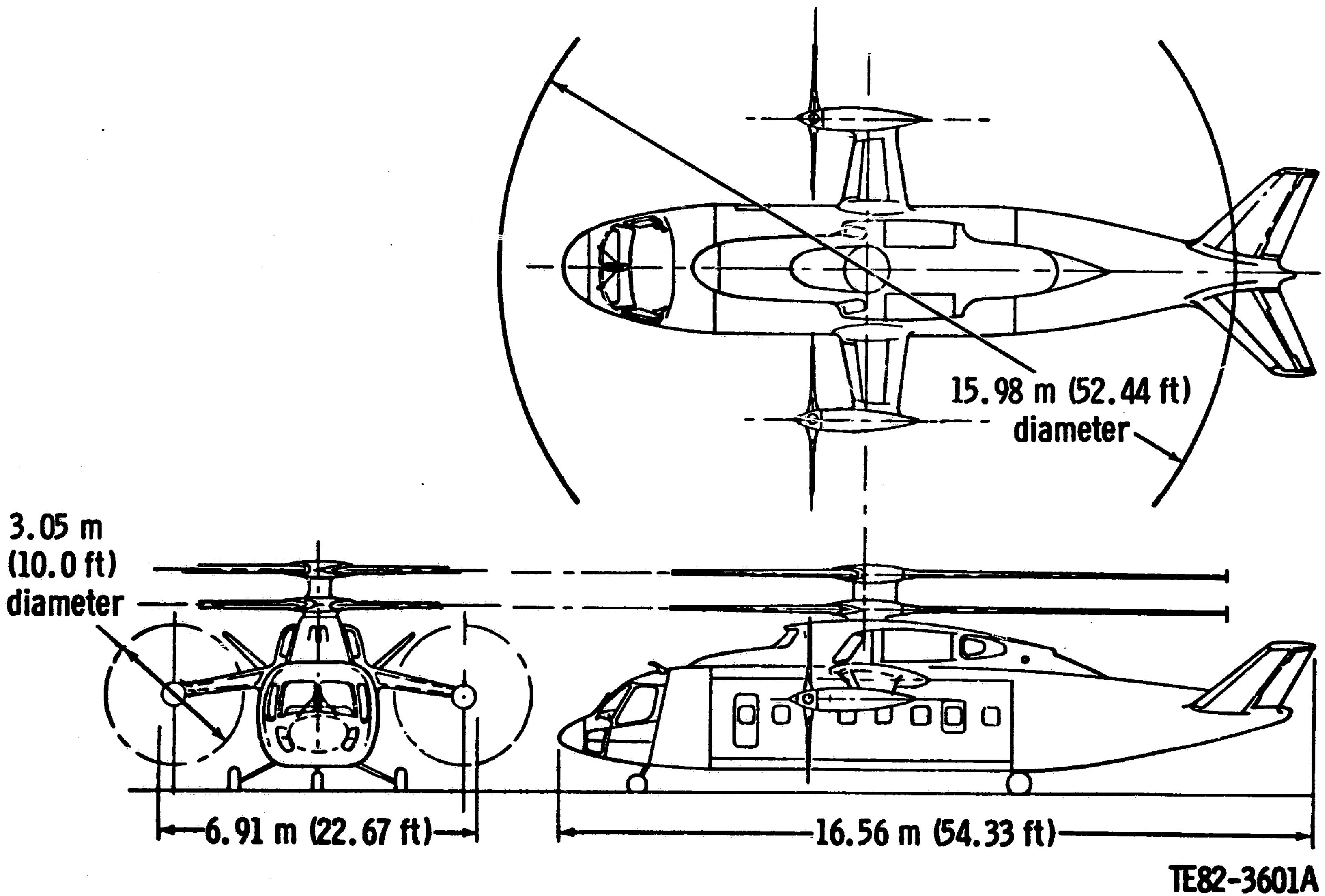


Figure 4. Sikorsky ABC Rotorcraft with convertible propulsion system.

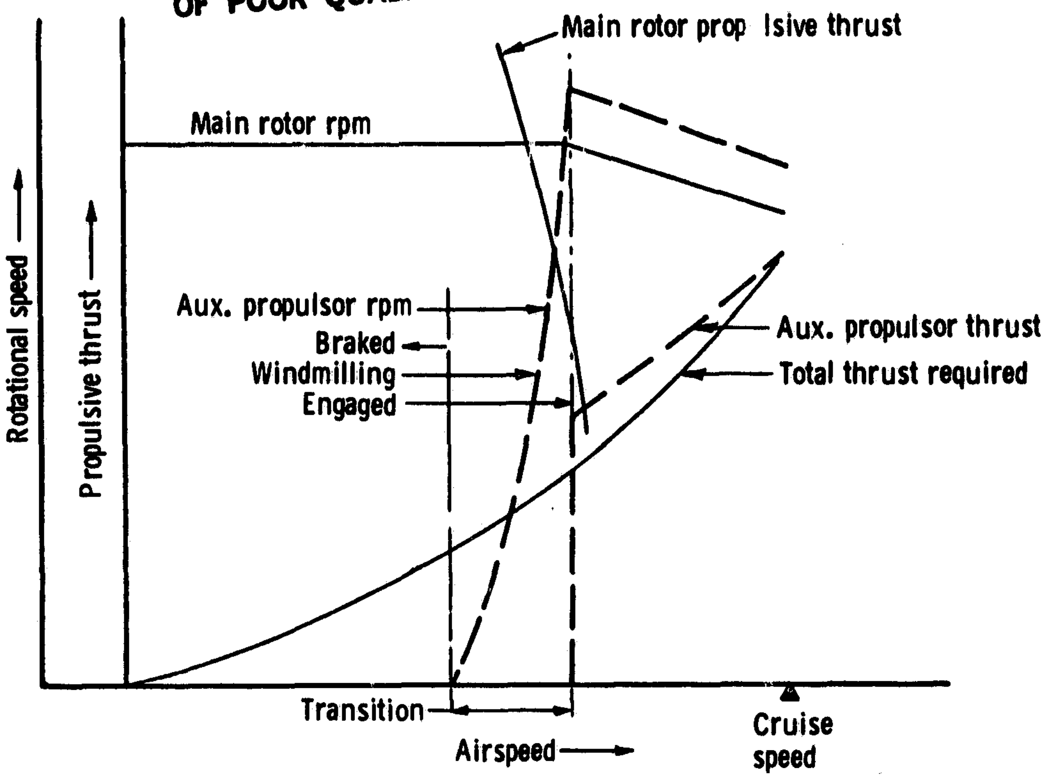
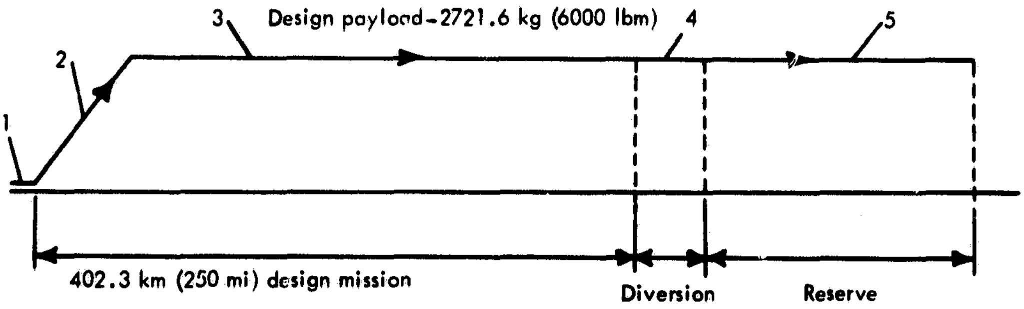


Figure 5. ABC Rotorcraft thrust and drive system speeds.



1. Warm-up, taxi, liftoff: equivalent 4.1 minutes engine operation at max continuous power SLSS, N_{PT} = 100%.
2. Climb from SL to 914.4 m (3000 ft), ROC = 182.9 m/min (600 fpm), standard temperature; distance credit 12.4 km (7.7 mi), V_{TYP} = 148.2 km/h (80 kt) at 457.2 m (1500 ft), 1198.1 kW (1629 shp), N_{PT} = 100%.
3. Level cruise, V = 463.0 km/h (250 kt), 914.4 m (3000 ft), 9.1°C (48.3°F), distance 389.9 km (242.3 mi) to destination, 2665.9 to 2575.6 kW (3575 to 3454 shp), N_{PT} = 77% for segments 3, 4, and 5.
4. Alternate airport diversion 40.2 km (25 mi); at 914.4 m (3000 ft), 9.1°C (48.3°F), V = 463.0 km/h (250 kt).
5. Reserve 30 minutes, V = 463.0 km/h (250 kt), 914.4 m (3000 ft), 9.1°C (48.3°F).

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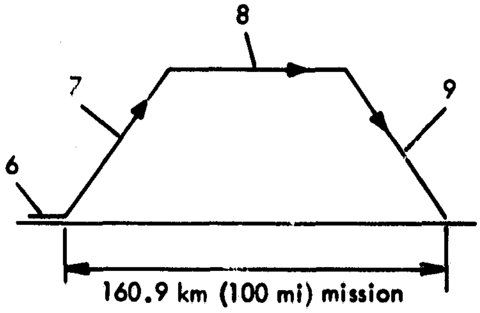
Figure 6. ABC Rotorcraft design mission.

Payload 2721.6 kg (6000 lbm)



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6. Warm-up, taxi, liftoff, maneuvers: equivalent 3.3 min engine operation at max continuous power SLSS, N_{PT} = 100%.
7. Climb to 914.4 m (3000 ft) at 182.9 m/min (600 fpm) ROC, V = 333.4 km/h (180 kt) average, standard temperature, distance credit 27.8 km (17.3 mi), 1763.6 kW (2365 shp), N_{PT} = 100% at 457.2 km (1500 ft).
8. Level cruise, V = 463.3 km/h (250 kt), 914.4 m (3000 ft), 9.1°C (48.3°F), distance 105.3 km (65.4 mi), 2635.3 to 2626.4 kW (3534 to 3522 shp), N_{PT} = 77%.
9. Descent and land at 182.9 m/min (600 fpm) ROD, V = 333.4 km/h (180 kt) average, distance credit 27.8 km (17.3 mi), 1681.6 kW (2255 shp) at 457.2 m (1500 ft), N_{PT} = 100%.

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Figure 7. ABC Rotorcraft typical mission.

Takeoff: One takeoff design condition is two-engine hover out-of-ground effect (HOGE) at 914.4 m (3000 ft), 33.1°C (91.5°F) at design gross weight (DGW) with lift engines at maximum power at 100% N_{PT}. The other takeoff condition is landback capability at DGW on a 121.9 m (400 ft) runway at 304.8 m (1000 ft), 32.2°C (90°F) at 100% N_{PT}, subsequent to a lift engine failure prior to reaching the critical decision point, with the remaining lift engine advanced to 110% of maximum power. The hover out-of-ground effect at 914.4 m (3000 ft). 32.2°C (90°F) is slightly more demanding on power and, therefore, sizes the lift engines.

Climb: The design mission profile assumes a maximum rate of climb of 182.9 m/min (600 fpm) to minimize pascenger discomfort due to pressure change. Climb velocity is assumed to be 148.2 km/h (80 kt) with only the lift engines operating and with 100% lift system rotational speed. The cruise engines do not operate during climb and their propellers are feathered.

Cruise: The aircraft is designed to maintain a level flight cruise speed of 463.0 km/h (250 kt) at any pressure altitude from 914.4 m (3000 ft) to 3048 m (10,000 ft) at standard temperature. Because of the engine's lapse rate with altitude, the 3048 m (10,000 ft) standard temperature condition is the most demanding and therefore sizes the cruise engines. However, cruise at 914.4 m (3000 ft) requires more fuel and, therefore, sizes the aircraft fuel capacity.

Descent: During descent, 463.0 km/h (250 kt) is maintained as long as possible before decelerating and landing, resulting in average descent segment speeds of 333.4 km/h (180 kt). For simplicity, the design mission profile does not incorporate a descent segment since mission time does not have a major impact on the design and since the fuel required to cruise the full distance is slightly conservative compared to a typical descent and landing maneuver.

Convertible System

Start and Ground Maneuver: Same as for separate life/cruise propulsion system.

Takeoff: The two takeoff design conditions are (1) two-engine hover out-of-ground effect at 914.4 m (3000 ft), 33.1°C (91.5°F) at design gross weight, 100% N_{PT}, and engine power not exceeding maximum power and (2) landback capability at design gross weight on a 121.9 m (400 ft) runway at 304.8 m (1000 ft), 32.2°C (90°F), 100% N_R, subsequent to an engine failure prior to reaching the critical decision point, with the remaining engine advanced to 110% of maximum power. The propellers are disengaged and feathered during takeoff and landback. The out-of-ground effect hover at 914.4 m (3000 ft), 33.1°C (91.5°F) requires greater power but neither of these two takeoff conditions demands more engine power than the design cruise condition and therefore does not size the engines.

Climb: The design mission profile assumes a maximum rate of climb at 182.9 m/min (600 fpm) to minimize passenger discomfort due to pressure changes. Climb velocity is assumed to be 148.2 km/h (80 kt) with the engines operating at 100% N_{PT}. The propellers are declutched and feathered during climb. In the typical mission, the propellers are in operation as soon as the noise sensitive takeoff area has been cleared, resulting in an average climb segment velocity of 333.4 km/h (180 kt).

Cruise: The mission description is the same as that for the separate lift/cruise propulsion system. The convertible propulsion system engines are sized by the 463 km/h (250 kt) cruise power requirements at 914.4 m (3000 ft) with 77% N_R, which are more demanding than the takeoff requirements.

Descent: Same as for separate lift/cruise propulsion system.

Technical Requirements Summary

The technical requirements applicable to the Sikorsky ABC Rotorcraft are summarized in Table III.

Aircraft System Sensitivity to Engine Parameters

During this study, the airframe subcontractor conducted mission analyses using baseline engine data with variations in five variables of those engines believed to significantly affect aircraft design. Table IV shows the sensitivity values established by the analysis of these variables for the separate lift/cruise propulsion system. The aircraft characteristics were gross weight, ABC rotor diameter, design fuel for the 402.3 km (250 mi) design mission, DOC and required fuel for the typical 160.9 km (100 mi) mission, and aircraft operating cost. The engine parameters varied were sfc, weight, engine acquisition cost, and engine maintenance cost. In each case, a 10% change in the engine parameter produced the indicated change in the aircraft system parameter. The upper left number in the array is the variation of the aircraft system parameter

Table III.
Technical requirements defining ABC Rotorcraft.

	4 conventional engines	2 convertible engines
Design cruise	463.0 km/h (250 kt) @ TOGW, 914.4 to 3048 m (3000 to 10,000 ft), at not more than max. cont. power of cruise engines at 100% N_{PT}.	463.0 km/h (250 kt) @ DGW 914.4 to 3048 m (3000 to 10,000 ft), at not more than max. cont. power of both engines at 77% N_{PT}.
Takeoff	HOGE 914.4 m (3000 ft), 33.1°C (91.5°F) @ max. power and landback capability OEI on 121.9 m (400 ft) runway, 304.8 m (1000 ft), 32.1°C (89.8°F), remaining lift engine at 110% max. power.	HOGE 914.4 m (3000 ft), 33.1°C (91.5°F) at or below max. power, and landback capability OEI on 121.9 m (400 ft) runway, 304.8 m (1000 ft), 32.1°C (89.8°F), remaining engine at or below 110% max. power.
Enroute stay-up ability	Min. 45.7 m/min (150 fpm) ROC at V_{BE} 166.7 km/h (90 kt), 304.8 m (1000 ft), 32.1°C (89.8°F), TOGW, at not more than 30 minute power on any engine after failure of one lift engine in helicopter mode, or one cruise engine in cruise mode.	Min. 45.7 m/min (150 fpm) ROC at V_{BE} 166.7 km/h (90 kt), 304.8 m (1000 ft), 32.1°C (89.8°F), DGW, at not more than 30 minute power on one engine after failure of one engine @ 100% N_R in helicopter mode or one engine @ 77% N_R in cruise mode.
Engine interconnect	Both lift engines to main gearbox and rotor, operating throughout flight to provide rotor and accessory power. Each cruise engine driving one propeller with no cross-shafting.	Both engines to main gearbox and rotor. Main gearbox to propellers via clutches.
Noise criteria	Helicopter mode: NPRM 79-13 takeoff and approach and below 914.4 m (3000 ft): rotor tip speed limited to 204.2 m/s (670 fps), propellers stationary. Cruise: applicable parts of FAR-36 (fixed wing standards).	Same as for conventional engines.
Aircraft design	FAR part 29, airworthiness standards, transport category rotorcraft.	Same as for conventional engines.

Table IV.
ABC Rotorcraft sensitivity factors, separate lift/cruise propulsion system (% change in aircraft parameter with 10% change in engine parameter).

Aircraft parameter	Aircraft base value	Engine parameters(3) sfc	Weight	Diameter	Acq. cost	Maint. cost
Gross weight	16,635.5 kg (36,675 lbm)	0.66/1.94 2.60	0.36/0.50 0.86	0.20/1.12 1.32	- -	- -
Rotor diameter	17.0 m (55.80 ft)	0.32/0.96 1.28	0.18/0.24 0.42	0.11/0.53 0.64	- -	- -
Fuel--design(1)	2113.3 kg (4659 lbm)	3.40/7.20 10.60	0.38/0.44 0.82	0.71/3.35 4.08	- -	- -
Fuel--typical(2)	535.7 kg (1181 lbm)	3.26/7.68 10.94	0.12/0.12 0.24	0.36/2.01 2.37	- -	- -
DOC--typical(2)	15.22¢/ASkm (24.50¢/ASmi)*	1.64/3.76 5.40	0.08/0.08 0.16	0.16/0.98 1.14	0.20/0.28 0.48	0.16/0.28 0.44
Acquisition cost	$11.039 million	NA/NA	NA/NA	NA/NA	0.80/1.02 1.82	- -

(1) Design mission--402.3 km (250 mi)
(2) Typical mission--160.9 km (100 mi)
(3) 2 lift /2 cruise
Total 4 engines

NA = Not available
- - = Not applicable
* ASmi = Available Seat statute mile
ASkm = Available Seat kilometer

due to a 10% change in the lift or turboshaft engines only. The upper right number in the array is for a similar change in the cruise or turbofan engines only. The lower number in the array is the combined effect of a 10% change for both pairs of engines. The nominal aircraft system base value from which the percent deviations were calculated is also shown. Table V shows the sensitivity values established for the convertible propulsion system.

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Table V.
ABC Rotorcraft sensitivity factors--convertible propulsion system
(% change in aircraft parameter with 10% change in engine parameters).

Aircraft parameter	Aircraft base value	Engine parameters(3)				
		sfc	Weight	Diameter	Acq. cost	Maint. cost
Gross weight	14,695.0 kg (32,397 lbm)	2.44	0.64	0.17	- -	- -
Rotor diameter	16.0 m (52.44 ft)	1.22	0.30	0.08	- -	- -
Fuel--design(1)	1841.6 kg (4060 lbm)	10.78	0.24	0.57	- -	- -
Fuel--typical(2)	489.4 kg (1079 lbm)	10.94	0.36	0.46	- -	- -
DOC--typical(2)	13.39¢/ASkm (21.55¢/ASmi)	6.30	0.28	0.32	0.28	0.28
Acquisition cost	$9.218 million	1.42	0.42	0.15	1.29	- -

(1) Design mission--402.3 km (250 mi)
(2) Typical mission--160.9 km (100 mi)
(3) Two engines
- - Not applicable

The most significant measure of aircraft sensitivity to engine change is direct operating cost (DOC). Figure 8 shows a breakdown of engine-related DOC elements for the ABC Rotorcraft in pie graph format. These data apply to the typical mission and show that fuel is by far the largest cost item, being 51.3% of the total engine related cost. The importance of fuel consumption is also reflected in the sensitivities of Table V, which show that DOC is about 20 times more sensitive to a percent change in sfc than to a percent change in engine weight, size, or cost.

FOLD TILT ROTOR AIRCRAFT

Background

Bell Helicopter Textron, in cooperation with NASA and the U.S. Army, designed, built, and tested the XV-15, a twin engine, tilt rotor research aircraft (Refs. 4 and 5). The XV-15 expands the flight operating envelope of a conventional fixed-wing aircraft to include the capabilities of both an aircraft and a helicopter. For example, the XV-15 has a maximum design speed of over 556 km/h (300 kt), but can also take off and land vertically as well as hover.

Public enthusiasm for the tilt rotor concept was given a boost by the participation of one of the research aircraft at the Paris Air Show during the summer of 1981.

Aircraft Description

Concept

The Fold Tilt Rotor Aircraft is a variant of the XV-15 concept but differs in that the proprotors can be stopped in flight, feathered, indexed, and folded. Propulsion of the aircraft is transferred to a turbofan engine, which permits

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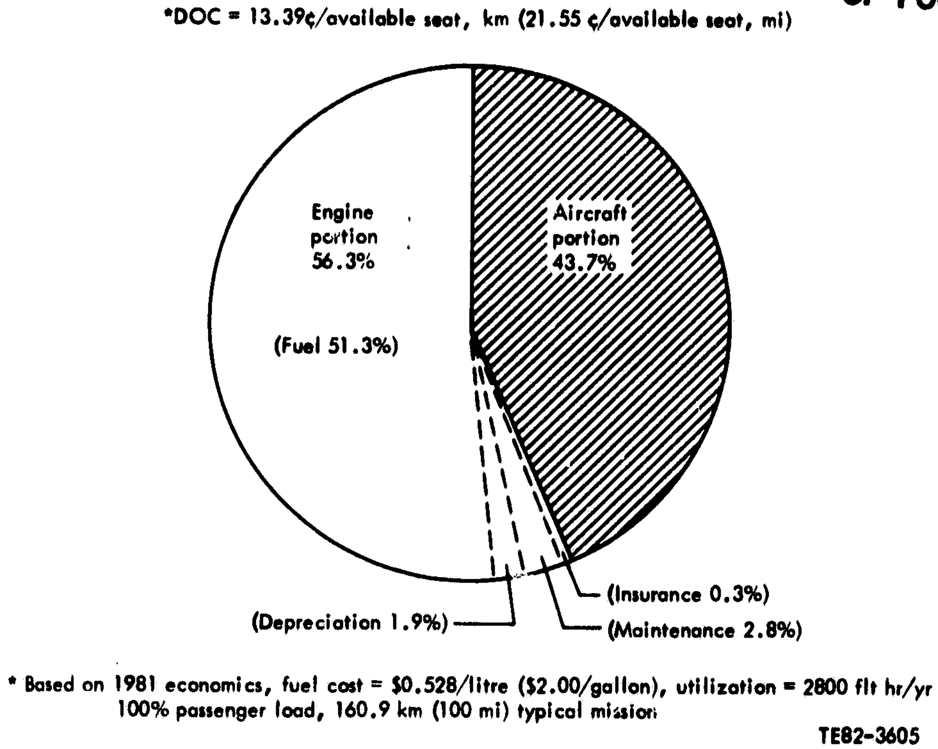


Figure 8. ABC Rotorcraft DOC with convertible engines.

efficient operation at still higher aircraft speeds. Thus, the Fold Tilt Rotor concept permits a further expansion of the aircraft operating envelope over that of conventional aircraft and the XV-15.

The folding proprotor principle has been demonstrated in wind tunnel tests. A 1.5 m (5 ft) model was successfully run in 1971, and a 7.6 m (25 ft) folding proprotor (the same diameter used in the XV-15) was later tested (Ref. 6).

Operational Capabilities

Bell Helicopter has performed many studies over the years on potential applications for the Fold Tilt Rotor Aircraft. Two commercial applications were of particular interest, namely the commuter transport and the off-shore oil rig transport. A commuter aircraft carrying 30 passengers was selected as the nearest term prospect. Variants of the aircraft could be adapted to the off-shore oil market (Ref. 6). Potential military application includes a long-range air/sea rescue aircraft.

Airframe

The fuselage of the Fold Tilt Rotor Aircraft provides accommodations for 30 passengers in a high wing, T-tail design. At the tip of each wing is a three-bladed, folding proprotor. The main fuel tank has a capacity of 2600 L (687 gal).

Furnishings and Equipment

The cabin is furnished as appropriate for commercial, commuter-type operation. Heating, ventilating, and air conditioning are provided by an independent environmental control system. The avionics complement offers full IFR capability.

The primary design characteristics of the Fold Tilt Rotor Aircraft are given in Table VI.

Table VI.
Fold Tilt Rotor Aircraft design data.

	SI units	Customary units
Available passenger seats	30	30
Payload	2721.6 kg	6000 lbm
Crew	240.4 kg	530 lbm
Wing		
Wing loading	3.98 kPa	83.2 lbf/ft^2
Aspect ratio	5.5	5.5
Taper ratio	1.0	1.0
Sweep, degrees	-6.5	-6.5
Dihedral, degrees	2.0	2.0
Fuselage		
Length	18.3 m	60 ft
Width	2.4 m	8 ft
Height	2.4 m	8 ft
Rotor (two)		
Diameter	11.0 m	36.1 ft
Number of blades	3	3
Disk loading	0.85 kPa	17.8 lbf/ft^2
Rotor speed, tip		
Helicopter mode	231.6 m/s	760 fps
Airplane mode	182.9 m/s	600 fps
Blade twist, degrees	25	25

Propulsion

Propulsion is provided by turboshaft engine driven proprotors for vertical takeoff and landing as well as climb and descent. Conversion from helicopter mode to airplane mode is made prior to climb-out and consists of rotating the proprotor pylons from vertical to the forward flight position. Proprotor cyclic pitch is locked out in the airplane mode. Transition from proprotor propulsion to turbofan propulsion is made at 6096 m (20,000 ft) at approximately 426 km/h (230 kt). During cruise operation, turbofans provide forward thrust.

Separate Lift/Cruise System

This aircraft, shown in Figure 9, has four conventional gas turbine engines. Two turboshaft engines power the proprotors and are located in rotatable na-

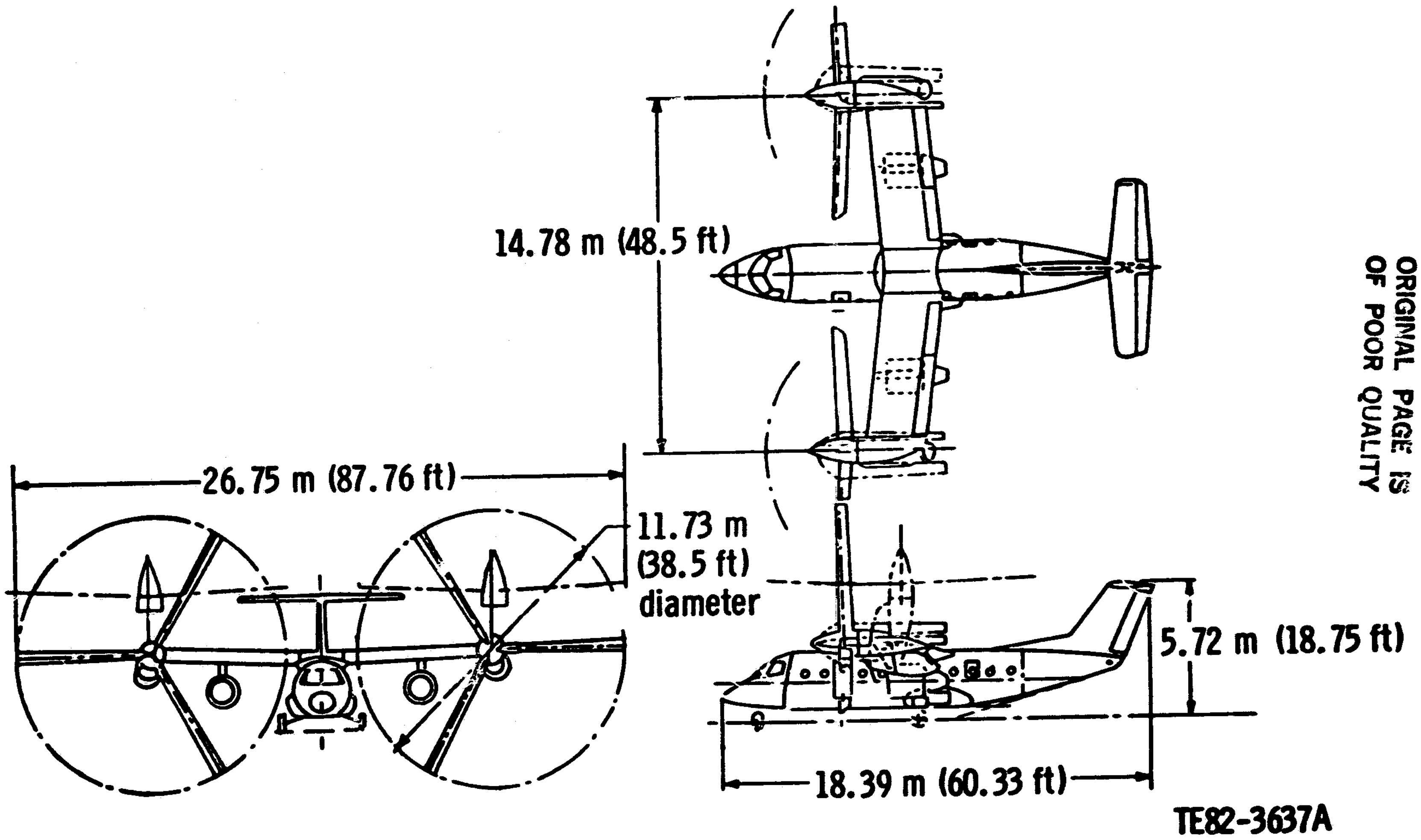


Figure 9. Bell Fold Tilt Rotor Aircraft with conventional separate engines.

celles at each wing tip. The nacelles are oriented in the vertical position for helicopter mode during takeoff and landing and are rotated to the horizontal position during climb and transition to cruise. Cross-shafting is provided between rotors to permit symmetrical thrust in the event one turboshaft engine loses power.

Two turbofan engines provide forward thrust during cruise and are located one under each wing in pylon-mounted nacelles. There is no cross-shafting between the two turbofan engines.

During the transition to cruise, after the turbofans are providing cruise thrust, the proprotors are decelerated, stopped, indexed, and folded back along the nacelles. When preparing to land, the reverse of the above process takes place and the aircraft normally lands in the helicopter mode.

Convertible System

This aircraft is powered by two convertible gas turbine engines which are located, one under each wing, in pylon-mounted nacelles as shown in Figure 10. These engines are capable of delivering their full output either as fan thrust or as mechanical shaft power. During takeoff, climb, or landing operation, shaft power is delivered to an aircraft power transmission system that divides the power equally between the two wing tip mounted, rotatable proprotor pods. During cruise operation, fan thrust is provided and the proprotors are stopped, indexed, and folded back along their pods.

Aircraft Design and Mission Rationale

The Fold Tilt Rotor Aircraft design mission, shown in Figure 11, was established with a range of 1111.2 km (600 nmi) and a 30-passenger load capacity. The requirement for cruise was 0.75 Mach at 6096 m (20,000 ft). The typical revenue mission range is 370.4 km (200 nmi) with a load of 19 passengers, as shown in Figure 12. Cruise for this mission is 740.8 km/h (400 kt) at an altitude of 6096 m (20,000 ft). Maximum speed capability of the aircraft is 851.9 km/h (460 kt). Appropriate fuel reserves were carried on both missions.

Aircraft System Sensitivity to Engine Parameters

The conventional engine powered Fold Tilt Rotor Aircraft system sensitivity to change in engine parameters is shown in Table VII. The aircraft characteristics analyzed were gross weight, design fuel for the 1111.2 km (600 nmi) mission, fuel and DOC for the typical 370.4 km (200 nmi) mission, and aircraft acquisition cost. The engine parameters varied were sfc, weight, engine acquisition cost, and engine maintenance cost. In each case, a 10% change in the engine parameter produced the indicated change in the aircraft system parameter. The upper left number in the array is the variation of the aircraft system parameter due to a 10% change in the lift or turboshaft engines only. The upper right number in the array is for a similar change in the cruise or turbofan engines only. The lower number in the array is the combined effect of a 10% change for both pairs of engines. The nominal aircraft system base value from which the percent deviations were calculated is also shown.

Table VIII shows a similar set of aircraft system parameter sensitivities for the convertible engine powered tilt rotor aircraft. In this case, a 10% parameter change in the pair of convertible engines brings about the indicated change in aircraft system parameter.

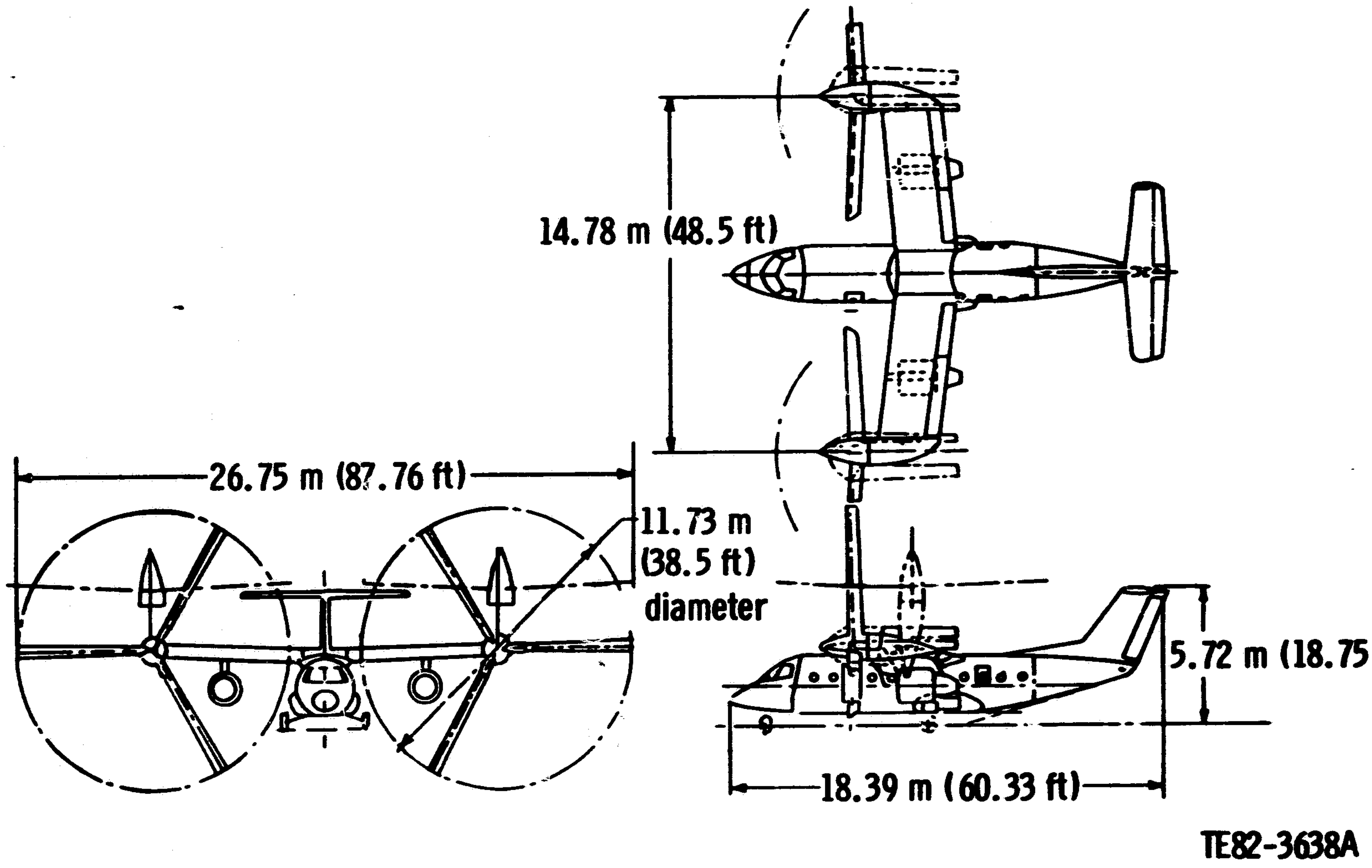
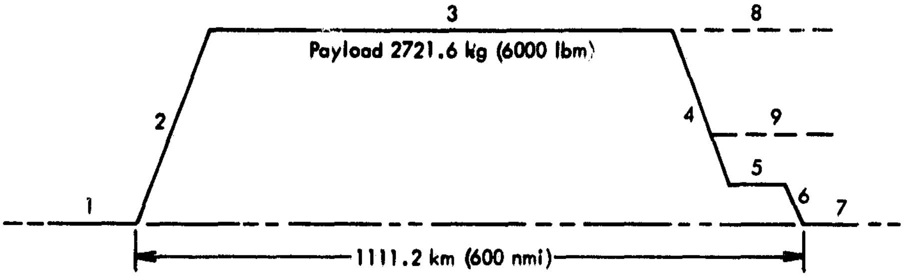


Figure 10. Bell Fold Tilt Rotor Aircraft with convertible engines.



1. Warm-up, hover, loiter—4.0 minutes—TS at 50%, 64%, and 25% MCP, respectively.
2. Climb to 6096 m (20,000 ft), V_{AVER} = 366.7 km/h (198 kt) for 6.7 minutes, 40.7 km (22 nmi)—TS at 54% to 78% IRP.
3. Cruise at 6096 m (20,000 ft), 559.3 km/h (302 kt) for 1:46—TF at 56% to 54% MCP.
4. Descent to 609.6 m (2000 ft), 620.4 km/h (335 kt) for 7.2 minutes, 74.1 km (40 nmi)—TS at flight idle.
5. Loiter at 609.6 m (2000 ft), 255.6 km/h (138 kt) for 1.5 minutes—TS at 23% MCP.
6. Descent to sea level, 255.6 km/h (138 kt) for 0.8 minutes, 3.7 km (2 nmi)—TS at flight idle.
7. Ground operation for 1.0 minutes—TS at 50% MCP.
8. Reserve cruise at 6096 m (20,000 ft), 555.6 km/h (300 kt) for 10 minutes, 92.6 km (50 nmi)—TF at 52% MCP.
9. Reserve loiter at SL, 277.8 km/h (150 kt) for 20 minutes—TS at 24% MCP.

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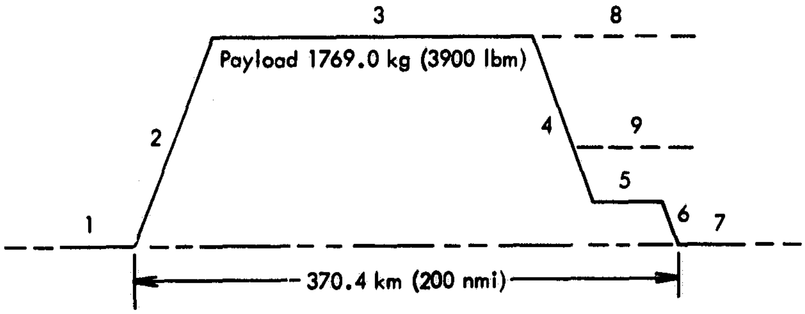
Figure 11. Fold Tilt Rotor Aircraft design mission.



1. Warm-up, hover, loiter—4.0 minutes—TS at 50%, 54%, and 21% MCP, respectively.
2. Climb to 6096.0 m (20,000 ft), V_{AVER} = 337.1 km/h (182 kt) for 5.3 minutes, 29.6 km (16 nmi)—TS at 54% to 80% IRP.
3. Cruise at 6096.0 m (20,000 ft), 742.7 km/h (401 kt) for 0:21—TF at 83% MCP.
4. Descent to 609.6 m (2000 ft), 616.7 km/h (333 kt) for 7.2 minutes, 74.1 km (40 nmi)—TS at flight idle.
5. Loiter at 609.6 m (2000 ft), 248.2 km/h (134 kt) for 1.5 minutes—TS at 21% MCP.
6. Descent to sea level, 248.2 km/h (134 kt) for 0.8 minutes, 3.7 km (2 nmi)—TS at flight idle.
7. Ground operation for 1.0 minutes—TS at 50% MCP.
8. Reserve cruise at 6096.0 m (20,000 ft), 740.8 km/h (400 kt) for 7.5 minutes, 92.6 km (50 nmi)—TF at 52% MCP.
9. Reserve loiter at SL, 257.4 km/h (139 kt) for 20 minutes—TS at 24% MCP.

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Figure 12. Fold Tilt Rotor Aircraft typical mission.

As can be seen in Table VII and VIII, changes in sfc have a much greater impact on aircraft system parameters than do changes in engine weight or cost. Figure 13 shows a breakdown in aircraft DOC in the form of a pie graph. This breakdown applies to the typical 370.4 km (200 nmi) mission and shows that fuel costs are responsible for 38.7% of the total DOC.

Table VII.
Fold Tilt Rotor Aircraft sensitivity factors, conventional engines
(% change in aircraft parameter with 10% change in engine parameters).

Aircraft parameter	Aircraft base value	Engine parameters (3) sfc	Weight	Acq. cost	maint. cost
Gross weight	18,859.9 kg (41,579 lbm)	0.75/2.55 3.30	0.82/1.47 2.29	- -	- -
Fuel--design(1)	2396.8 kg (5284 lbm)	3.14/10.48 13.62	1.10/1.50 2.60	- -	- -
Fuel--typical(2)	785.6 kg (1732 lbm)	4.33/9.47 13.80	0.40/0.81 1.21	- -	- -
DOC--typical(2)	13.34¢/ASkm (21.47¢/ASmi)	1.86/4.35 6.21	0.39/0.68 1.07	0.47/0.59 1.06	0.28/0.38 0.66
Acquisition cost	$16.617 million	0.40/1.36 1.76	0.42/0.76 1.18	0.79/1.16 1.95	- -

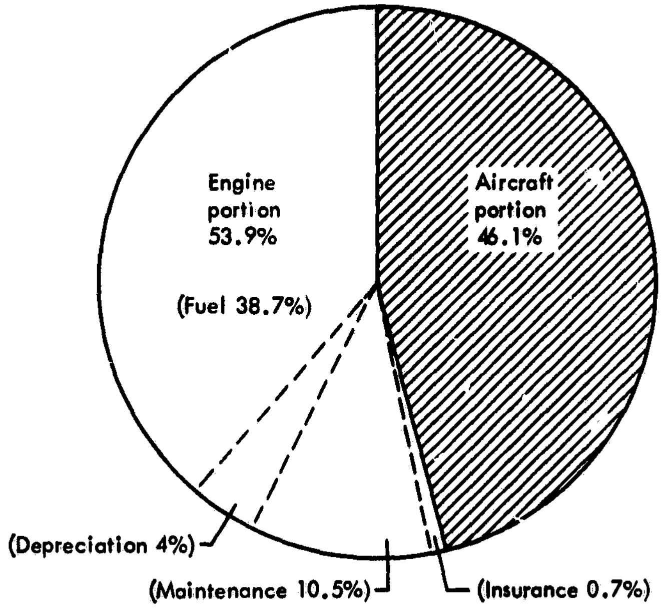
(1) Design mission--1111.2 km (600 nmi)
(2) Typical mission--370.4 km (200 nmi)
(3) $\frac{\text{2 lift / 2 cruise}}{\text{Total 4 engines}}$

Table VIII.
Fold Tilt Rotor Aircraft sensitivity factors, convertible engines
(% change in aircraft parameter with 10% change in engine parameters).

Aircraft parameter	Aircraft base value	Engine parameters sfc	Weight	Acq. cost	Maint. cost
Gross weight	17,742.2 kg (39,115 lbm)	2.69	1.50	- -	- -
Fuel--design(1)	2176.8 kg (4799 lbm)	11.81	1.04	- -	- -
Fuel--typical(2)	718.5 kg (1584 lbm)	13.64	0.76	- -	- -
DOC--typical(2)	11.62¢/ASkm (18.70¢/ASmi)	5.88	0.59	1.02	1.07
Acquisition cost	$14.816 million	1.18	0.55	1.72	- -

(1) Design mission--1111.2 km (600 nmi)
(2) Typical mission--370.4 km (200 nmi)

* DOC = 10.58 ¢/available seat, km (17.02 ¢/available seat, mi)



* Based on 1981 economics, fuel cost = \$0.528/litre (\$2.00/gallon), utilization = 2800 flt hr/yr, 65% passenger load, 370.4 km (200 nmi) typical mission

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Figure 13. Fold Tilt Rotor Aircraft DOC with convertible engines.

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IV. CONVERTIBLE POWERPLANT CONFIGURATIONS

GENERAL

A number of convertible powerplant configurations were examined for both the Fold Tilt Rotor Aircraft and the ABC Rotorcraft. The configurations included the following:

- o convertible fan/shaft engine with variable fan guide vanes employed to unload the fan
- o convertible fan/shaft engine with variable pitch blades to unload the fan
- o convertible propfan/shaft engine with variable pitch propfan blades
- o convertible engine employing independent power turbines--one to drive the rotor and the other to drive either a fan or a propeller. Power turbines were located either adjacent to the engine or remote, at the rotor hub.

The studies included definition of a baseline convertible engine, examination of the alternates, and selection of a preferred configuration for each application. Various advanced technology options were also examined and a preferred option selected.

Throughout these studies, 1990 engine technology was used with emphasis on identifying the unique requirements for convertible engines.

FOLD TILT ROTOR AIRCRAFT APPLICATION

A baseline convertible turbofan/turboshaft engine and six optional powerplant configurations were established and sketches prepared showing their unique features.

Figure 14 shows the features of the baseline convertible engine. This engine was a basic turbofan for cruise flight, but was equipped to operate as a turboshaft engine in the vertical flight and transition modes where propulsion was furnished by the proprotors. The fan/shaft engine featured a pair of hydraulically actuated clutches to selectively transfer power turbine output to either the engine-driven fan or the remotely located aircraft lift rotor system. Figure 15 provides a detail view of the power takeoff and fan drive clutches.

The fixed blade fan incorporated in the design contains variable inlet vanes and variable exit vanes. The variable geometry is required to reduce the power absorption of the fan rotor to a level low enough to permit clutch engagement without appreciably reducing power turbine speed. Constant power turbine speed is desirable to avoid loss of thrust during transition from the proprotor to the fan. Once clutch engagement is achieved, a clutch lock mechanism is engaged and the variable vanes are scheduled open to load the fan. Simultaneously, power delivered to the proprotor is reduced by changes in blade pitch until the full output is absorbed by the fan. At this point, the proprotor is feathered, folded, and stowed, and the transition to turbofan power is complete.

The fan drive clutch is sized for the baseline convertible engine with a maximum power transmission capability of 1864.2 kW (2500 shp) during engagement. When locked up, the clutch is capable of transmitting the full power available from the power turbine. When making the transition from turboshaft mode to

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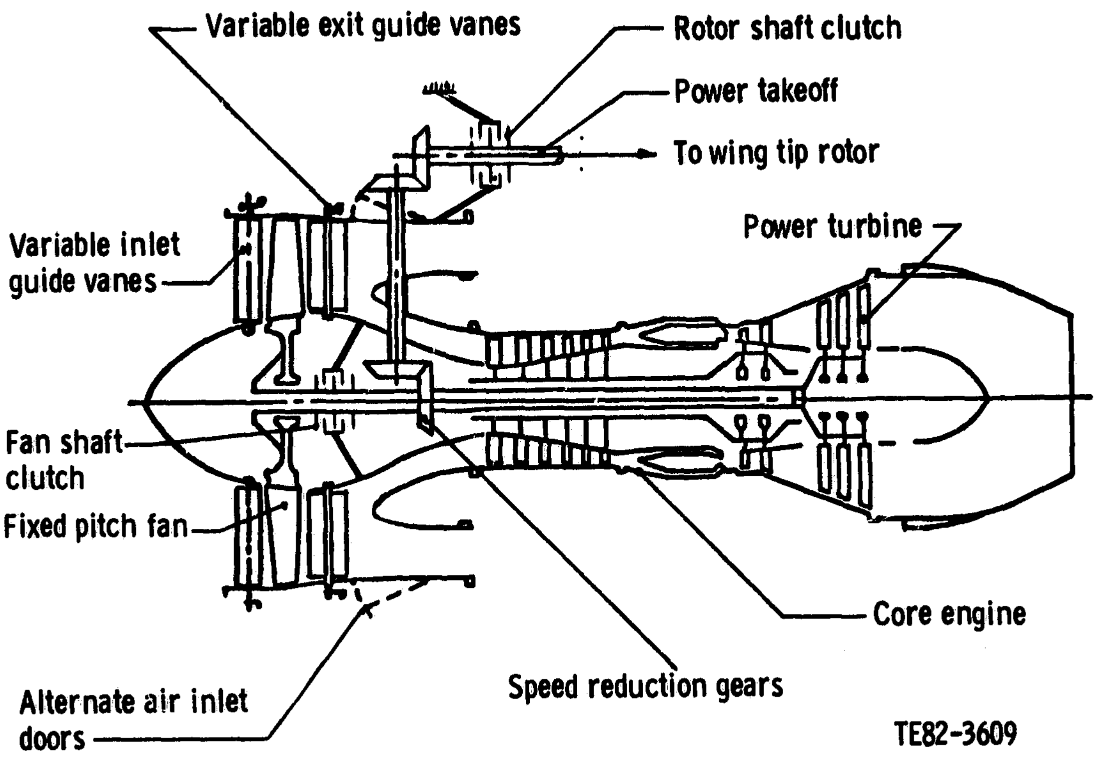

Figure 14. Baseline convertible fan/shaft engine with variable guide vanes--Configuration 1.

turbofan mode, the power absorption capability of the fan must in some way be reduced below the 1864.2 kW (2500 shp) limit. The method chosen for the baseline convertible engine utilizes the above-mentioned variable inlet and exit vanes. The resulting reduction in fan power is shown in Figure 16. It will be noted that both the inlet and exit vanes must be closed in order to reduce the fan power below the engagement limit. An adverse effect of closing the inlet and exit vanes is the buildup of heat in the fan cavity due to churning losses. Figure 16 also shows an approximation of this heat rise versus vane closure angle.

The design studies were based on using the DDA V/STOL lift fan clutch designed, built, and successfully tested on USN Contract N00019-76-C-0695 (Ref. 7). This clutch was resized to the convertible engine requirements. At unity size, the V/STOL clutch demonstrated the following characteristics:

Normal power--kW (shp)	6361.6 (8531)
Maximum power through clutch assembly--kW (shp)	8583.0 (11,510)
Design speed @ 100%--rpm	8432
Maximum speed--%	120
Engagement (lockup) power--kW (shp)	947.0 (1270)
Total system weight--kg (lbm)	97.5 (215)

Geometrical relationships of blade/vane spacing followed standard design practice. Nacelle air inlet doors were provided to reduce the inlet flow losses during turboshaft engine operation. The doors allow core inlet flow entry behind the fan exit guide vanes and into the gasifier inlet.

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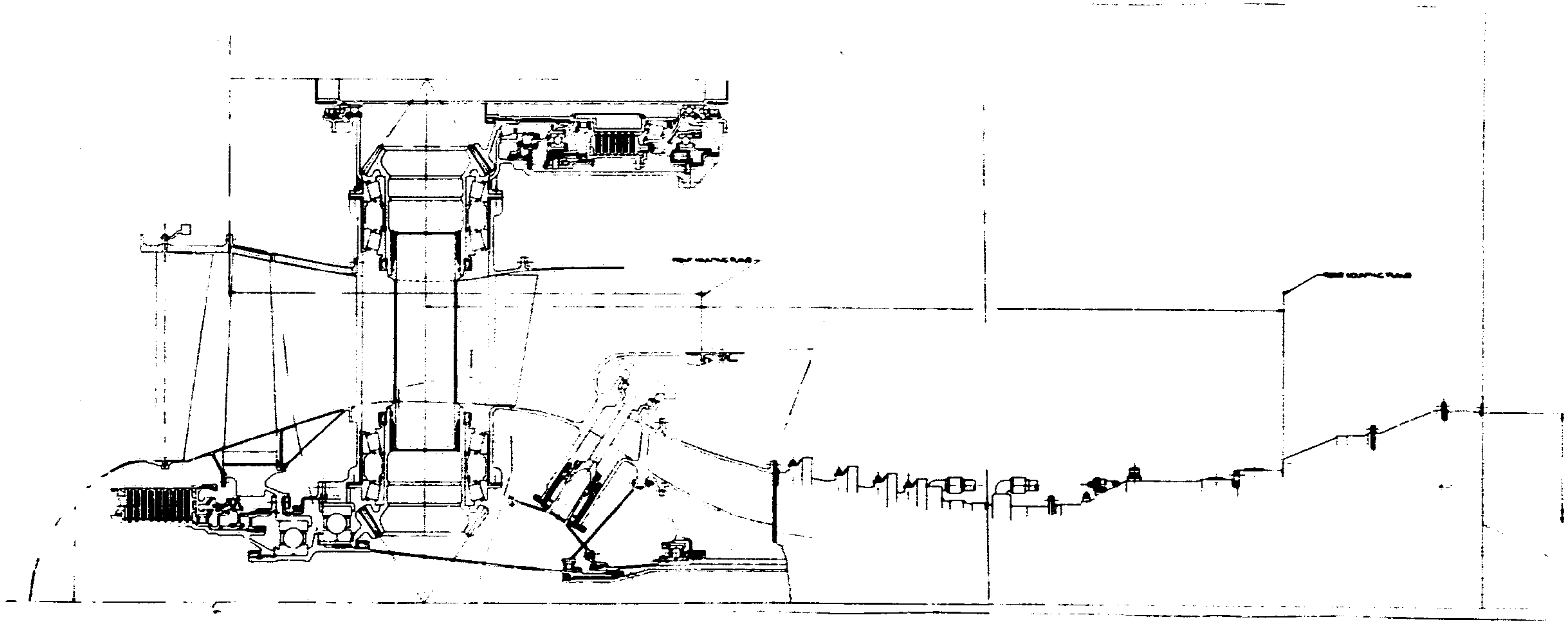

Figure 15. Baseline convertible engine power takeoff and fan drives.

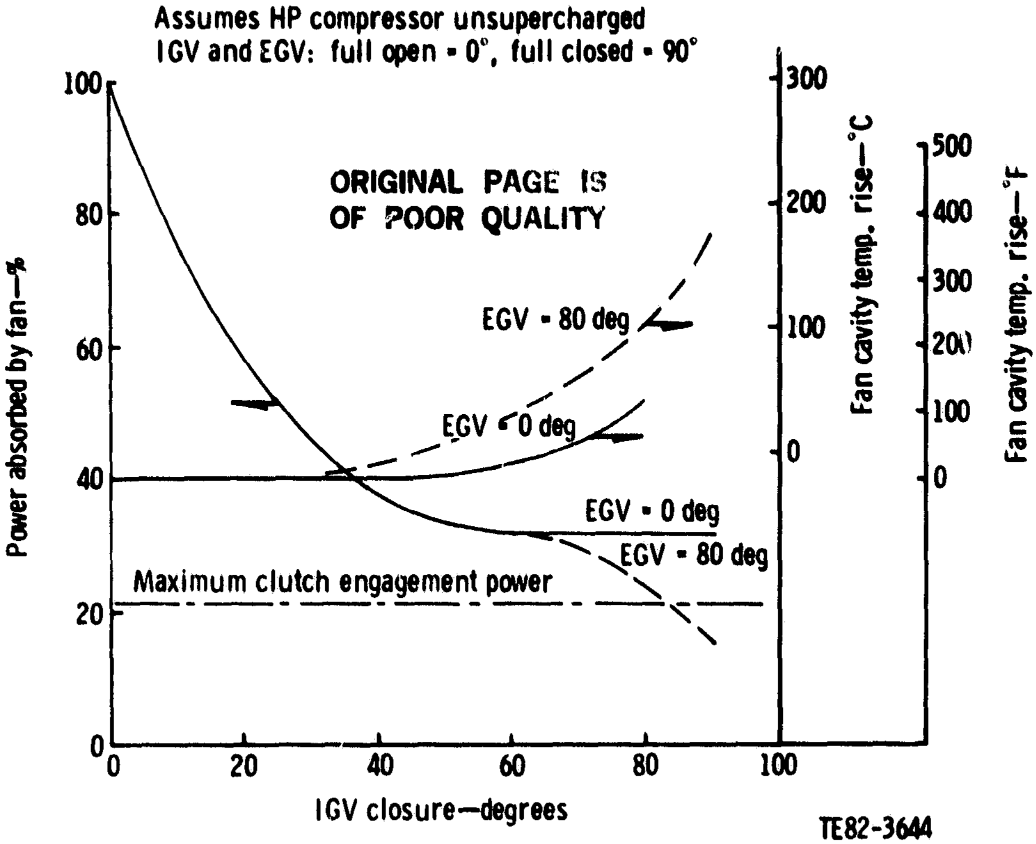

Figure 16. Variable fan vanes for the baseline convertible engine.

The design of the gasifier portion of the engine was based on technology anticipated for the 1990 time frame, a highly loaded axial compressor, an annular combustor, and a two-stage air-cooled turbine rotor mounted on a two-bearing system. The power turbine is a three-stage free turbine. The LP system contains three main bearings. Variable geometry is utilized in both the cold and the hot sections of the gas generator and LP system.

In addition to the baseline convertible fan/shaft engine, six optional powerplant configurations were established and sketches prepared showing their unique features.

In each of these study configurations, the same basic core engine was utilized with the assumption that identical output performance was developed by all of the engines.

Figure 17 illustrates the first optional configuration in which the alternate air inlet doors, fan drive clutch, and fan exit guide vanes are deleted and the fan inlet guide vanes modified to a partial span configuration. The part span vanes traverse the outer portion of the fan inlet but leave open the fan hub flow area. This configuration provides a level of fan hub flow, or gas generator supercharging, when operating in the turboshaft mode.

Figure 18 shows an optional scheme in which both inlet and exit fan guide vanes, alternate air inlet doors, and fan drive clutch are deleted and a variable fan exit nozzle added. In this engine, the fan pitch is variable. Figure 19 depicts a version of the baseline engine which uses a variable pitch propfan and reduction gear, in lieu of a fan, for cruise propulsion.

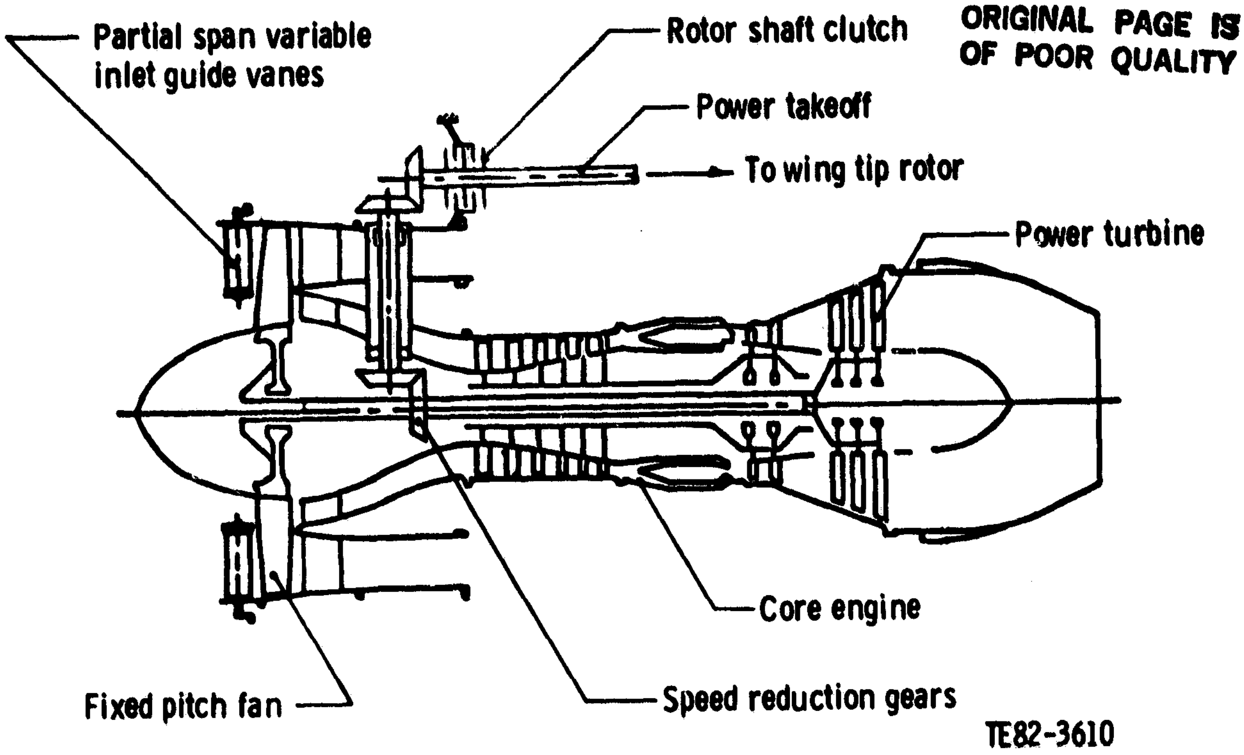

Figure 17. Convertible fan/shaft engine with partial span, variable inlet guide vanes--Configuration 2.

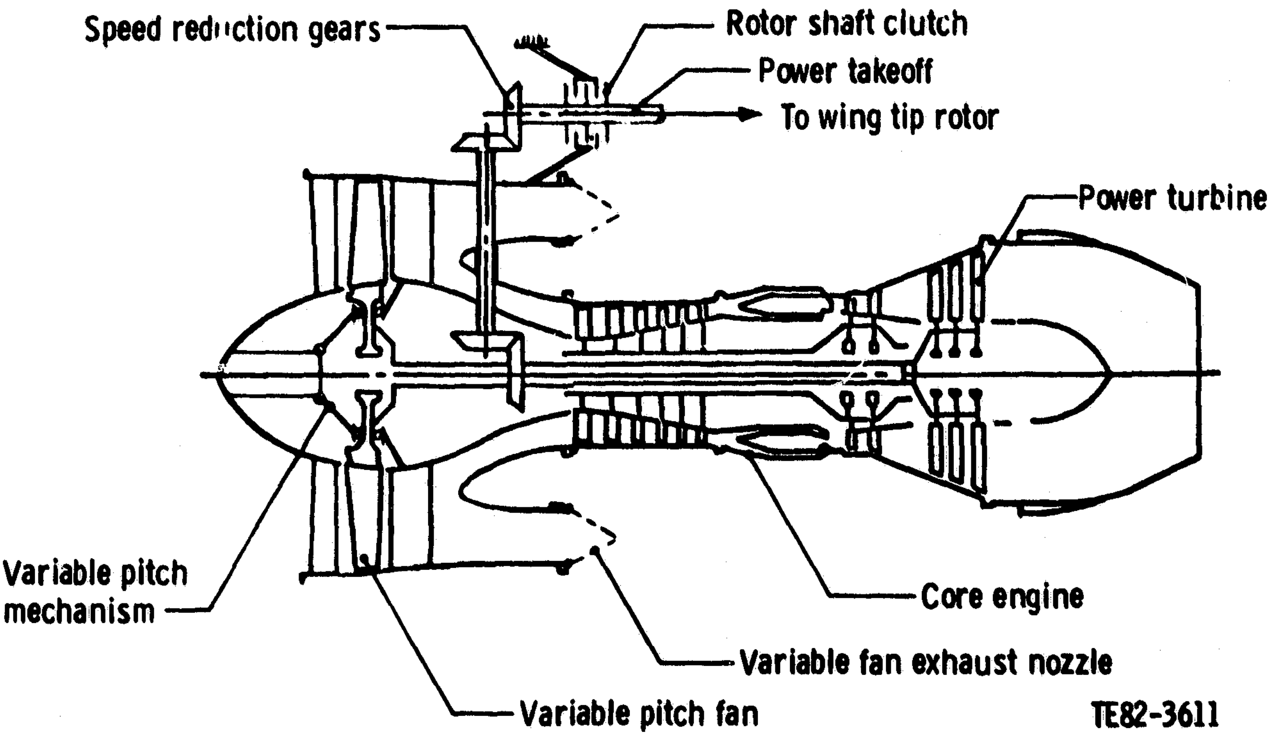

Figure 18. Convertible fan/shaft engine with variable pitch fan--Configuration 3.

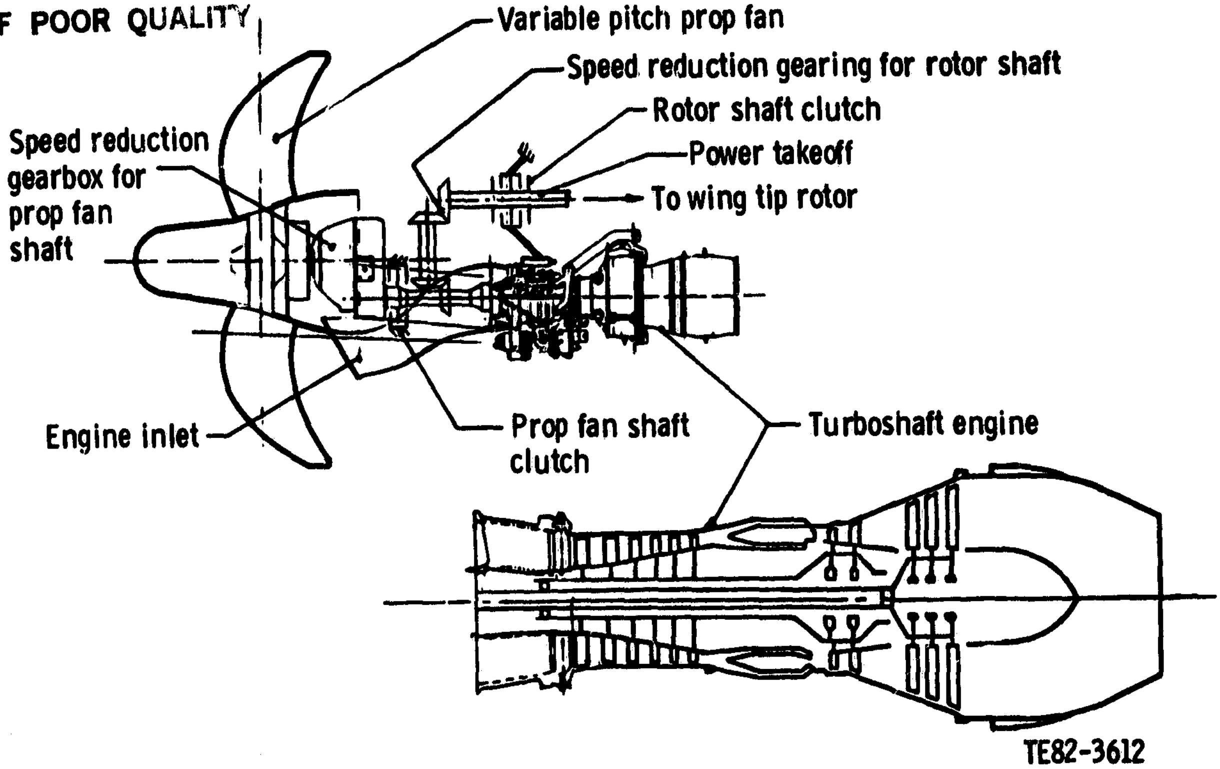

Figure 19. Convertible fan/shaft engine with variable pitch propfan--Configuration 4.

Figure 20 shows a turbine variation in which a second power turbine, located beside the core engine and sharing its interturbine plenum, provides a power output shaft for the rotor drive. Figure 21 illustrates an alternate independent power turbine concept in which the rotor drive turbine is remote from the core engine and connected by HP turbine exhaust ducts.

Figure 22 shows an option which is like the baseline engine except that its clutches are replaced with modulated fluid couplings and it does not have variable fan guide vanes or alternate air inlet doors.

For clarity of discussion, the seven configurations examined for application to the Fold Tilt Rotor Aircraft are assigned numbers as shown in Table IX.

For purposes of conducting the configuration assessment, a typical engine cycle was selected and all propulsion systems were configured with the same core engine. All of the propulsion systems were sized to provide 13,789 N (3100 lbf) thrust in the 6096 m (20,000 ft), 0.75 M_N cruise flight mode. With one exception, this yielded core engines which provide 4921.6 kW (6600 shp) in the sea level static, 32.2°C (90°F) day, intermediate power operating condition. The one exception is the propfan propulsion system configuration, which does not require as large a core engine to develop the design cruise thrust and, hence, provides only 4675.5 kW (6270 shp) in the sea level static, hot day, intermediate power operating condition. In all cases, however, the cruise power requirement is the flight condition which sizes the core engine; this results in each core engine, including that for the propfan propulsion system, having more power at the maximum rating point (defined as 1.1 times the intermediate rating) than is required by the Fold Tilt Rotor Aircraft at the sea level static, 90°F day, one engine inoperative hover, in ground effect condition.

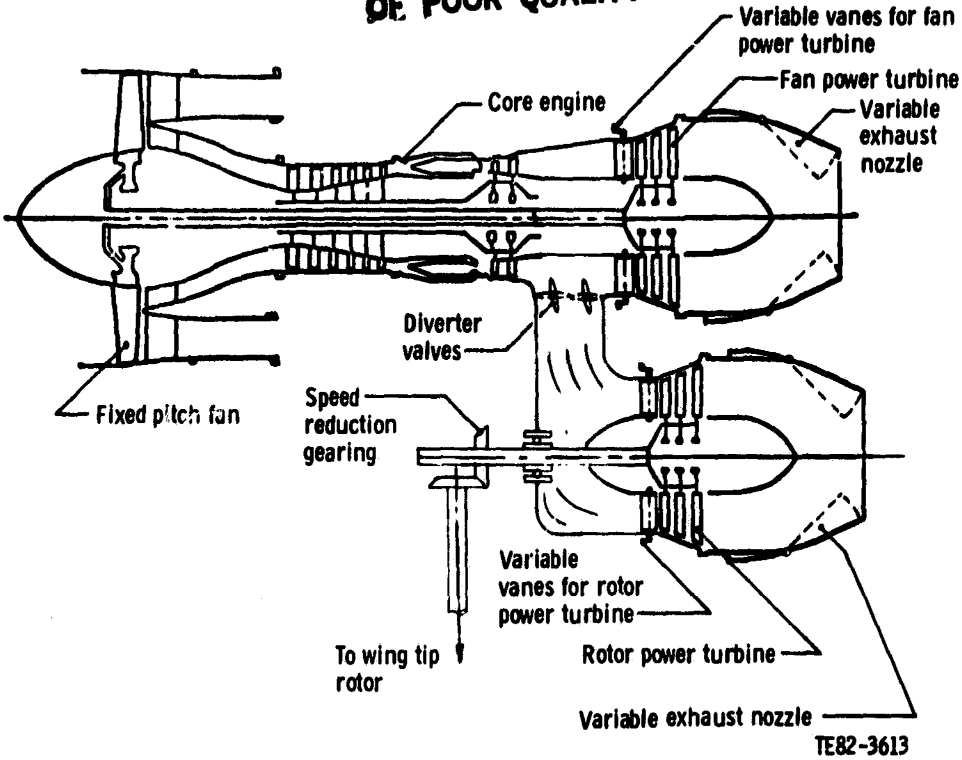

Figure 20. Convertible engine--independent power turbine--Configuration 5.

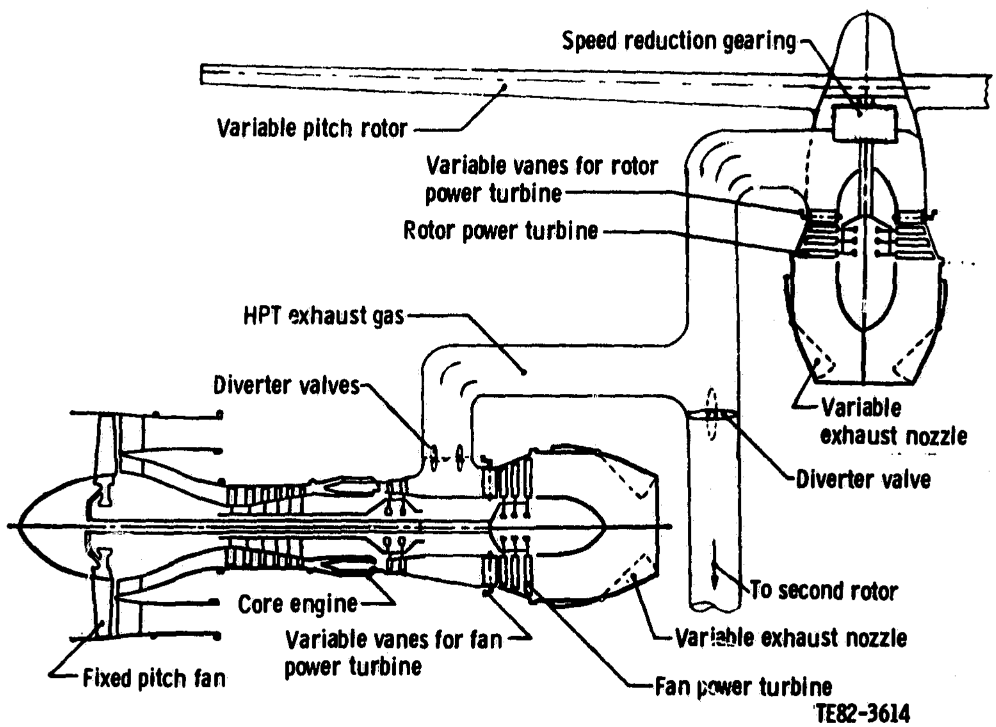

Figure 21. Convertible engine--remote power turbine--Configuration 6.

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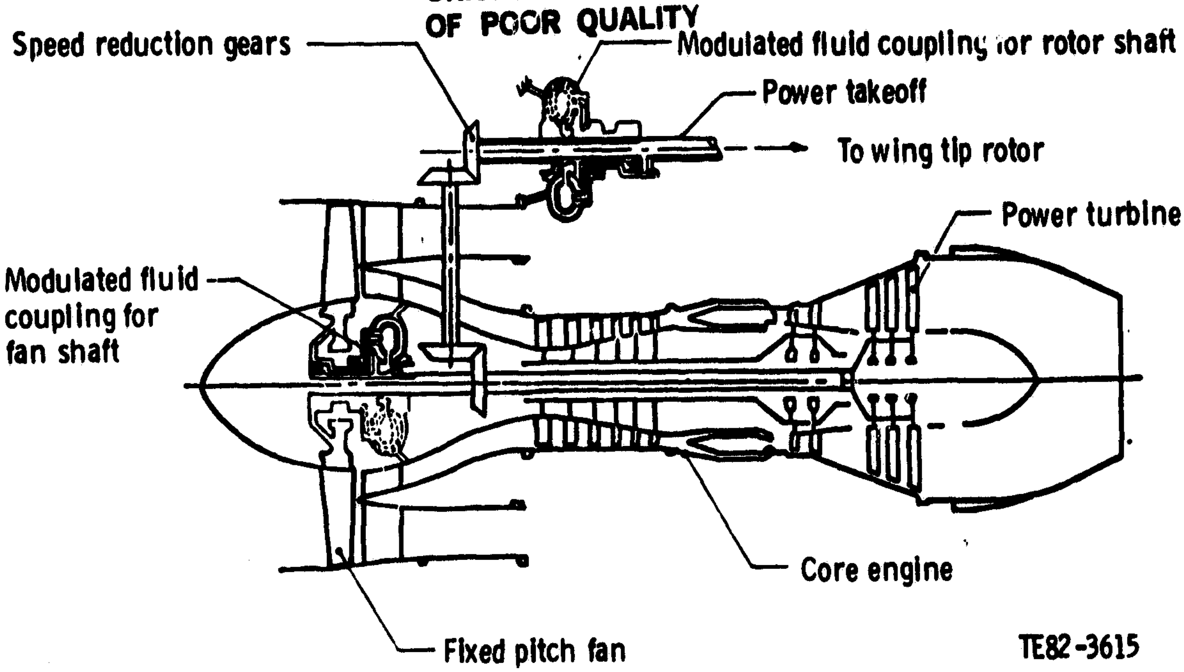

Figure 22. Convertible fan/shaft engine with modulated fluid couplings—Configuration 7.

Table IX.
Convertible engine configurations for Fold Tilt Rotor Aircraft.

Configuration No.	Identifying features
1 (baseline)	Variable inlet guide vanes (VIGV), variable exit guide vanes (VEGV), wet plate clutches for power transfer
2	Partial span VIGV, rotor shaft clutch only
3	Variable pitch fan blades, rotor shaft clutch only
4	Variable pitch propfan, propfan and rotor shaft clutches
5	Independent engine and rotor power turbines
6	Remote rotor power turbines
7	Fixed geometry fan, modulated fluid couplings for power transfer

Attributes and Limitations

The apparent attributes and limitations of each convertible engine configuration are summarized in Table X. In many cases, a clear superiority of one configuration over another is not clear, and the need for additional research and technology programs is indicated. An attempt is made to rank each engine on the basis of several important parameters in a subsequent section.

ADVANCING BLADE CONCEPT ROTORCRAFT APPLICATION

Alternate convertible engine schemes were studied for the twin-engine Sikorsky ABC Rotorcraft. In this aircraft, conventional turboshaft engines are used, and the "converting" from cruise mode (via propellers or fans) to vertical takeoff or landing mode is accomplished by changes within the aircraft power transmission system.

Table X.

Attributes and limitations of candidate convertible engines for Fold Tilt Rotor Aircraft.

Configuration	Attributes	Limitations
1.0 Baseline convertible fan/shaft engine with VIGV, VEGV, and wet plate clutches for fan drive and rotor drive	1.1 Uses clutch with demonstrated capability at the required power level (Ref. 8)	1.1 Time required for clutch engagement (5 to 10 seconds) may be excessive in some situations
	1.2 Fan thrust can be modulated from zero to maximum	1.2 Fan churning losses with closed VIGV and VEGV results in approximately 190.1°C (375°F) temperature rise in the fan cavity
	1.3 Fan can be operated at best design speed during cruise	1.3 R&T required to determine effect on fan blade and blade stresses of stall/flutter phenomenon and to understand requirements for control of power transfer system with four variables (two variable vane stages and two clutches)
2.0 Convertible fan/shaft engine with partial span VIGV and a wet plate clutch for rotor drive	2.1 Constant fan operation provides core supercharging for all modes of operation. This results in an improvement in sfc (19%) and specific power (23%)	2.1 R&T required to determine thrust/power splits possible with VIGV
	2.2 Fan clutch not required thus reducing engine weight approximately 65.8 kg (145 lbm)	2.2 Same as 1.3
	2.3 Potential for smoother and more rapid transition for power/thrust output than most configurations	2.3 R&T required to assess fan performance with close proximity trailing edge flow divider
	2.4 Provides for continuous split in power/thrust output	2.4 Partial span VIGV configuration causes high noise generation
3.0 Convertible fan/shaft engine with variable pitch fan and wet plate clutch for rotor drive	3.1 Potential for varying fan thrust from full forward to full reverse	3.1 Fan power absorption at flat pitch and wake effects at the compressor inlet may be significant design considerations
	3.2 Same as 2.2	3.2 Aerodynamic compromises required to achieve variable mechanism could be sizable leading to as much as 5% sfc penalty at cruise
		3.3 Fan blade stress levels would be relatively high with resultant weight penalties to maintain safe values

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Table X (cont).

Configuration	Attributes	Limitations
4.0 Convertible prop/shaft engine with variable pitch propfan and wet plate clutches for propfan and rotor drives	4.1 Max. propulsion efficiency at high cruise velocity (up to 0.8 Mach) with best cruise sfc	4.1 Propfan-to-rotor clearance inadequate for wing-mounted propfans
	4.2 No power section VIGV, VEGV, or inlet doors required with their attendant complexity and reliability penalty (approximate PRR difference of 0.1)	4.2 Aft-mounted propfans result in weight penalties in power transmission to wing tip mounted prop rotors
	4.3 Propfan thrust may be varied from full forward to full reverse	4.3 Weight increase over configuration 1 (due to prop. and reduction gear)--approximately 38%, cost increase--11%
5.0 Convertible fan/shaft engine with independent power turbine for rotor drive	5.1 Power turbine may be optimized for separate and different design conditions. This can result in turbine efficiency gains of as much as 0.5% with resulting sfc improvements of approximately 0.5%	5.1 Variable turbine vanes and diverter valves present a development risk primarily in the area of sealing to prevent gas leakage
	5.2 No requirement for clutches or variable fan geometry resulting in a more "conventional" turbofan portion of the total propulsion system with improved reliability	5.2 The gas flow path to the independent turbines requires several sets of turning vanes with losses to the cycle which cause an increase in sfc of 19% at cruise
6.0 Convertible fan/shaft engine with remote power turbine for rotor drive	6.1 Same as 5.1	6.1 Response time of the remote power turbine during transients is appreciably greater for gas coupled drive system compared to that of the mechanical drive systems
	6.2 Same as 5.2	6.2 Same as 5.2. A trade-off weight analysis would be required, once the aircraft configuration is established, to determine which of the power transfer systems (gas flow vs shaftpower) offers the greatest advantage in weight
7.0 Convertible fan/shaft engine with modulated fluid couplings for fan and rotor drive	7.1 Same as 1.2 and 1.3 but VIGV and VEGV not required, reducing weight approximately 24.5 kg (54 lbm)	7.1 R&T required to facilitate the design of torque converters for the recommended power levels and light weight requirements of aircraft applications
	7.2 Rapid power transfer possible (less than 5 sec), which provides improvement in system response time in comparison to other six systems	7.2 An additional oil system (reservoir, pumps, cooler, etc) required. No additional technology required for this conventional system
	7.3 Couplings do not exhibit wear problems associated with disk clutches and thereby benefit from increased reliability and longer life	

Figure 23 shows the baseline installation using propellers on outriggers for cruise propulsion and ABC, twin rotors to provide lift throughout the mission, and forward propulsion prior to, and after, conversion to cruise flight. Figure 24 illustrates an optional configuration using fixed pitch fans in lieu of propellers on the outriggers. In Figure 25, the configuration shown has a variable pitch fan but does not have a clutch in the fan input shaft.

In Figure 26, independent power turbines are used to drive the outrigger propellers during cruise while the core engines provide continual power to the lift rotor system. An alternate independent power turbine arrangement is shown in Figure 27. In it, a single power turbine furnishes the twin rotor drive while each of the two core engines drives one of the outrigger propellers.

Figure 28 depicts an option which differs from the baseline only in having a modulated fluid coupling, in lieu of a clutch, in the propeller input line. Figure 29 shows two convertible engines (with a modulated fluid coupling in the fan drive shaft) used in lieu of turboshaft engines. The convertible engines are located on the outriggers and provide fan thrust when required for cruise, as well as continuous shaft power to the rotors.

For clarity of discussion, the seven propulsion systems examined for application to the ABC Rotorcraft are assigned configuration numbers as shown in Table XI.

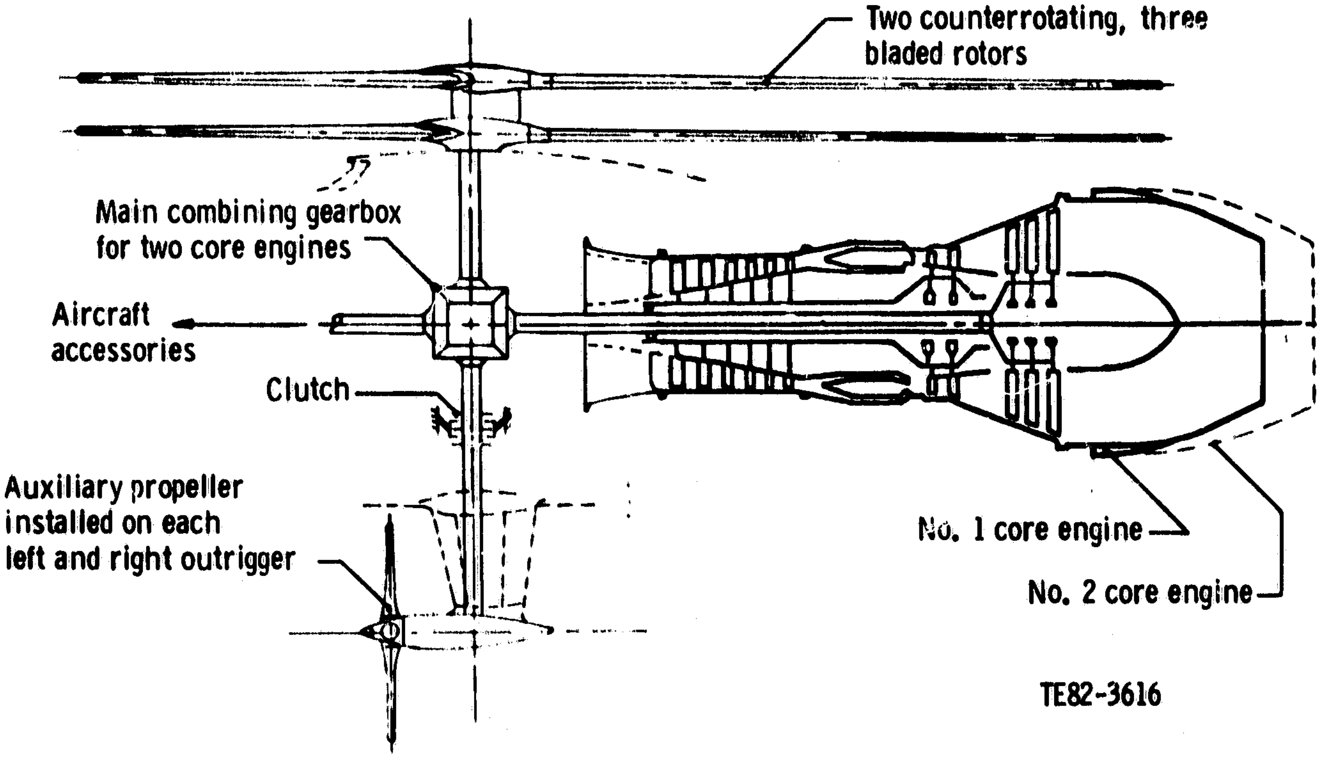

Figure 23. Baseline turboshaft convertible propulsion system--Configuration 8.

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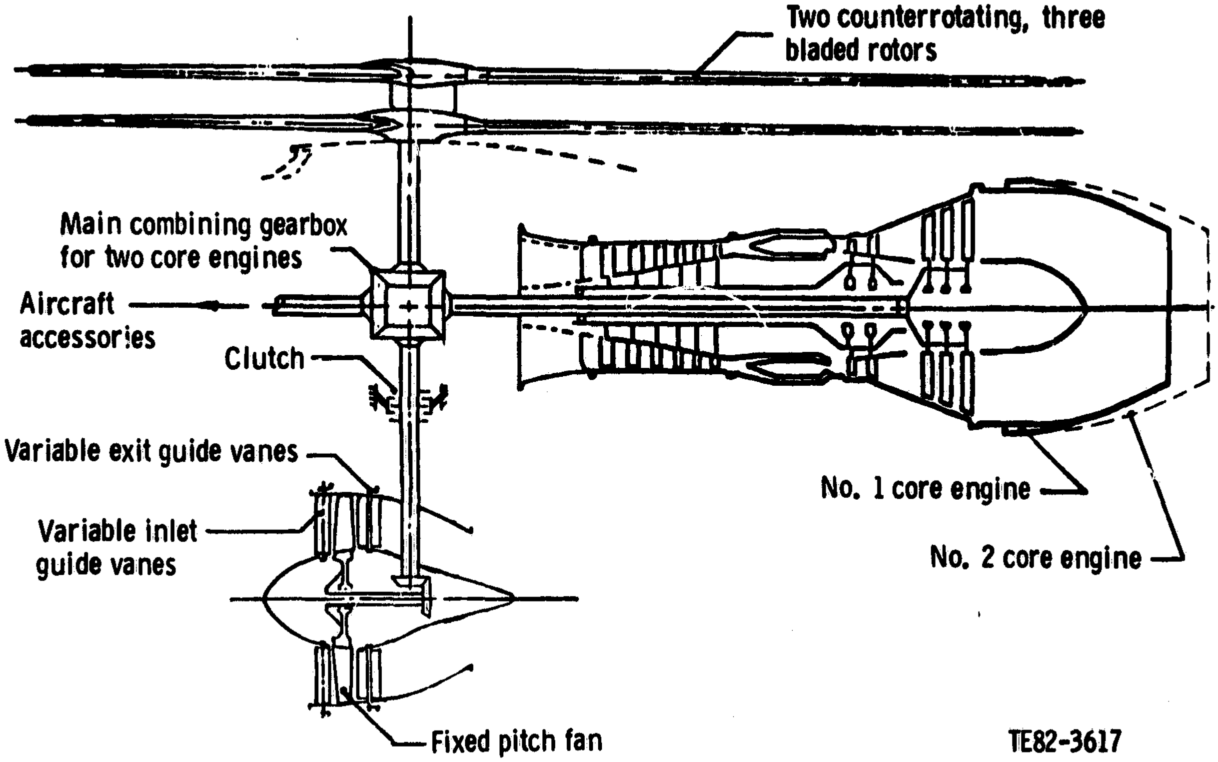

Figure 24. Convertible propulsion system with auxiliary fans (variable guide vanes)--Configuration 9.

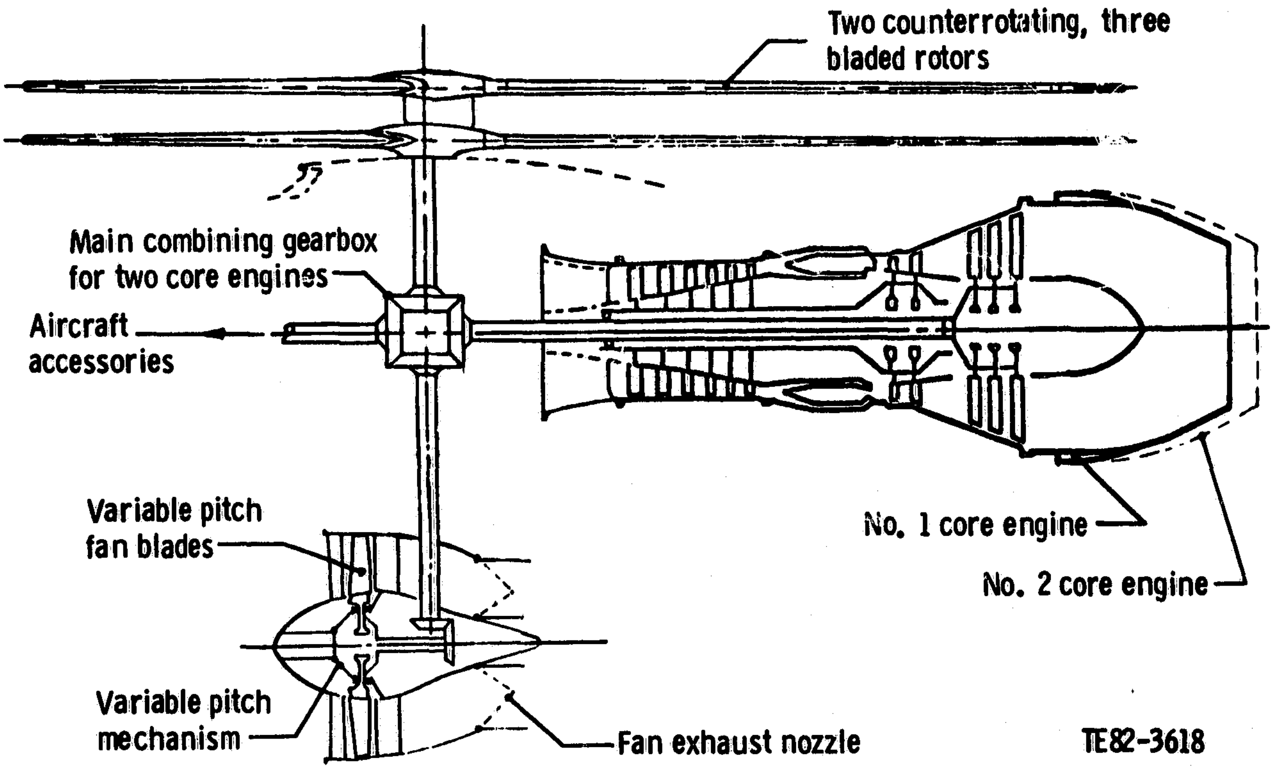

Figure 25. Convertible propulsion system with auxiliary fans (variable pitch blades)--Configuration 10.

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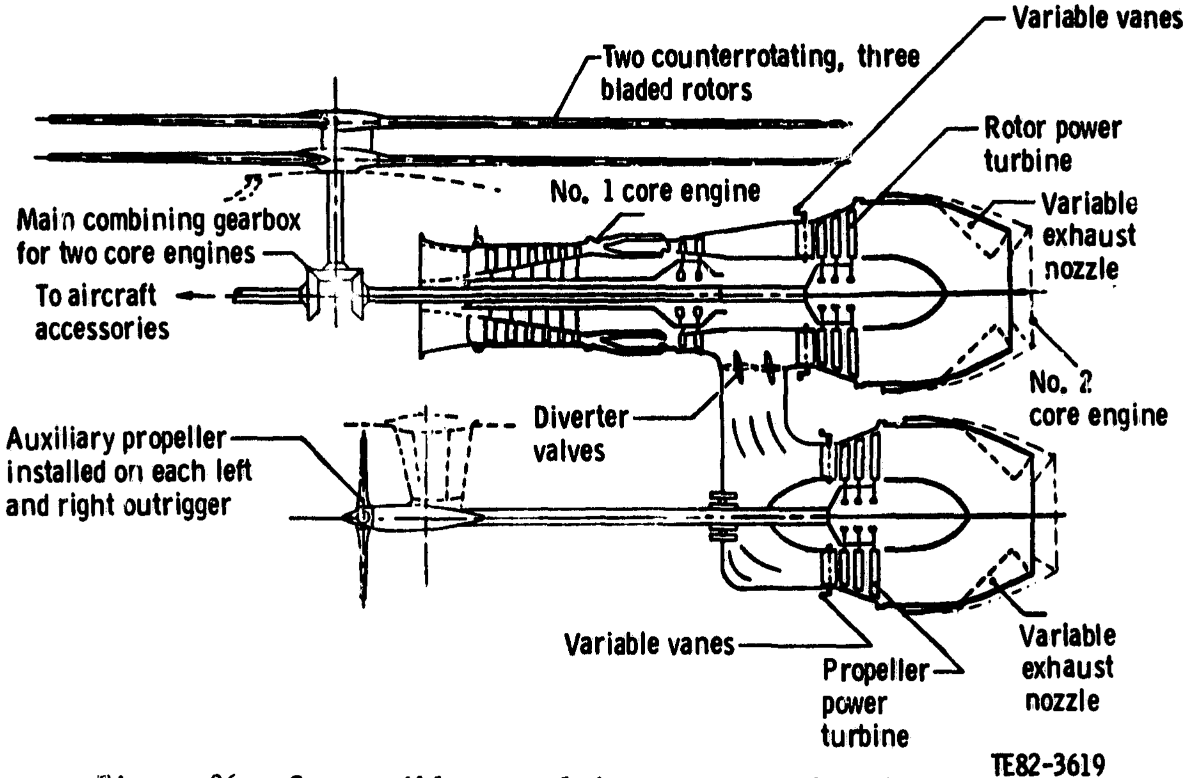

Figure 26. Convertible propulsion system with independent power turbines--Configuration 11.

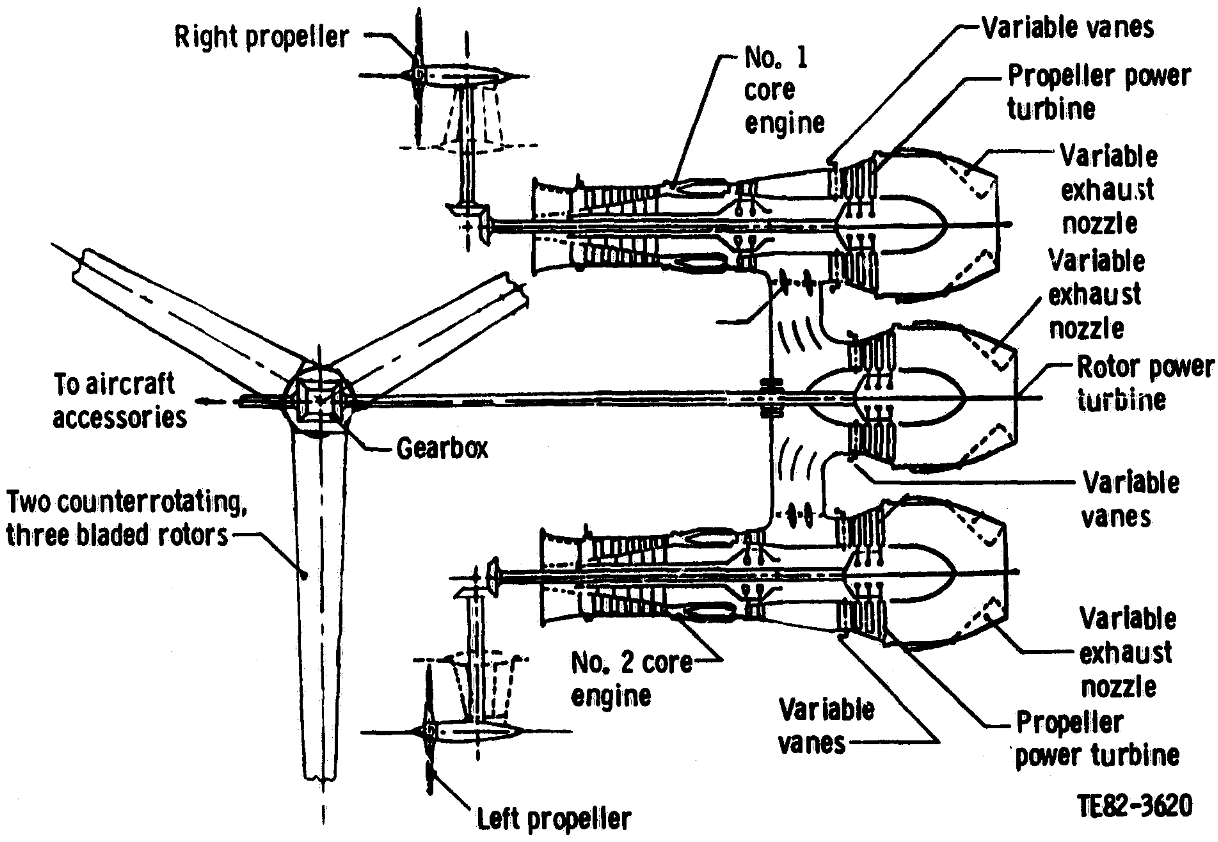

Figure 27. Convertible propulsion system with a single remote power turbine--Configuration 12.

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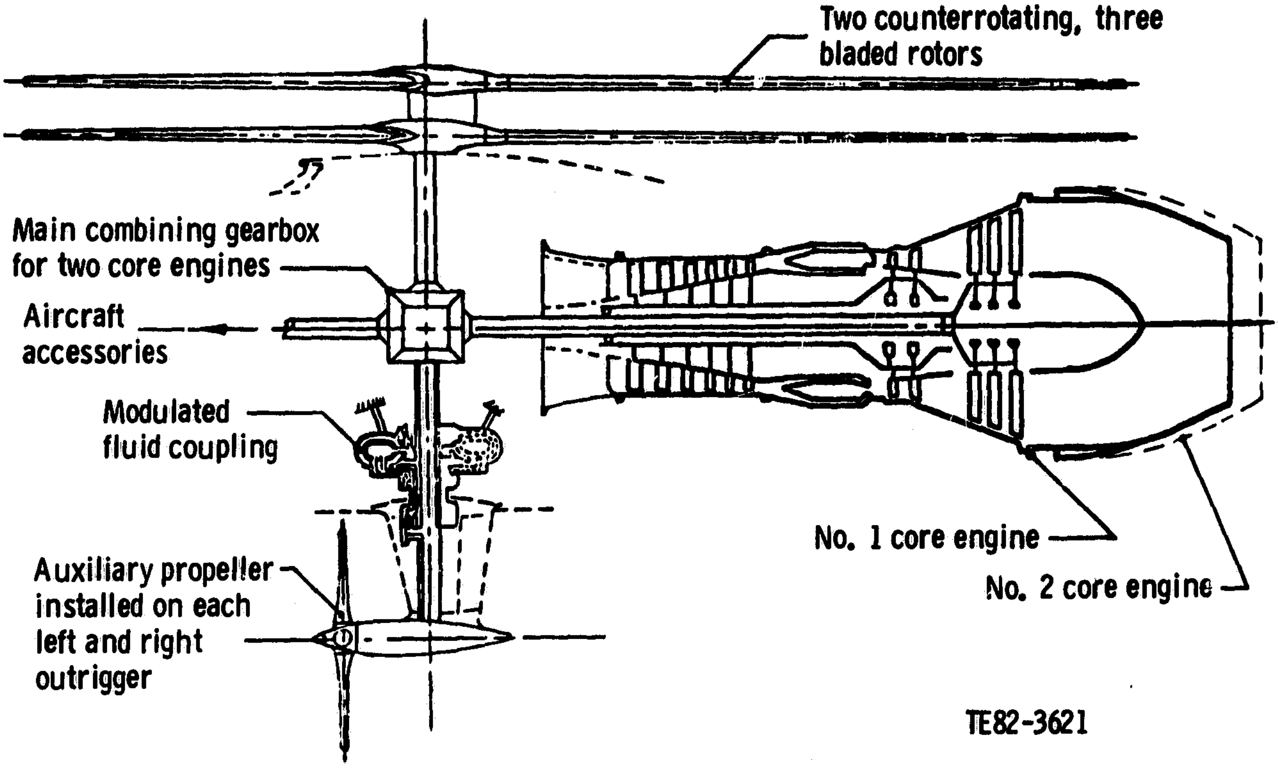

Figure 28. Convertible propulsion system with auxiliary propellers (modulated fluid couplings)--Configuration 13.

As with the configuration assessment of the alternative systems for the Fold Tilt Rotor Aircraft, the assessment of these alternative systems for the ABC Rotorcraft was conducted by selecting a typical engine cycle and all propulsion systems were configured with the same core engine. Due to the nature of the ABC Rotorcraft configuration, several of these propulsion system arrangements utilize typical turboshaft engines with the "convertible" features provided by the aircraft drive and transmission systems. In all cases, the core engines were sized to provide the same output performance. The core engine is an advanced-technology, two-spool, front-drive engine which delivers 3497.3 kW (4690 shp) in the sea level static, 32.2°C (90°F) day, intermediate power operating condition for takeoff. Each propulsion system is sized to provide 17,219 N (3871 lbf) thrust at the 914.4 m (3000 ft), 463.0 km/h (250 kt) cruise flight mode with the power turbine operating at 77.5% of design operating speed.

Attributes and Limitations

The apparent attributes and limitations of each convertible propulsion system configuration are summarized in Table XII. In many cases, a clear superiority of one configuration over another is not clear, and the need for additional research and technology programs is indicated. An attempt is made to rank each system on the basis of several important parameters in the following section.

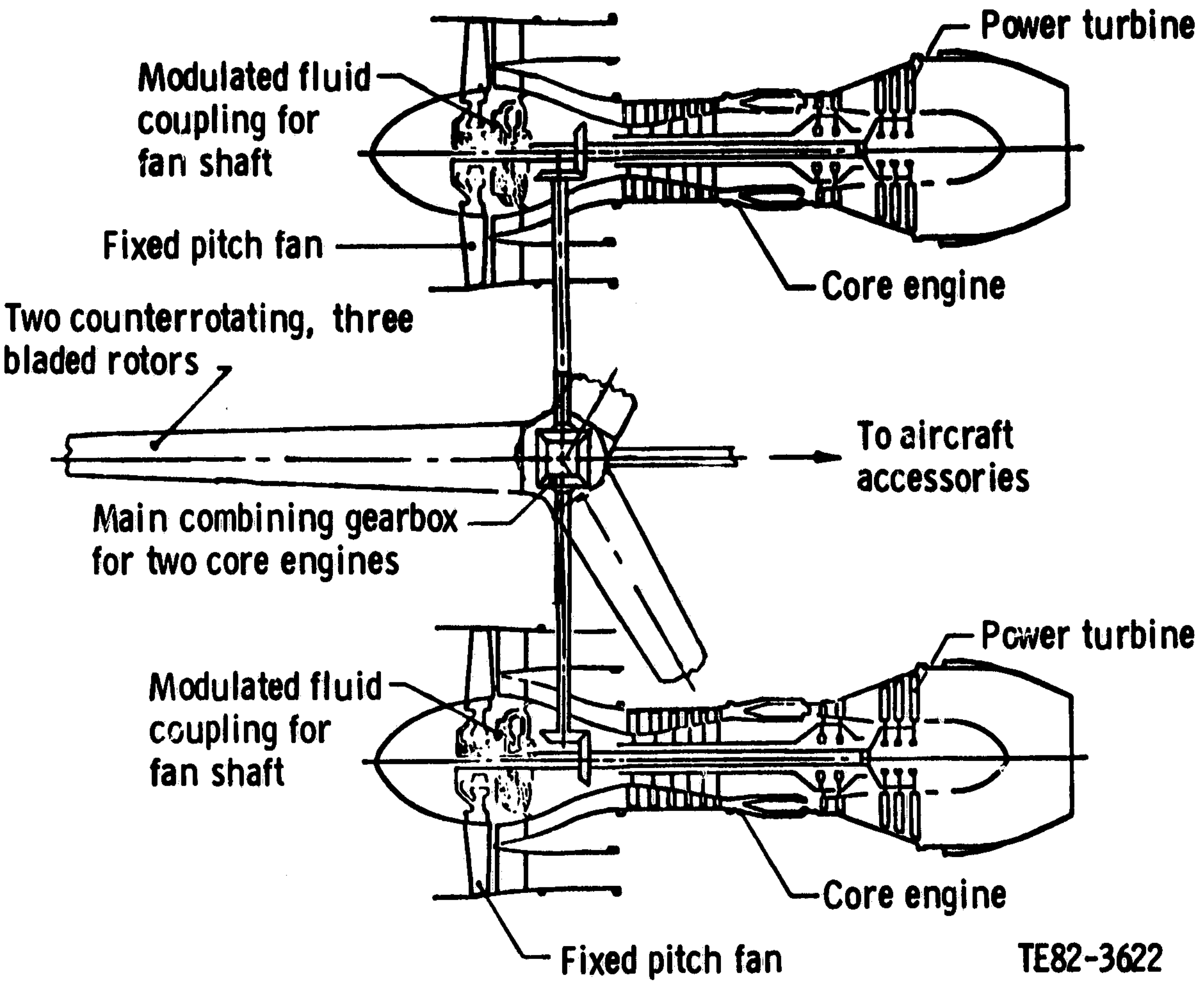

Figure 29. Convertible propulsion system with convertible fan/shaft engines--Configuration 14.

Table XI.
Convertible propulsion systems for ABC Rotorcraft.

Configuration No.	Identifying features
8 (baseline)	Propellers
9	Fan thrusters, VIGV, VEGV, clutches
10	Fan thrusters, variable pitch fan blades
11	Propellers, independent engine/rotor and propeller drive power turbines
12	Propellers, remote rotor power turbine
13	Propellers, modulated fluid couplings
14	Fan/shaft engines installed on outriggers, modulated fluid couplings for fans

Table XII.

Attributes and limitations of candidate convertible propulsion systems for ABC Rotorcraft. (Note: performance and weight changes are per aircraft.)

Configuration	Attributes	Limitations
8.0 Baseline convertible propulsion system with turboshaft engines, aux. propellers, and wet disk clutches in the prop drive line	8.1 Uses clutch with demonstrated capability at required power level (Ref. 8)	8.1 Time required for disk clutch engagement (5-10 sec) may be excessive for some situations
	8.2 Aux. propeller thrust can be modulated from full forward to full reverse	
9.0 Convertible propulsion system with turboshaft engines, aux. pylon-mounted fans having VIGV, VEGV, and wet disk clutches in the fan drive line	9.1 Same as 8.1	9.1 Same as 8.1
	9.2 Fan thrust can be varied from zero to maximum	9.2 Fan churning losses with closed VIGV and VEGV results in up to 190.1°C (375°F) temp. rise in fan cavity
10.0 Convertible propulsion system with variable pitch, pylon-mounted aux. fans having variable exhaust nozzles	10.1 Lack of clutches saves approximately 136.1 kg (300 lbm)	10.1 Minimum fan power absorption (at flat pitch) may be on the order of 2 to 4% of full power
	10.2 Potential for smooth and rapid transition for power/thrust output	10.2 Fan blade stress levels would be high leading to weight penalties to ensure integrity of variable fan
	10.3 Permits continuous split in power/thrust output	
	10.4 Potential for varying fan thrust from full forward to full reverse if required	
11.0 Convertible propulsion system with independent power turbines for rotor drive and aux. propeller drive	11.1 Power turbines may be optimized for separate and different design conditions resulting in turbine efficiency gains of as much as 0.5% (sfc improvement of approximately 0.5%)	11.1 The additional gas flow path to the independent power turbines via turning vanes and cascades may result in pressure and temperature losses to the cycle causing an increase in sfc of 4% at cruise
		11.2 Gas leakage losses will require extra development
12.0 Convertible propulsion system with aux. propellers and a single, remote power turbine for the rotor drive	12.1 Only one power turbine for rotor drive saves 6.6% weight in comparison to configuration No. 11. This causes a 0.2% reduction in DOC for ABC Rotorcraft rotor drive	12.1 Same as 11.1
	12.2 Rotor drive power turbine may be optimized for separate and different design conditions from that of the aux. propeller drive power turbine	
	12.3 Less ducting to the single power turbine than that of configuration No. 11 with lower pressure loss (6-8%)	
13.0 Convertible propulsion system with aux. propellers and modulated fluid couplings for propeller drives	13.1 Rapid power transfer at higher energy levels possible in comparison to most other configurations	13.1 R&T required to facilitate design of high torque/high speed torque converters
	13.2 Couplings do not exhibit wear problems associated with disk clutches, thereby benefiting from increased reliability and longer life	13.2 An additional oil system (reservoir, pumps, cooler, etc) required
14.0 Convertible fan/shaft engines on outriggers with modulated fluid couplings in the fan drive, aux. direct driven rotor drive	14.1 Same as 13.1	14.1 Same as 13.1
	14.2 Same as 13.2	14.2 Same as 13.2
	14.3 More "conventional" turbofan/nacelle than other aux. fan configurations	

CONFIGURATION SELECTION

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Propulsion System Ranking

The convertible engine propulsion systems defined for the Fold Tilt Rotor Aircraft and the ABC Rotorcraft were evaluated and ranked from the most to least desirable propulsion system for each rotorcraft. Quantitative data were used where possible and numerical values were assigned to those items where judgment was required in order to obtain as nearly a quantitative ranking as possible. All of the alternative propulsion systems were evaluated in terms of the following: engine thrust sfc during cruise, engine weight (including remote turbines and power transfer devices but excluding drive system components supplied by the Rotorcraft manufacturer), OEM price, engine complexity and reliability, and engine generated noise. The resulting alternative propulsion system rankings for the Fold Tilt Rotor Aircraft and ABC Rotorcraft are summarized in Tables XIII and XIV, respectively. Lower numbers indicate more desirable systems and, conversely, higher numbers indicate less desirable systems. Supporting data and ranking rationale are presented in the following subsections of this report.

Table XIII.
Convertible engine comparisons--Fold Tilt Rotor Aircraft.

Constant output performance:

Turboshaft mode--4921.6 kW (6600 shp), SLS, 32.2°C (90°F) day [except propfan/turboshaft = 4675.5 kW (6270 shp)]
Turbofan mode--cruise thrust--14,105 N (3171 lbf) @ 6096 m (20,000 ft), 0.7 Mach

Configuration No.	1	2	3	4	5	6	7
Configuration descriptions	Baseline	Partial span VICV	Variable pitch fan	Propfan turbo-prop	Independ. power turbine	Remote power turbine	Modulated fluid coupling
Cruise tsfc, mg/N.s(lbm/lbf-hr)	16.1(0.568)	16.1(0.568)	16.1(0.568)	14.2(0.501)	19.1(0.676)	19.1(0.676)	16.1(0.568)
Rank	2	2	2	1	3	3	2
Engine wt, kg (lbm)	707.2(1559)	730.7(1611)	735.3(1621)	979.8(2160)	797.9(1759)	802.0(1768)	682.7(1505)
Rank	2	3	4	7	5	6	1
OEM price, $000s	916	1029	1036	1014	1081	1096	901
Rank	2	4	5	3	6	7	1
Complexity, rank	3	2	4	5	6	7	1
Reliability, rank	3	1	4	5	6	7	2
Noise, rank	1	7	6	3	4	5	2
	13	19	25	24	30	35	9
Overall rank	2	3	4	5	6	7	1

Cruise sfc

Engine thrust sfc values were calculated for each of the alternative convertible engine propulsion systems at the specified cruise flight condition of each rotorcraft system. Certain alternative systems impose more than the typical engine performance losses. More specifically, the alternative propulsion systems which incorporate individual engine and propulsor component power turbines and remote rotor power turbines have additional performance losses associated with transition ducting and associated flow directing and/or diverting devices. Estimated performance losses for these system components and the resulting sfc values for these as well as the remaining alternative systems for both rotorcraft are presented in Tables XV through XVIII. Ranking of the alternative propulsion systems in Tables XIII and XIV was done simply by assigning a numerical value of 1 for the system or systems with the lowest sfc and sequential numerical assignments for systems with higher sfc values.

Table XIV.
Convertible propulsion system comparisons--ABC Rotorcraft.

Constant output performance:

Turboshaft mode--max 2 x 3497.3 kw (4690 shp), SLS, 32.2°C (90°F) day
Turbofan/prop mode--cruise 2 x 17,219.1 N (3871 lbf) F_N @ 914.4 m (3000 ft), 463.0 km/h (250 kt), 77.5% N_2

Configuration No.	8	9	10	11	12	13	14
Configuration descriptions	Baseline turboshaft/prop	VIGV and VEGV fan turboshaft/fan	Variable pitch fan turboshaft/fan	Auxiliary power turbine turboshaft/prop	Single power turbine turboshaft/prop	Modulated fluid coupling turboshaft/prop	Convertible engines turboshaft/fan
Cruise tsfc, mg/N.s(lbm/lbf-hr)	11.1(0.391)	16.2(0.573)	16.2(0.573)	11.4(0.402)	11.4(0.402)	11.1(0.391)	15.3(0.539)
Rank	1	4	4	2	2	1	3
System wt, kg (lbm)	2803.2(6180)	2765.6(6097)	2648.5(5839)	3064.4(6756)	2861.3(6308)	2815.0(6206)	2703.9(5961)
Rank	4	3	1	7	6	5	2
OEM price, $000s	1719	2017	1944	2074	1937	1734	1975
Rank	1	6	4	7	3	2	5
Complexity, rank	4	4	2	7	6	3	1
Reliability, rank	1	3	3	7	6	2	3
Noise, rank	1	1	6	2	2	1	1
	12	20	19	32	25	14	15
Overall rank	1	4	4	7	6	2	3

Table XV.
Estimated performance losses for Fold Tilt Rotor Aircraft convertible engines (SI units)

Configuration No.	1	2	3	4	5	6	7
Power--PTO shaft--kW max, SLS, 32.2°C day	4922	4922	4922	4676	4922	4922	4922
Power--turbine output--kW max, SLS, 32.2°C day	4922	6152	6152	4676	4922	4922	4922
Thrust--cruise--N max cont, 0.7 M, 6096 m	13,790	13,790	13,790	13,790	13,790	13,790	13,790
Cruise:							
Pressure loss--% (transition + piping)	-	-	-	-	0.5	0.5	-
Temperature drop--°C (transition + piping)	-	-	-	-	5.6	5.6	-
Leakage--% (variable vanes)	-	-	-	-	0	0	-
Leakage--% (diverter valves)	-	-	-	-	1	1	-
Tsfc--mg/N·s	16.1	16.1	16.1	14.2	19.1	19.1	16.1

Table XVI.
Estimated performance losses for Fold Tilt Rotor Aircraft convertible engines (customary units).

Configuration No.	1	2	3	4	5	6	7
Power--PTO shaft--shp max, SLS, 90°F day	6600	6600	6600	6270	6600	6600	6600
Power--turbine output--shp max, SLS, 90°F day	6600	8250	8250	6270	6600	6600	6600
Thrust--cruise--lbf max cont, 0.7 M, 20,000 ft	3100	3100	3100	3100	3100	3100	3100
Cruise:							
Pressure losses (transition + piping)--%	-	-	-	-	0.50	0.50	-
Temperature drop (transition + piping)--°F	-	-	-	-	10	10	-
Leakage (variable vanes)--%	-	-	-	-	0	0	-
Leakage (diverter valves)--%	-	-	-	-	1	1	-
Tsfc--lbm/lbf-hr	0.568	0.568	0.568	0.501	0.676	0.676	0.568
Propfan, η--%	-	-	-	85	-	-	-

It should be noted that turboshaft/fan engines No. 9 and 10, which exhibit the poorest sfcs, have fans mounted remote from the core engines and do not therefore derive any supercharging benefit from the fan. This is responsible for a poor sfc, as is the fact that a constant 12% of the available shaft power is required in driving the rotor system and power transfer shafting.

Table XVII.
Estimated performance losses for ABC Rotorcraft convertible propulsion systems (SI units).

Configuration No.	8	9	10	11	12	13	14
Power--kW max, 32.2°C day, SLS, 100% N_2	3497	3497	3497	3497	3497	3497	3497
Thrust--cruise--N, max cont, 914 m, 463 km/h, 77.5% N_{PT}	17,219	17,219	17,219	17,219	17,219	17,219	17,219
Cruise:							
Pressure loss--% (transition + piping)	-	-	-	1.0	0.8	-	-
Temperature drop--°C (transition + piping)	-	-	-	27	27	-	-
Leakage--% (variable vanes)	-	-	-	0	0	-	-
Leakage--% (diverter valves)	-	-	-	0	0	-	-
Tsfc--mg/N·s	11.1	16.2	16.2	11.4	11.4	11.1	15.3

Table XVIII.
Estimated performance losses for ABC Rotorcraft convertible propulsion systems (customary units).

Configuration No.	8	9	10	11	12	13	14
Power--shp, SLS, 90°F day, max 100% N_2	4690	4690	4690	4690	4690	4690	4690
Thrust--cruise--lbf, max cont, 3000 ft, 250 kt, 77.5% N_{PT}	3871	3871	3871	38[illegible]	3871	3871	3871
Cruise:							
Pressure losses--% (transition + piping)	-	-	-	1.0	0.80	-	-
Temperature drop--°F (transition + piping)	-	-	-	15	15	-	-
Leakage--% (variable vanes)	-	-	-	0	0	-	-
Leakage--% (diverter valves)	-	-	-	0	0	-	-
Tsfc--lbm/lbf-hr	0.391	0.573	0.573	0.402	0.402	0.391	0.539
Auxiliary propeller, η--%	81	-	-	81	81	81	-

It would have been possible to improve the sfcs approximately 9% for the remote fan configurations by redesigning the aircraft to place the fans in line with the core engines. Further, additional improvement would have been possible if data were generated for a new, lower pressure ratio fan rather than use existing data for the 1.65 R_f fan from the Fold Tilt Rotor Aircraft fan/shaft convertible engine. Typically, reducing the pressure ratio of the fan 10% would reduce the tsfc by approximately 8%. However, it was believed that these improvements would have been far short of that required to be competitive with the turboshaft/prop configurations. Therefore, the turboshaft/fans were left as is.

Propulsion System Weights

Weights were estimated for each of the alternative propulsion systems. The weight estimates for the Fold Tilt Rotor Aircraft, as presented in Tables XIX and XX, are expressed in terms of individual engine weights, including the propulsor (either fans or propfans), remote turbines, and power transfer devices where applicable. These weight estimates do not include the aircraft drive system components which interconnect the two engines (shafting, bearings, and combiner gearbox) or the rotors and associated components. For comparison,

Table XIX.
Estimated component weight breakdown for Fold Tilt Rotor Aircraft convertible engines (SI units).(1)

Configuration No.(4)	1	2	3	4	5	6	7
Fan rotor	54.9	54.9	65.8	242.7(2)	54.9	54.9	54.9
Fan case	75.3	75.3	75.3	191.4(3)	75.3	75.3	75.3
Core engine	367.4	476.7	459.5	349.3	367.4	367.4	367.4
Subtotal engine weight	497.6	606.9	600.6	783.4	497.6	497.6	497.6
Bearing and cross-shaft	9.1	9.1	9.1	9.1	6.8	-	9.1
Rotor shaft clutch/coupling	83.9	83.9	83.9	83.9	-	-	83.9
Fan shaft clutch/coupling	73.9	-	-	94.3	-	-	83.9
Variable fan vanes	29.0	20.9	-	-	-	-	-
Fixed fan vanes	-	-	12.2	-	-	-	8.2
Extended fan case	13.6	10.0	-	-	-	-	-
Variable fan pitch mechanism	-	-	13.6	-	-	-	-
Fan variable exhaust nozzle	-	-	15.9	-	-	-	-
Inlet and support	-	-	-	5.9	-	-	-
Extended front shaft	-	-	-	3.2	-	-	-
Extended turbine transition	-	-	-	-	29.9	29.9	-
Variable fan turbine vanes and actuating system	-	-	-	-	4.1	4.1	-
Fan turbine exhaust nozzle and actuating system	-	-	-	-	15.9	15.9	-
Diverter valves	-	-	-	-	1.8	3.6	-
Second power turbine	-	-	-	-	196.0	196.0	-
Second power turbine piping	-	-	-	-	25.9	34.9	-
Second PT variable vanes and actuating system	-	-	-	-	4.1	4.1	-
Second PT exhaust nozzle	-	-	-	-	15.9	15.9	-
Subtotal component weight	209.6	123.8	134.7	196.4	300.3	304.4	185.1
Total weight	707.2	730.7	735.3	979.8	797.9	802.0	682.7

(1) All weights are kg
(2) Propfan
(3) Reduction gearbox
(4) Reference Table IX

total weight of a turbofan cruise engine and a turboshaft lift engine was 845 kg (1863 lbm).

Due to the nature of the ABC Rotorcraft configuration, weight estimates for these systems are expressed in Tables XXI and XXII in terms of the entire propulsion system excluding the rotor and associated components. In the majority of the alternative propulsion systems for this aircraft, the convertible features were external to the engine itself and included in the drive system. The only fair way to evaluate these systems, therefore, was to compare the entire propulsion system. Further, in the case of the remote rotor power turbine, two individual engines are used to drive one remote turbine and, hence, it seemed cumbersome to try to evaluate these systems on an engine weight basis.

Table XX.
Estimated component weight breakdown for Fold Tilt Rotor Aircraft convertible engines (customary units).(1)

Configuration No. (4)	1	2	3	4	5	6	7
Fan rotor	121	121	145	535(2)	121	121	121
Fan case	166	166	166	422(3)	166	166	166
Core engine	810	1051	1013	770	810	810	810
Subtotal engine weight	1097	1338	1324	1727	1097	1097	1097
Bearing and cross-shaft	20	20	20	20	15	-	20
Rotor shaft clutch/coupling	185	185	185	185	-	-	185
Fan shaft clutch/coupling	163	-	-	208	-	-	185
Variable fan vanes	64	46	-	-	-	-	-
Fixed fan vanes	-	-	27	-	-	-	18
Extended fan case	30	22	-	-	-	-	-
Variable fan pitch mechanism	-	-	30	-	-	-	-
Fan variable exhaust nozzle	-	-	35	-	-	-	-
Inlet and support	-	-	-	13	-	-	-
Extended front shaft	-	-	-	7	-	-	-
Extended turbine transition	-	-	-	-	66	66	-
Variable fan turbine vanes and actuating system	-	-	-	-	9	9	-
Fan turbine exhaust nozzle and actuating system	-	-	-	-	35	35	-
Diverter valves	-	-	-	-	4	8	-
Second power turbine	-	-	-	-	432	432	-
Second PT piping	-	-	-	-	57	77	-
Second PT variable vanes and actuating system	-	-	-	-	9	9	-
Second PT exhaust nozzle	-	-	-	-	35	35	-
Subtotal component weight	462	273	297	433	662	671	408
Total weight	1559	1611	1621	2160	1759	1768	1505

(1) All weights are lbm
(2) Propfan
(3) Reduction gearbox
(4) Reference Table IX

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Table XXI.

Estimated component weight breakdown for ABC Rotorcraft convertible propulsion systems (SI units). (1)

Configuration No. (2)	8	9	10	11	12	13	14
Two engines	460.8	484.9	484.9	460.8	460.8	460.8	484.9
Air induction	15.4	15.4	15.4	15.4	15.4	15.4	15.4
Exhaust	9.5	9.5	9.5	9.5	9.5	9.5	9.5
Fuel system	315.2	315.2	315.2	315.2	315.2	315.2	315.2
Engine controls	15.4	15.4	15.4	15.4	15.4	15.4	15.4
Starting system	40.4	40.4	40.4	40.4	40.4	40.4	40.4
Prop propulsion pod	618.2	-	-	618.2	618.2	618.2	-
Fan propulsion pod	-	483.1	523.4	-	-	-	483.1
Drive systems	1172.1	1172.1	1172.1	1172.1	1055.1	1172.1	1172.1
Clutches	156.0	156.0	-	-	-	167.8	167.8
Subtotal engine weight	2803.2	2692.1	2576.4	2647.2	2530.1	2815.0	2703.9
VIGV and VEGV	-	73.5	-	-	-	-	-
Fixed vanes	-	-	17.2	-	-	-	-
Variable geometry (and actuating system)	-	-	54.9	30.8	30.8	-	-
Extended turbine transition	-	-	-	42.6	42.6	-	-
Second turbine	-	-	-	343.8	257.6	-	-
Subtotal component weight	-	73.5	72.1	417.3	331.1	-	-
Total weight	2803.2	2765.6	2648.5	3064.5	2861.3	2815.0	2703.9

(1) All weights are kg (2) Reference Table XI

Although these differences in the weight estimates for the two rotorcraft preclude a direct comparison between the two systems, the principal purpose of this exercise was to establish a relative ranking of the alternative propulsion systems for each rotorcraft. Hence, whether these data are expressed in terms of individual engines or entire propulsion systems makes no difference as long as the convertible features of each are considered in the ranking process. The methodology employed in this study has accomplished that goal.

For additional clarification of the alternative propulsion system weight estimate data, a more detailed component weight breakdown of the alternative systems for the Fold Tilt Rotor Aircraft is presented in Table XX and for the ABC Rotorcraft in Table XXII.

The weight estimates for both rotorcraft propulsion systems are based on a brief analysis of the conceptual engine/aircraft configurations.

Ranking of the alternative propulsion systems by engine weight was accomplished by assigning a numerical value of 1 to the lowest weight and sequential numerical assignments to higher weight values.

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Table XXII.

Estimated component weight breakdown for ABC Rotorcraft convertible propulsion systems (customary units).(1)

Configuration No. (2)	8	9	10	11	12	13	14
Two engines	1016	1069	1069	1016	1016	1016	1069
Air induction	34	34	34	34	34	34	34
Exhaust	21	21	21	21	21	21	21
Fuel system	695	695	695	695	695	695	695
Engine controls	34	34	34	34	34	34	34
Starting system	89	89	89	89	89	89	89
Prop propulsion pod	1363	-	-	1363	1363	1363	-
Fan propulsion pod	-	1065	1154	-	-	-	1065
Drive systems	2584	2584	2584	2584	2326	2584	2584
Clutches	344	344	-	-	-	370	370
Subtotal engine weight	6180	5935	5680	5836	5578	6206	5961
VIGV and VEGV	-	162	-	-	-	-	-
Fixed vanes	-	-	38	-	-	-	-
Variable geometry (and actuating system)	-	-	121	68	68	-	-
Extended turbine transition	-	-	-	94	94	-	-
Second turbine	-	-	-	758	568	-	-
Subtotal component weight	-	162	159	920	730	-	-
Total weight	6180	6097	5839	6756	6308	6206	5961

(1) All weights are lbm (2) Reference Table XI

Price

OEM price estimates were prepared for each of the alternative convertible engine propulsion systems. The price estimates for the Fold Tilt Rotor Aircraft were based on the Fold Tilt Rotor Aircraft baseline engine price. As was the case for the weight estimates, the alternative systems OEM costs are expressed in Table XIII in terms of individual engines including associated propulsors, remote turbines, and power transfer devices where applicable, but excluding the rotors and aircraft furnished drive components. Prices were established for the baseline engine by major component or subassembly. For each alternative system, then, prices of components or subassemblies which were not common to baseline engine were deleted. Prices for components or subassemblies which were unique to certain alternative systems were estimated by applying a price per pound of finished component weight, based upon a material index factor, to the estimated weight of the unique component. The baseline engine price was then adjusted by simply adding in the estimated price of the unique components. Where appropriate, engine prices were finally scaled to account for differences in size between the baseline and the alternative engine. The price scaling relationship used to account for engine size differences was the following:

$$\text{Scaled OEM price} = \text{Baseline OEM price} \times (\text{Scaled engine output}/\text{Baseline engine output})^{0.805}$$

In this pricing formula, engine output is expressed in terms of shp for turboshaft engines and pounds of propulsive thrust for turbofan engines.

OEM price estimates for the alternative propulsion systems for the ABC Rotorcraft were based on the ABC aircraft baseline engine price. As for the weight estimates, the alternative systems OEM price estimates are expressed in Table XIV in terms of the entire propulsion system including propulsors, remote turbines, power transfer devices, and other associated drive system components excluding the rotor systems. Again, baseline engine OEM prices were adjusted by deleting component or subassembly prices not common to the baseline engine and adding in price estimates of components and subassemblies unique to a particular alternative system. Also, engine prices were scaled, when necessary, by the price scaling formula given in the preceding paragraph.

Complexity Assessment Rationale

The seven alternative propulsion systems for both rotorcraft were evaluated in terms of system complexity and numerically ranked from "least" complex to "most" complex. Factors that were considered in the complexity evaluation included the quantity and type of advanced technology, high risk components in each system, the degree of confidence in the successful development of these components, the projected degree of difficulty to coordinate and control the various systems and their functions during transition from one flight mode to another, and the projected difficulty of integrating these alternative propulsion systems into the respective airframe designs.

The complexity evaluation of these alternative systems was a judgment assessment based on knowledge and experience in the design, development, and integration of propulsion systems and components for a variety of aircraft applications including conventional fixed-wing aircraft, single and multiengined helicopters, and both subsonic and supersonic V/STOL aircraft conceptual designs. A numerical value of 1 was assigned to the least complex alternative propulsion system with successively higher numerical values assigned to the more complex propulsion systems for both rotorcraft designs.

Reliability Assessment Rationale

The reliability assessments of the various alternative propulsion systems for both rotorcraft were made on the basis of such factors as the quantity of rotating components in each system, the quantity and type of advanced technology, high risk components in each system, and the quantity of moveable components in each system requiring coordination and control during aircraft flight transition. The reliability evaluation was similar to the propulsion system complexity evaluation in that it, too, was a judgmental assessment based on knowledge and experience with the design, development, and integration of similar components. In addition, there is a direct correlation between complexity and reliability wherein more complex systems with a greater quantity of components are generally less reliable than less complex systems. However, the quantity of components is not the only reliability consideration since the reliability of the individual components certainly affects the reliability of the overall system.

The reliability assessment of these alternative propulsion systems considered both the complexity of the overall system and the projected reliability of the individual components of each system. A numerical value of 1 was assigned to the system judged to have the highest reliability and successive numerical assignments were made to systems judged to have less reliability. These rankings are presented in Tables XIII and XIV.

Noise Assessment

The seven alternative propulsion systems for each rotorcraft were reviewed and judged with regard to their noise generation characteristics during takeoff and approach to landing. Core engine noise was estimated for a simulated takeoff to provide for a comparison of engine-only noise and proposed helicopter certification requirements.

Comment concerning each of the alternative propulsion systems is contained in Table XXIII. Additional comments which pertain to most of the configurations as follows:

- o Speed reduction gearboxes should be regarded as potential noise generators.
- o Advanced compressors, such as would be incorporated in the core engine, will generate substantially higher noise levels than current production engine compressors because of increased tip speeds and pressure ratios. As a result, the trade between incorporating noise reduction by increased blade/vane spacing or using a moderately high Mach number in the inlet guide vane throat versus the performance loss due to inlet duct acoustic treatment needs to be investigated.

Convertible rotorcraft are within the class of aircraft which would be required to comply with the proposed (NPRM 79-13) helicopter noise certification standards. The proposed rule is similar to the current fixed wing rule in that the limit levels are a function of aircraft gross weight for three flight conditions. Engine noise estimates were made with and without the compressor to evaluate the effect of compressor inlet duct treatment. Combustion noise was scaled from current production engine data since current prediction methods gave estimates differing by about 10dB. Core engine noise estimates for rotorcraft employing convertible engine propulsion systems and flying a high performance takeoff are shown in Table XXIV.

The following conclusions were drawn from this noise assessment of the alternative propulsion systems:

Fold Tilt Rotor Configurations:

- o The fan/shaft engine, with variable inlet and exit guide vanes followed by propfan engine, was judged to be the quieter configuration.
- o The fan/shaft engine with partial span inlet guide vanes was judged to be the most noisy configuration. It was followed by the fan/shaft engine with variable pitch fan blades.

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Table XXIII.
Noise characteristics of candidate convertible propulsion systems.

Configuration number	Fan config. for takeoff and approach	Fan/core noise generation	Comment
Fold Tilt Rotor configurations:			
1	VIGV and VEGV rotate to closed position. No fan rotation.	No fan noise front or rear. Low compressor noise expected due to air inlet path.	Engine combustion and turbine noise only.
2	Partial span VIGV rotates to closed position. Fan rotates.	Front fan noise depends upon blade M_n at VIGV span. Fan windage noise radiates to rear. Compressor noise has normal propagation path.	Min. fan flow of approximately 40-50% and pressure ratio of 1.2 to 1.3 would be very noisy with the IGV.
3	Variable pitch fan goes to min. pitch--fan exhaust duct closed.	Near-normal fan noise radiated from inlet. No rear fan noise	Spacing between VIGV and fan and fan and VEGV will affect fan noise generation.
4	Propfan declutched and stationary.	Normal turboshaft engine noise.	
5	Fan windmills--no turbine drive.	Normal core engine except for exhaust through rotor power turbine. Fan noise will be low--depends upon windmill speed.	Duct diverter vanes may generate noise.
6	Fan windmills--no turbine drive.	Normal core engine except for exhaust through rotor power turbine. Low fan noise--depends upon windmill speed.	Diverter valves may generate noise.
7	Fan and rotor fluid-coupled to core.	Fan noise depends upon decoupled windmill speed. Normal core engine noise.	
ABC configurations:			
8	Propellers declutched and stationary.	Normal turboshaft engine noise.	
9	Fan with VIGV and VEGV --declutched.	Normal turboshaft engine noise.	
10	Variable pitch fan--min. pitch.	Near-normal fan noise radiated from inlet. No rear fan noise.	Spacing between VIGV and fan and fan and VEGV will affect noise generation.
11&12	Propellers assumed stationary.	Normal compressor--combustion noise propagates through duct and rotor power turbine.	Diverter valves add to engine exhaust noise.
13&14	Propeller or fan decoupled.	Normal turboshaft engine noise.	

ABC Configurations:

- o The convertible propulsion system with variable pitch fan was judged to be the most noisy.
- o The remaining six configurations produced turboshaft engine noise only during takeoff and approach, assuming that the forward thrust propellers or fans were inoperative. If forward thrust is used, the fan configurations may produce more noise than the propeller configurations.

A core engine designed without regard to low noise generation could prevent a convertible rotorcraft from meeting the proposed helicopter certification requirements.

Table XXIV.
Takeoff noise estimates for convertible propulsion systems
(NPRM 79-13 takeoff flight path--15° climb, 185.2 km/h [100 kt]).

Engine noise assumptions	Engine noise level--EPNdB		NPRM 79-13 limit--EPNdB	
	4921.6 kW (6600 shp)--Fold Tilt	3504.8 kW (4700 shp)--ABC	17690 kg (39000 lbm GW)--Fold Tilt	14515 kg (32000 lbm GW)--ABC
Combustion noise* plus compressor noise--no inlet duct treatment	99	97.5	99.4	98.6
Combustion noise* plus compressor noise--with inlet duct treatment	95	93.5	99.4	98.6

*Scaled from a current production engine

Based on these conclusions, a judgment was made of each alternative propulsion system's relative noise generating characteristics compared to those of the other alternative systems for both types of rotorcraft. A numerical value of 1 was assigned to the system judged to be the quietest propulsion system with successive numerical values assigned to the systems judged to generate more noise. The results of this assessment are presented in Tables XIII and XIV.

Configuration Recommendations

The overall propulsion system ranking of the seven alternative Fold Tilt Rotor systems and seven alternative ABC convertible engine propulsion systems is based on the ranking data presented in Tables XIII and XIV and discussed in the preceding sections of this report. The overall ranking of each alternative system was obtained by simply summing the numerical values of the rank assigned for each category. The propulsion system receiving the lowest overall numerical value was thereby judged to be the most desirable propulsion system and, conversely, the system receiving the highest numerical value was judged to be the least desirable system.

The recommended powerplant for the Fold Tilt Rotor Aircraft is the convertible turbofan engine which utilizes hydraulic couplings for power transfer between the rotors and fixed geometry fan. The mechanical arrangement of the fluid coupling unit itself was studied including heat rejection requirements, modulated versus nonmodulated schemes, and mechanical lockup devices.

The recommended powerplant for the ABC Rotorcraft is the baseline turboshaft engine. This convertible propulsion system utilizes conventional turboshaft engines to drive the main counter-rotating rotor system full time and drive auxiliary propellers during cruise flight. The "convertible" features of the propulsion system are external to the engine and are integrated into the aircraft mechanical drive shafting and gearbox system. Power transfer to the variable pitch auxiliary propellers is accomplished with a simplified clutch mechanism integrated into the aircraft-furnished combiner gearbox.

ADVANCED TECHNOLOGY OPTIONS

Power Transfer Systems

Various hydraulic power transfer systems were considered for the convertible fan/shaft engines to engage and disengage the fan from the power turbine. These systems are described in the following subsections.

Simple Fluid Coupling

A typical simple fluid coupling consists of an input impeller, or pump, and an output turbine. Oil serves as the interfacing medium between the input impeller and output turbine. With the use of newly developed vane configurations in both turbine and impeller elements it is possible to achieve approximately 70 times more power transfer capacity than was previously attainable with typical straight vanes. The simple fluid coupling has one major disadvantage in that there is an inherent slippage, or speed and power differential, between the input and output shafts during operation. This slippage results in work being done on the oil which heats the oil. The heat must then be extracted from the oil through oil coolers. Preliminary calculations of the heat rejection in a simple fluid coupling, sized to the engine requirements of the Fold Tilt Rotor Aircraft, indicate that its heat rejection would be approximately four times that of a turboprop reduction gear of comparable power.

Modulated Fluid Coupling

The modulated fluid coupling is different from the simple coupling in that the output turbine unit consists of the turbine torus cast as a rotor with the vanes cast to a piston. In assembly, the turbine vanes enter the torus through slots that match the vane profile. In operation, output power is modulated by changing the effective turbine vane length via piston movement as shown in Figure 30.

The major drawbacks of the modulated fluid coupling are the same as those of the simple fluid coupling. First, there is a speed and power differential between the input impeller and output turbine due to the slippage of the fluid coupling. Further, this slippage results in a substantial heat input to the oil similar to that of the simple fluid coupling.

Fluid Coupling with Mechanical Clutch and Lockup

The concept of this system is to eliminate the fluid coupling slippage between the input impeller and output turbine. In this concept, the fluid coupling is utilized to accelerate the fan to approximately 95% of the input impeller speed. An integral clutch is then engaged to synchronize the output turbine speed to the input impeller speed. When the input and output speeds are synchronized, a mechanical lockup device is engaged to allow direct drive from the input shaft to the output shaft without slippage. With the input impeller and output turbine synchronized in speed, there should not be any work being done on the interfacing oil. However, in the event that churning, sloshing, or friction does occur, elimination of this heat input to the oil can be accomplished by draining the oil from the interfacing torus after the mechanical lockup has been engaged and recharging the torus with oil just prior to the disengagement process.

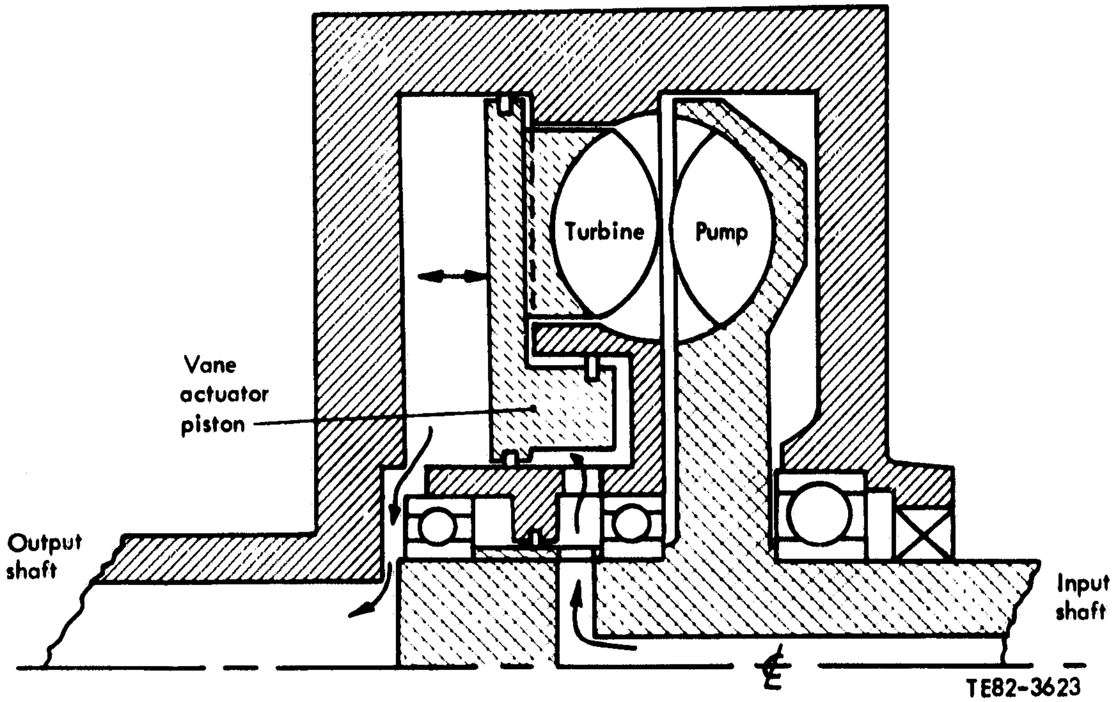

Figure 30. Modulated fluid coupling.

The major drawback to this system is that the clutch must be sized to transmit full input power rather than just the power differential between the input impeller and the output turbine resulting from the fluid coupling slippage. Once the clutch is engaged to accelerate the output turbine from 95% to 100% speed, the full input load is transferred to the clutch. If the clutch engagement is to be accomplished at high engine power input, the size of the clutch would become prohibitively large. Further, once the input and output speeds are synchronized and the mechanical lockup device is engaged, the clutch is then disengaged and the full load of the system is carried by the mechanical lockup device. A second drawback of this type of system is that the force required to disengage the lockup device, in the disengaging sequence, will be extremely high and hence the system needed to disengage the lockup device will have to be relatively large. The major objective of this system, as opposed to the original wet plate clutch concept, was to be able to accomplish these system engagements and disengagements at high engine power and speed.

<u>Fluid Coupling with Overspeed Gears</u>

Since the simple fluid coupling exhibits a speed and power differential of approximately 5% between the input impeller and output turbine and since the size of supplemental devices such as a clutch and the system needed to disengage a mechanical lockup device become very large, other design concepts were given consideration. One such concept is a system which utilizes a gear train to drive the input impeller to a greater speed than the engine input speed such that the output turbine is driven to the same speed as the engine input speed.

Thus, the fluid coupling input impeller is essentially being driven to an overspeed condition. A mechanical lockup device can then be utilized to couple the output turbine to the engine input shafting, bypassing the input impeller and its overspeed gears.

The major drawback of this system is the added size, weight, and cost of the overspeed gear train. In addition, since there is a constant speed differential between the input impeller and the output turbine, even after the lockup device is engaged, there will be a substantial heat input to the oil and, consequently, a requirement for a large oil cooler for this system. This heat rejection problem could be reduced by draining the oil from the interfacing torus while the mechanical lockup is engaged and then recharging the torus with oil prior to the disengagement sequence.

Torque Converter

In its simplest form, the torque converter consists of three elements working in a closed circuit: an impeller rotated by the input shaft (engine power output), a turbine attached to the fan shaft, and a stationary reactor, fixed to the housing. Figure 31 shows a torque converter applied to the fan drive in a convertible engine. The impeller pumps fluid centrifugally into the turbine. In turn, the turbine absorbs the energy of the fluid by deflecting and discharging it in a backward direction relative to the impeller rotation. The reactor obtains a torque reaction by directing the flow of the fluid from the turbine in a forward direction, discharging it into the impeller. This completes the circulating cycle.

As the torque converter output speed increases, a centrifugal head is built up that is counter to the head of the impeller. This gradually reduces the fluid flow which, in combination with the changing speed ratio, results in changes in the flow vectors relative to the blades and consequently reduces the blade force or torque converter torque required to achieve input and output synchronized speed for a minimum-load mechanical lockup engagement.

This description applies to conventional torque converter operation in automotive use where the torque converter is completely filled with oil under pressure provided by the transmission control system pump. The following paragraph describes its application to the convertible engine.

In the convertible aircraft engine fan drive application, the torque converter is empty at the beginning of the transition from rotor mode to fan mode. When power transfer to the fan is initiated, fluid must be pumped into the torque converter which operates in a partially filled condition during the fan acceleration to the 80% continuous power speed point, thus avoiding an overload to the engine power turbine. During the partially filled operation, the fluid must be allowed to flow through the system to provide cooling. Therefore, the torque converter fill control system must control the quantity of oil retained within the unit as well as the rate at which oil flows through the unit. The amount of oil retained and the cooling flow rate required are both functions of the torque converter speed ratio and the input speed. At the end of the transition, the torque converter is filled with oil as required to achieve synchronized speed for mechanical lockup.

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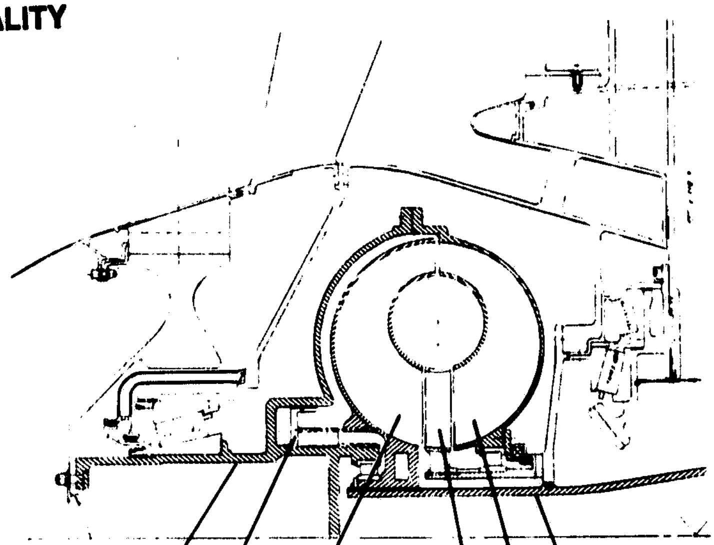

Figure 31. Fan drive torque converter.

During the lockup operation, turbulence in the rotating chamber of oil, caused by the stationary reactor vanes, results in some heat rejection to the oil. This heat source may be eliminated by dumping the oil from the chamber and replacing it prior to the transfer of power back to the power takeoff drive. An optional method of reducing the generation of heat to an acceptable level during lockup operation, without draining the oil, would entail the use of a device to permit the reactor vane assembly to rotate with the synchronized elements after lockup but that would keep it stationary during the power transfer sequence.

Attributes and Limitations

The attributes and limitations of the five alternative fluid coupling systems are summarized in Table XXV.

Selection of the Preferred Power Transfer System

The following are the advantages which led to the selection of the torque converter as the best power transfer system:

- o Combined functions--The torque converter, in performing the combination of functions for which it is suitable, offers the advantage of smoothness during its speed ratio changes and torque ratio changes.
- o Simplicity--Considering the complex nature of the combined functional changes, the unit is relatively simple, completely automatic, and reliable.

Table XXV.
Attributes and limitations of candidate fluid coupling systems.

Configuration	Attributes	Limitations
Simple fluid coupling	Simple construction, compact size, light weight, low cost.	Speed and power differential between input and output. Large heat input to the oil requiring large oil coolers.
Modulated fluid coupling	Same attributes as simple fluid coupling except that output power can be modulated and controlled.	Same limitations as simple fluid coupling plus added cost, weight, size, and complexity for modulation system.
Fluid coupling with clutch and lockup device	Capable of achieving a 1:1 input-to-output speed ratio. Mechanical lockup can be engaged for direct drive eliminating fluid coupling slippage. Minimized heat rejection problems.	Clutch must be sized to accommodate high engine power input and, hence, will be large, heavy, and more costly. Large force required to disengage lockup device at high engine power input.
Fluid coupling with overspeed gears	Capable of achieving a 1:1 input-to-output speed ratio. Mechanical lockup can be engaged for direct drive eliminating fluid coupling slippage.	Overspeed gear train adds size, weight, and cost. Oil must be drained from interface torus to minimize heat rejection problem during steady-state operation.
Torque converter	Capable of achieving synchronized speed for lockup and then eliminating heat rejection by emptying oil immediately after lockup. Torque multiplication and infinitely variable transmission of shaft power capabilities. Rugged, durable device, simple construction with "fluid smooth" startup.	Heat rejection of oil transients. A stationary member is required to support the reactor component.

- Synchronization speed--The torque converter can synchronize input-output shaft speeds for a simple, minimum-load mechanical lockup.
- Durability--The torque converter, with no wear surfaces, can be designed to be sufficiently rugged, light in weight, and durable enough to last the life of the rotorcraft.

Drive Gear Trains

Traction and roller-gear drive trains were considered for application to convertible engine power takeoff drives. A limited amount of information is available on these two new power transmission/variable ratio devices. It was felt by DDA, and personnel at NASA-Lewis, that the state of the art for such devices, in power sizes suitable for aircraft applications, would not be developed sufficiently for incorporation in commercial aircraft by the 1990s.

Two of the advanced gear trains which were investigated early in the study are described below.

<u>Traction Drive</u>

The traction drive, based on an advanced friction roller concept, includes a sun roller in the center, two or more rows of planet rollers surrounding the sun, and a ring roller enclosing the total complex at the perimeter. By introducing power to either the outer ring or the control sun roller, output speed can be increased or reduced. The basic concept in traction drives is to transmit power from one smooth rolling element to another. In fixed-ratio drives, the contacting radii of the drive elements are fixed. In variable speed drives, different drive radii (via cone, ball, or toroid shaped elements) come into contact causing drive ratio changes.

The traction drive provides a smooth, quiet, continuously variable transmission. Generally, drives with one and two rows of planet rollers are suitable for ratios of up to 7 to 1 and 35 to 1, respectively, while drives with three rows of planet rollers will handle ratios of up to 150 to 1.

The traction drive is attractive as a power transfer device because of its inherent balanced preload with much less noise and vibration than a similar geared unit and because of its low cost and high operating efficiency. Traction drives have transmitted 2.2 kW (3 shp) and 3.7 kW (5 shp) at 480,000 rpm and 150,000 rpm, respectively, and higher horsepower drives suitable for gas turbine applications are under study.

Tests show that traction drives tend to slip at contact points under starting torque if pressure between the rollers is insufficient. This decreases operating efficiency. Another disadvantage is that the sun rollers cannot be made as small as equivalent sun gears or they will slip excessively. Thus, the speed-change ratio of a planetary drive of a given size is limited. Because of the high contact stresses and surface velocities associated with high power transfer, current experience indicates that these traction drives would have a relatively short service life. From the standpoint of failure in concentrated contacts, the characteristics of traction lubrication in terms of its variation with sliding speed, rolling speed, load, and pressure and temperature-viscosity coefficient of the lubricant are understood experimentally, but the ability of making a reasonable failure prediction analytically is still limited to contacts under very moderate loads.

<u>Roller-Gear Drive</u>

The multiroller friction drive is a kinematical frame in which all rollers keep their position, with only one row restrained by bearings. To overcome the contact slippage and to improve the traction drive's reliability, the multiroller friction drive kinematical frame can be applied to gear drives. The so-called roller-gear drives are conversions from friction transmission to tooth transmission, through replacement of the large part of the roller axial lengths with gears and keeping the small part of the rollers only for bearing function. This principle has been successfully tested on a 223.7 kW (300 shp)/46:1 ratio engine with a 98.5% efficiency and an 820.3 kW (1100 shp)/38:1 ratio engine with 99% efficiency. The multiroller gear drive is not only compact but is also significantly lighter in weight than the single planetary drive, especially for high ratios.

V. DEFINITION OF PREFERRED POWERPLANTS

One powerplant was defined for each of the two aircraft types studied, the Fold Tilt Rotor Aircraft and the Advancing Blade Concept Rotorcraft. These powerplants were considered to be representative selections suitable for the purpose of identifying convertible engine requirements and related research and technology needs. The technology level is consistent with acceptable readiness for commercial development by 1988 with full commercial application in the early 1990s.

CONVERTIBLE TURBOFAN/TURBOSHAFT ENGINE FOR FOLD TILT ROTOR AIRCRAFT

Cycle Selection and Rationale

A parametric engine thermodynamic cycle study was conducted to evaluate a range of turbine rotor inlet temperatures (RIT), fan pressure ratios (R_f), and engine overall pressure ratios (R_{co}) in order to select a representative cycle for a convertible fan/shaft engine for the Fold Tilt Rotor Aircraft.

The key flight conditions for the Fold Tilt Rotor Aircraft are presented in Table XXVI.

Table XXVI.
Fold Tilt Rotor Aircraft key flight conditions.

Max cruise	
Altitude--m (ft)	6096 (20,000)
Airspeed--Mach	0.75
Thrust--N (lbf)	13,496 (3034)
Typical cruise	
Altitude--m (ft)	6096 (20,000)
Airspeed--km/h (kt)	741 (400)
Thrust--N (lbf)	11,992 (2696)
Takeoff (HOGE, OEI, max power)	
Altitude--m (ft)	0 (0)
Airspeed--km/h (kt)	0 (0)
Temperature day--°C (°F)	32.2 (90)
Power--kW (shp)	4083 (5475)

The maximum cruise velocity flight condition was selected as the turbofan engine design point.

The matrix of turbofan engine cycle design parameters selected for the study is presented in Table XXVII.

Table XXVII.
Engine design point matrix for the Fold Tilt Rotor Aircraft.

R_f	1.32:1, 1.40:1, 1.65:1
R_{co}	25:1, 30:1, 40:1
RIT--K	1311, 1422, 1533, 1644
RIT--°F	1900, 2100, 2300, 2500

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Engine performance data were calculated for each combination of design point parameters in this study matrix. Appropriate component performance characteristics, turbine cooling airflows, engine leakage flows, and pressure losses were assigned to each combination of design parameters and were selected to be consistent with an engine operational capability in commercial service in the 1990 time period. The resulting engine performance data were plotted, using engine specific fuel consumption as the figure of merit, as shown in Figure 32.

The 6096 m (20,000 ft) altitude, 0.75 Mach number, maximum continuous power, maximum cruise flight condition design point was selected for this parametric engine cycle analysis. The relative merits of mixed versus separate jet turbofan exhaust flows were considered to be beyond the scope of this study and judged to have little effect on the cycle selection process. Thus, separate jet turbofan engine cycles were used in this analysis. The engine bypass ratio was selected in each case to provide the minimum engine sfc for each combination of design parameters in the study matrix. The resulting bypass ratio trends are shown in Figure 33.

As can be seen in Figure 32, uninstalled engine sfc decreases as fan pressure ratio decreases. In each case, a turbine RIT of 1644 K (2500°F) and an engine overall pressure ratio of between 25:1 and 30:1 appeared to provide the lowest engine sfc, regardless of fan pressure ratio.

The matrix engines were sized to provide the required thrust at the 6096 m (20,000 ft) altitude, 0.75 Mach number, maximum cruise flight condition. The engine size, expressed in terms of inlet corrected airflow versus fan pressure ratio, is shown in Figure 34. Uninstalled engine sfc versus fan pressure ratio is also shown in Figure 34 for two values of engine overall pressure ratio. Although uninstalled engine sfc improves with the selection of lower fan pressure ratio, as shown in Figure 34, the engine size (primarily fan diameter) significantly increases in order to accommodate higher inlet airflows.

In previous turbofan engine cycle optimization studies conducted by DDA, it was learned that installation factors associated with engine size, particularly fan diameter, have a very significant effect on fan pressure ratio selection. Inlet pressure losses, bypass duct losses, and nacelle drag tend to force the selection to higher fan pressure ratios in order to minimize these installation losses. The data shown in Figure 35, for example, were developed by DDA during the NASA Quiet Clean STOL Experimental Engine (QCSEE) Program (Ref. 8) and show the effect of a 1% change in inlet recovery on net thrust as a function of fan pressure ratio. As can be seen from Figure 35, lower fan pressure ratio engines are much more sensitive to inlet pressure losses, in terms of net thrust loss, than higher ratio engines.

The additional QCSEE program results presented in Figure 36 show the effects of various installation losses on installed engine thrust and sfc. Typical levels of compressor bleed, inlet pressure loss, fan duct loss, and primary duct loss were assumed for three different fan pressure ratio engines. In addition, nacelle drag was calculated for each configuration and ranged from 6% for the 1.65:1 R_f engine to 16% for the 1.25:1 R_f engine. Note, also, that this evaluation was made at a typical cruise flight condition where sfc and drag are of primary importance. Similar results have been found in other subsonic turbofan engine application studies.

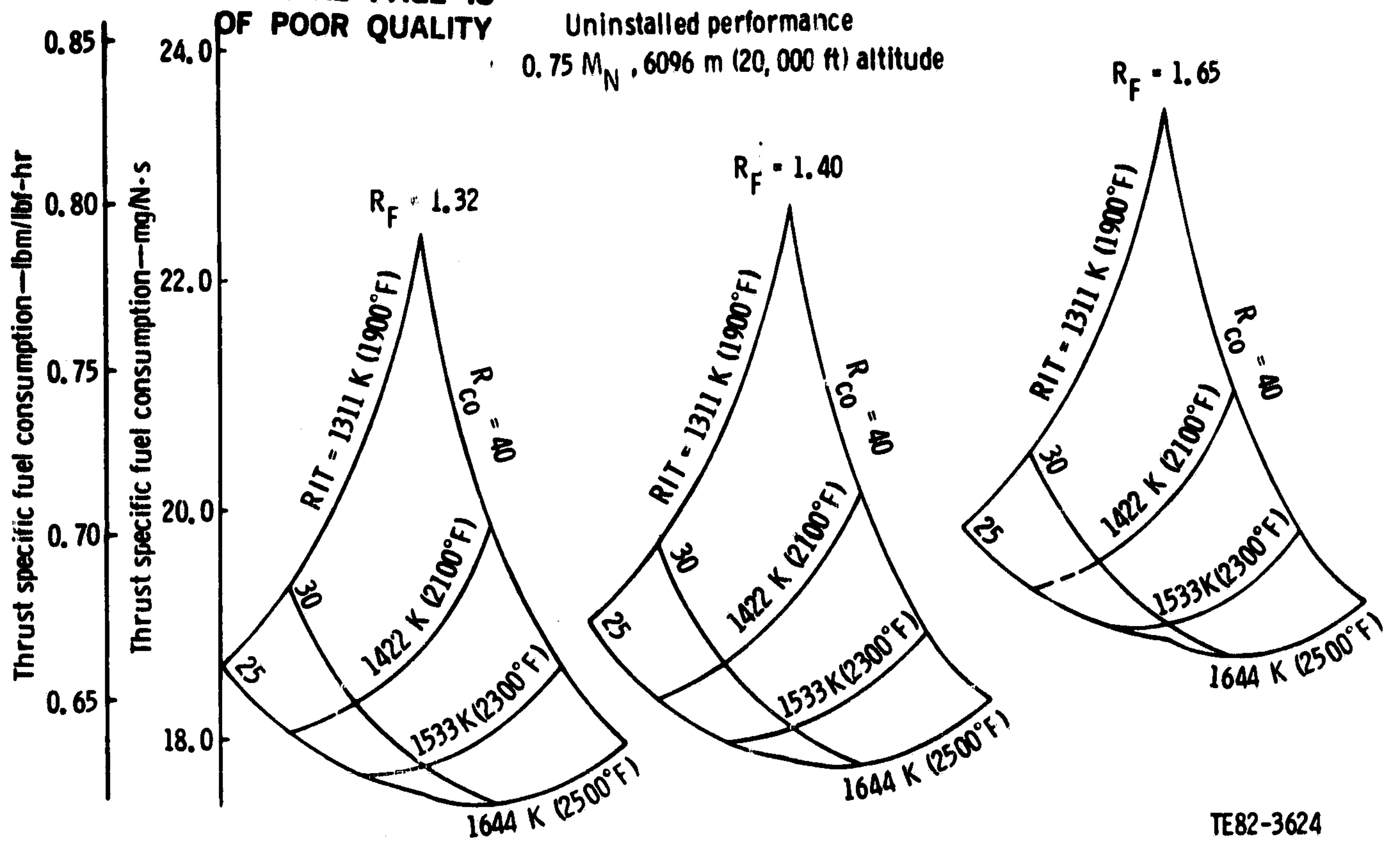

Figure 32. Fold Tilt Rotor Aircraft cycle study--sfc.

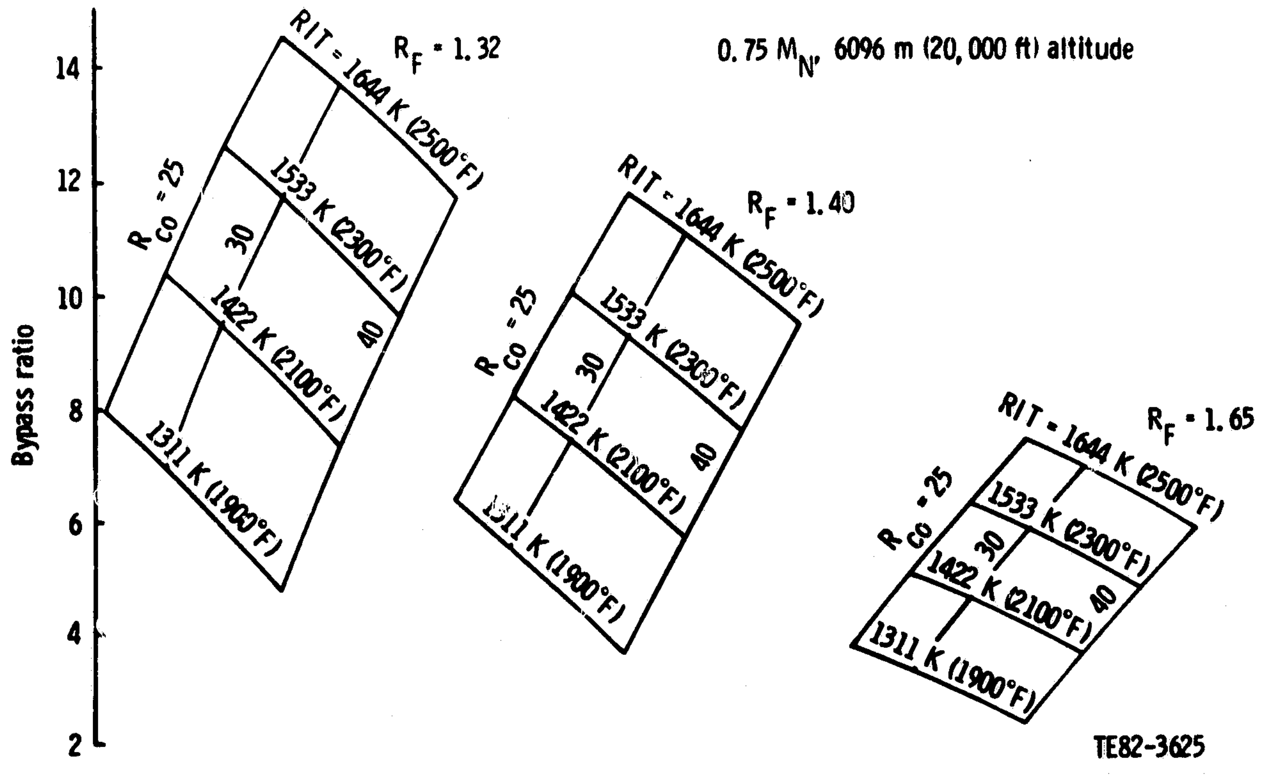

Figure 33. Fold Tilt Rotor Aircraft cycle study--BPR.

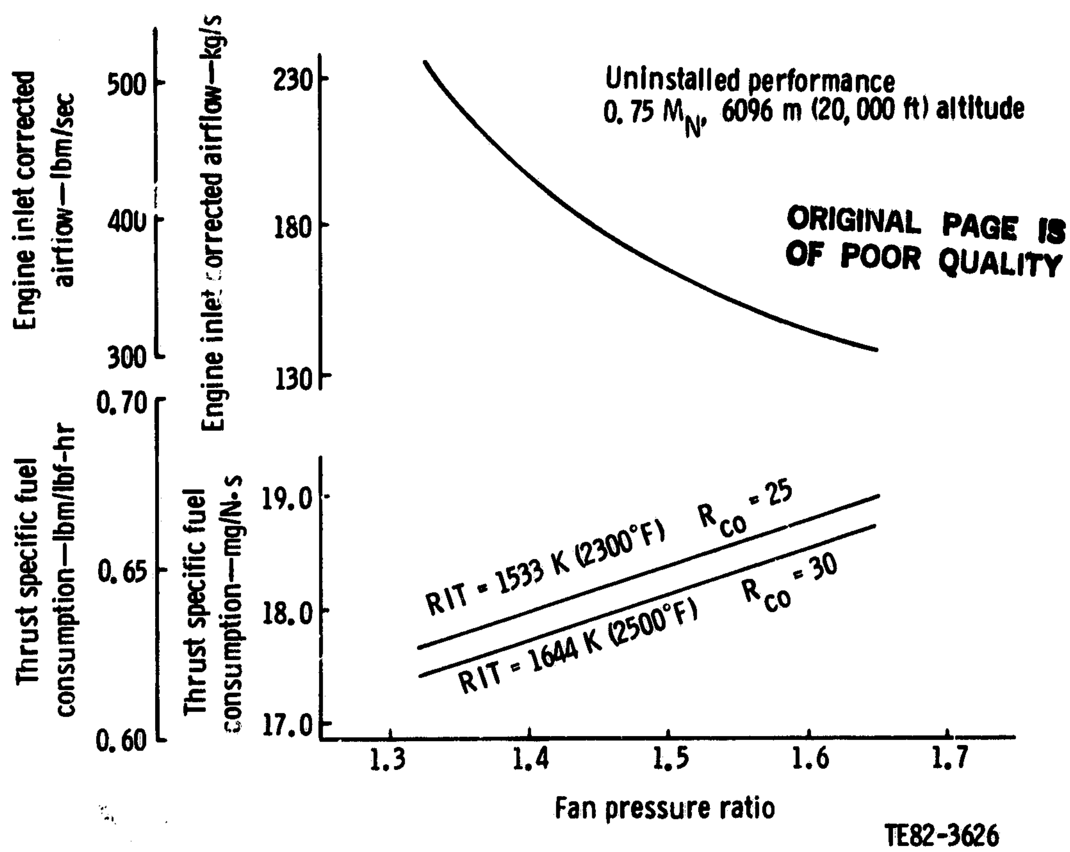

Figure 34. Fold Tilt Rotor Aircraft cycle study--design point.

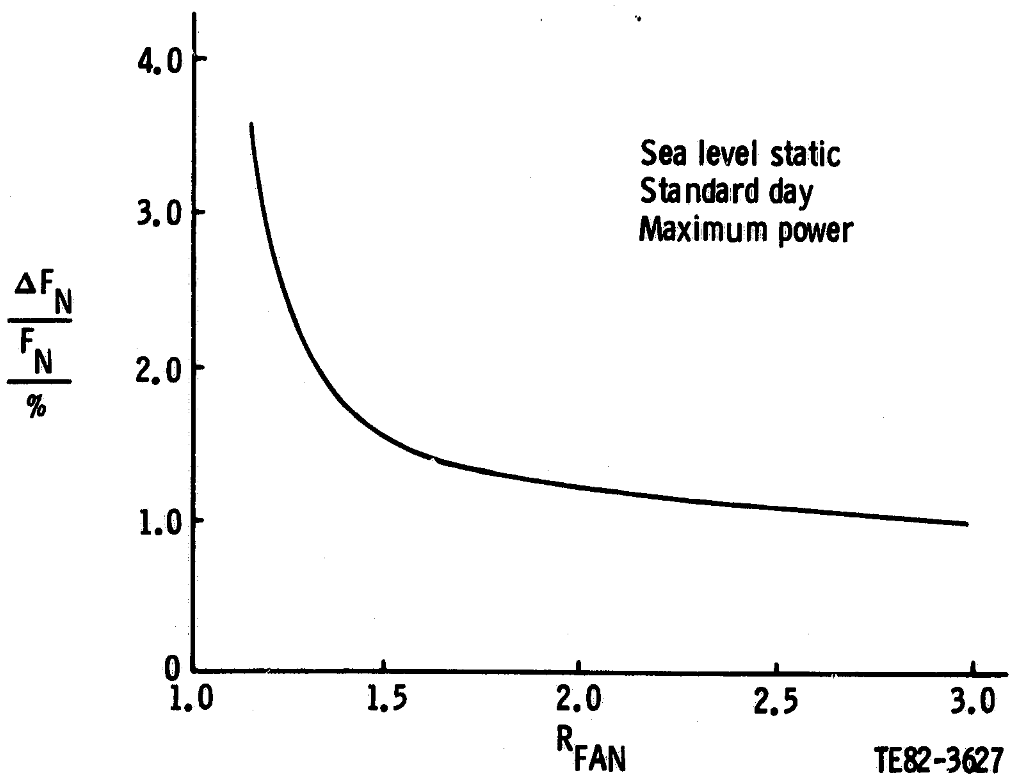

Figure 35. Fold Tilt Rotor Aircraft cycle study--thrust versus inlet recovery.

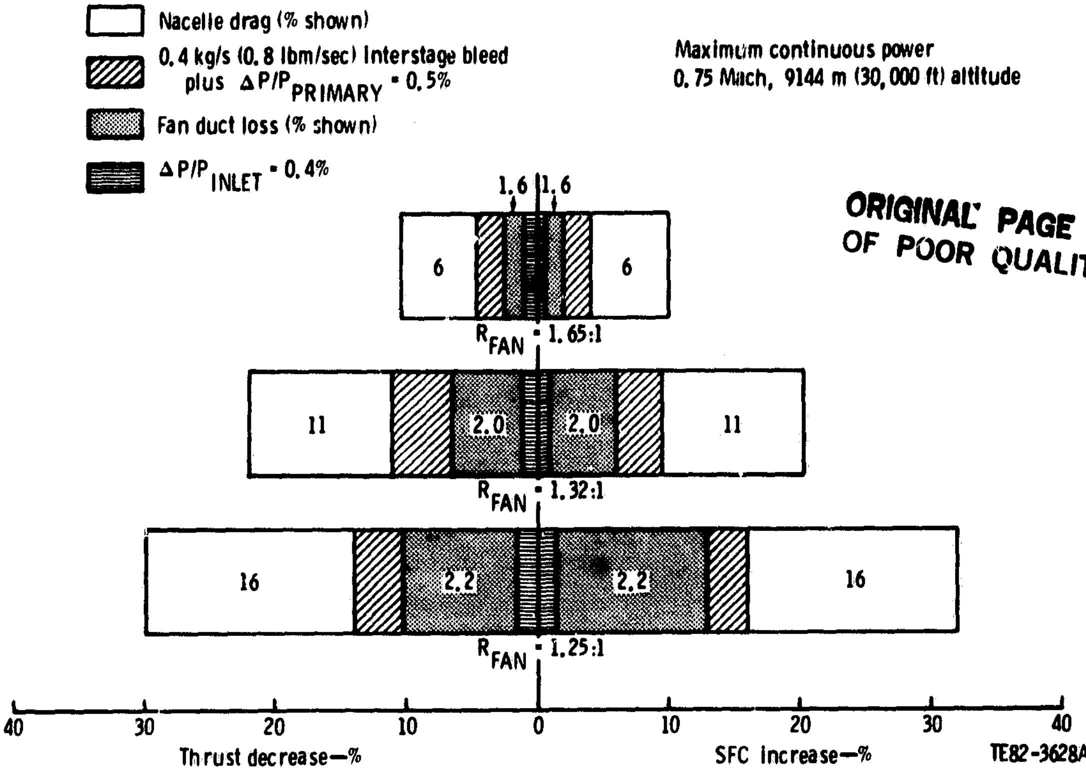

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Figure 36. Turbofan installation losses.

Although an engine installation analysis was beyond the scope of this program, in an effort to select the engine cycle that would be most realistic and representative of a convertible fan/shaft engine for the Fold Tilt Rotor Aircraft, engine installation factors were given due consideration. The turbofan engine cycle that was selected for the Fold Tilt Rotor Aircraft application is presented in Table XXVIII.

Table XXVIII.
Design point engine cycle for Fold Tilt Rotor Aircraft.

R_f	1.65:1
R_{co}	30:1
RIT	1589 K (2400°F)

Although Figure 32 indicates that an even higher turbine temperature would yield better engine sfc, the selected level of temperature was judged to be near the upper limit of the turbine cooling technology that will be available for an engine entering commercial service in the 1990 time period, particularly considering that a 1589 K (2400°F) maximum continuous RIT translates to a temperature of approximately 1700 K (2600°F) for max power engine operation on a 32.2°C (90°F) day. The bypass ratio (approximately 7:1) is such that a direct drive fan rather than a geared fan can be used to simplify the mechanical requirements by eliminating the bulk, weight, and complexity of a reduction gearbox. Overall pressure ratio was selected on the high side of the sfc minimum to favor improved sfc in the unsupercharged turboshaft mode.

Table XXIX provides detail performance and design data for the convertible turbofan/turboshaft engine operating at its altitude cruise design point.

Table XXIX.
Fold Tilt Rotor Aircraft convertible fan/shaft engine data.

	SI units	Customary units
Condition	6096 m/0.75 Mach	20,000 ft/0.75 Mach
Jet thrust	13500 N	3035 lbf
Cycle		
R_c	30.23:1	30.23:1
RIT	1589 K	2400°F
sfc	18.440 mg/N.s	0.651 lbm/lbf-hr
Corrected airflow	137.9 kg/s	304.0 lbm/sec
Inlet recovery	100%	100%
Nozzle pressure ratio	2.396:1	2.396:1
Overboard seal leakage	1.0%	1.0%
Components		
Fan:		
η adiabatic	85.37%	85.37%
Rpm @ 100%	8734	8734
Tip speed ($U_t/\sqrt{\theta}$)	474.3 m/s	1556 ft/sec
R_c	1.65:1	1.65:1
Aspect ratio	3.64:1	3.64:1
BPR	6.85:1	6.85:1
Compressor:		
η adiabatic	84.29%	84.29%
Rpm @ 100%	22,456	22,456
Axial:		
Tip speed ($U_t/\sqrt{\theta}$)	413.31 m/s	1356 ft/sec
R_c aver./stage	1.34:1	1.34:1
AR blades, aver.	1.21:1	1.21:1
Combustor:		
η	99.9%	99.9%
$\Delta P/P$	0.04	0.04
Turbines		
High pressure		
η adiabatic	89.0%	89.0%
Ave. stage loading coefficient ($gJ\Delta h/\bar{U}^2$ mean)	1.55	1.55
Equivalent work ($\Delta h/\theta cr$)	47.330 MJ/kg	44.86 Btu/lbm
Expansion ratio	5.168:1	5.168:1
Inlet temperature	1589 K	2400°F
Cooling airflow	7.43%	7.43%
Type of cooling (first blade)	Impingement film, cast-in	Impingement film, cast-in
Low pressure		
Rpm @ 100%	8734	8734
η adiabatic	91.0%	91.0%
Ave. stage loading coefficient ($gJ\Delta h/\bar{U}^2$ mean)	1.65	1.65

Table XXIX (cont).

	SI units	Customary units
Equivalent work ($\Delta h/\theta cr$)	47.024 MJ/kg	45.57 Btu/lbm
Expansion ratio	5.296:1	5.296:1
Inlet temperature	1126 K	1567°F
Cooling airflow	0.5%	0.5%
Weight	615.1 kg	1356 lbm
Length	1.773 m	69.80 in.
Max diameter (fan)	1.024 m	40.30 in.
Price*	$847,800	$847,800

* OEM price at 15/mo, 1400 units, 1981 economics

Engine Features

The preferred convertible fan/shaft engine configuration, shown in Figure 37, was selected for the Fold Tilt Rotor Aircraft and features a fixed geometry, single-stage fan matched for best efficiency at cruise conditions. The compressor is a 10-stage axial with a pressure ratio of 18.3 at the altitude cruise design point. The high pressure turbine is a 2-stage axial and operates at a maximum rotor inlet temperature of 1700 K (2600°F). The low pressure turbine is a 3-stage axial power turbine and drives either the engine fan via a torque converter or the aircraft tilt proprotor through a power takeoff on the fan case.

Engine Operation

At the beginning of transfer from takeoff mode to cruise mode, transfer of power from the proprotor to the fan is obtained by unloading the proprotor (changing its blade pitch) and simultaneously accelerating the engine fan by engaging the torque converter located inside the fan case. This is accomplished by partially filling the converter with oil as required to prevent overloading the power turbine. When the fan and LP turbine shaft speeds are matched, the shafts are mechanically locked and the oil drained out of the torque converter to eliminate losses. When the proprotor power absorption drops to its minimum value, the proprotor is disengaged from its drive shaft and is permitted to windmill, then is feathered. The proprotor is braked to a stop, folded, and stowed, and the power transfer from the proprotor to the fan is complete. The engine then operates as a conventional two-spool turbofan. Conversion from turbofan mode to turboshaft mode is the reverse of the above process.

The power transfer sequence of the torque converter from takeoff (proprotor) mode to cruise (fan) mode is illustrated in Figure 38, where several engine and aircraft parameters are plotted against time. Point A is the time at which the torque converter begins to fill with oil. The oil level is controlled to maintain the power absorption by the fan within acceptable values. Point B is the time at which the turbine temperature is increased in order to increase engine power output. At point C, the torque converter input and output speeds

Engine dry weight = 615.1 kg (1356 lbm)

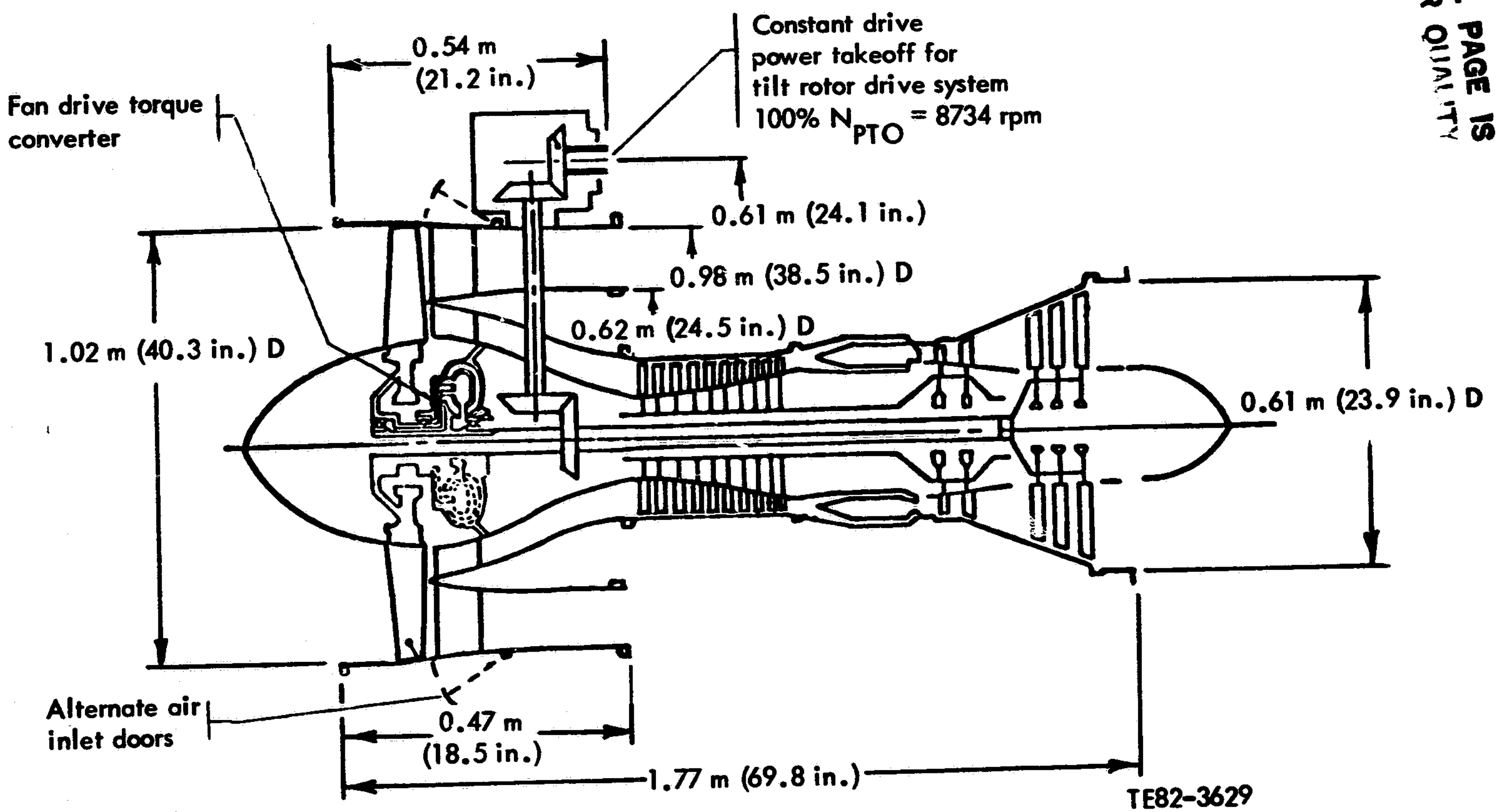

Figure 37. Preferred convertible fan/shaft engine for the Fold Tilt Rotor Aircraft.

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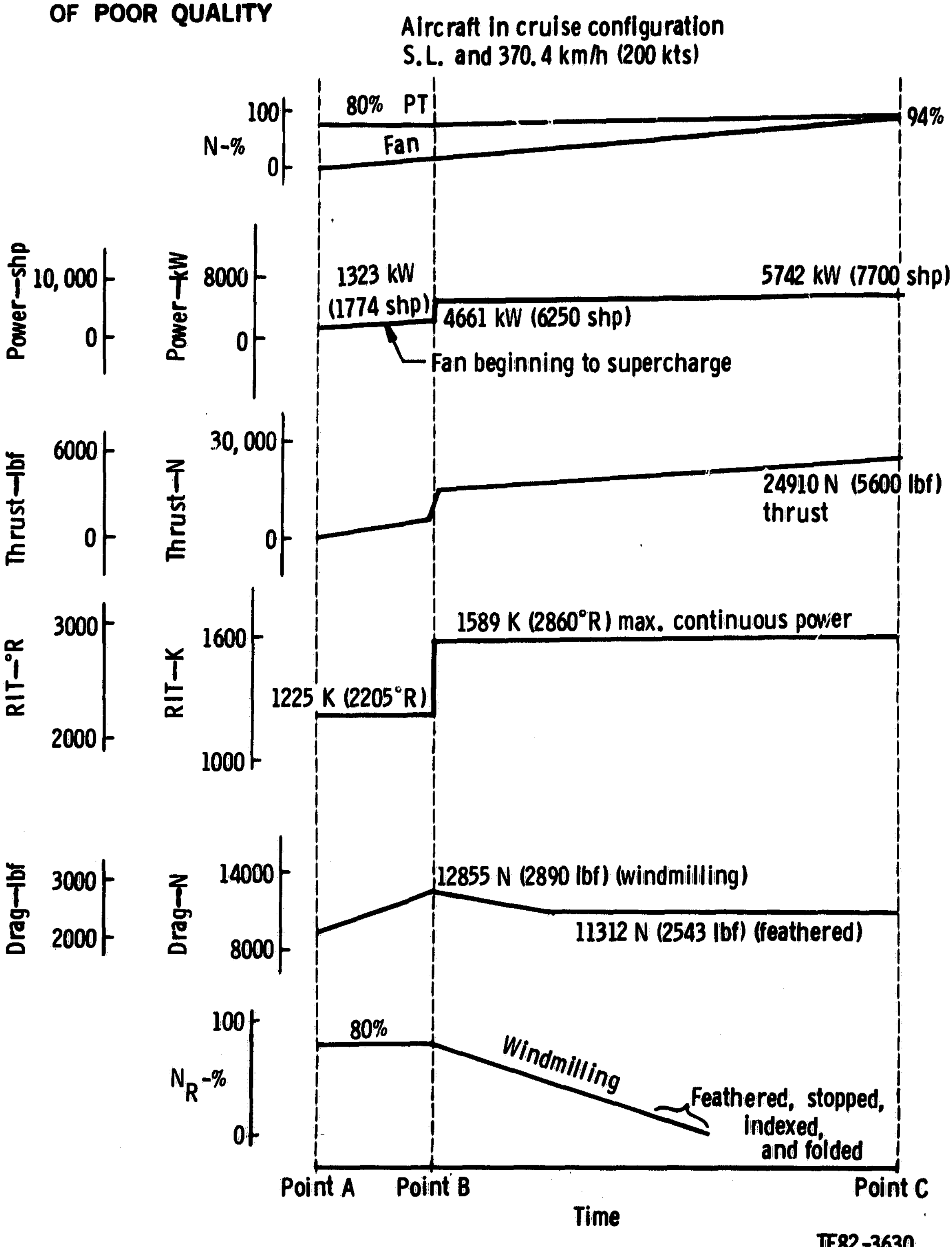

Figure 38. Fan drive torque converter power transfer sequence.

(rotor and fan) are synchronized, the mechanical locking device is engaged, and the torque converter oil is drained. During torque converter operation, the oil flow rate through the converter is controlled to maintain safe oil temperatures and the quantity of oil within the converter is controlled to limit the power absorbed. The oil fill requirement and oil cooling rate are both functions of torque converter speed ratio and input speed.

Figure 39 shows the relationship of fan torque and power turbine torque available versus rpm. At the lockup point C, the fan requires a torque of 6678.8 nmi (4926 lbf-ft). At point B, the torque available from the power turbine is 6369.6 nmi (4698 lbf-ft). Therefore, this is an excess of 309.1 nmi (228 lbf-ft) torque available to accelerate the fan from point B to point C.

Table XXX lists the torque converter design criteria and general design considerations.

Inlet air to the convertible turbofan gas generator is available through the windmilling fan, the fan duct, and the auxiliary air inlet doors. Shaft power from the gas generator comes off the power turbine shaft through right angle drives to two power transfer shafts which pass through separate struts in the fan case. A combiner gearbox is provided on the outside of the fan case and a single power takeoff pad is furnished for airframe connection to the proprotor drive system. The auxiliary inlet doors are closed during turbofan operation.

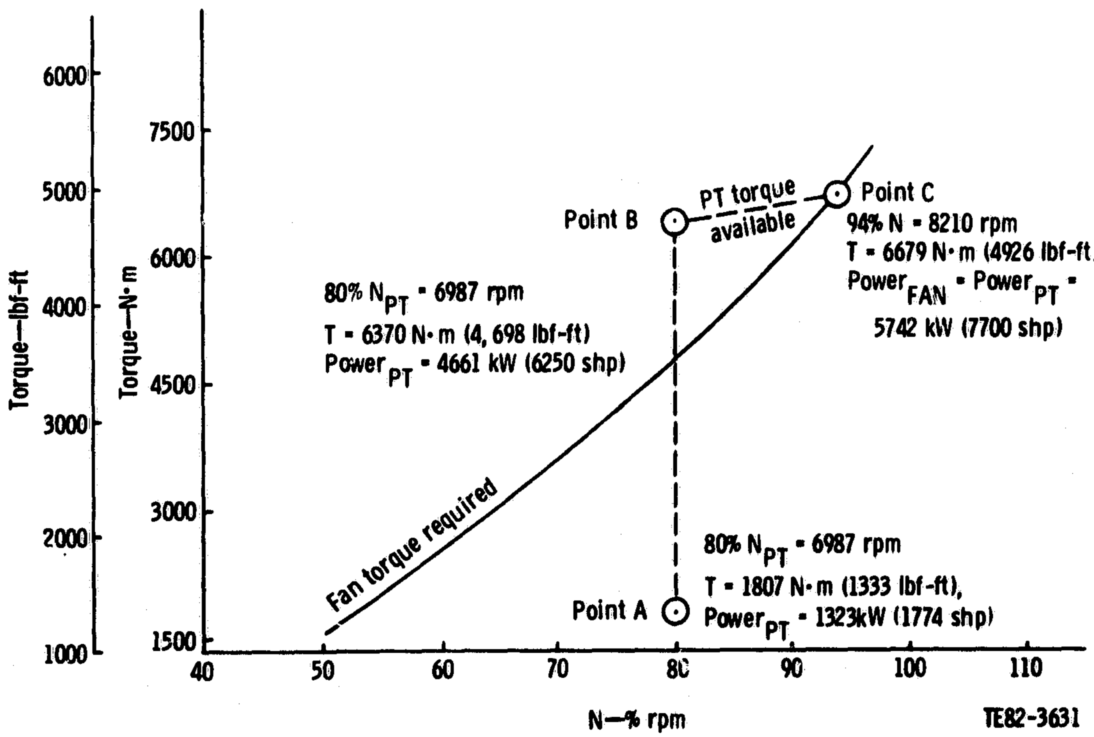

Figure 39. Torque requirements for power transfer transition points.

Table XXX.
Torque converter design criteria.

Design Parameters

Design point conditions	Sea level, 370.4 km/h (200 kt)
Input power (at lockup)	5741.8 kW (7700 shp)
Input torque (at lockup)	6678.8 N·m (4926 ft-lbf)
Output power (after lockup)	5741.8 kW (7700 shp)
Maximum power speed (100%)	8734 rpm
Lockup speed (94%)	8210 rpm
Maximum continuous power speed (80%)	6987 rpm
Fan moment of inertia	3.16 kg-m^2 (75 lbm-ft^2)

Design Considerations

Partially filled operation
Input/output speed synchronization
Mechanical lockup
Design life--60,000 engagement cycles
Service life--30,000 hr
Aircraft engine materials used for minimum weight

Engine Performance

At unity size, the convertible turbofan engine provides 5015 kW (6725 shp) at sea level takeoff on a 32.2°C (90°F) day in the turboshaft mode. During cruise, the thrust developed by the engine is 13,536 N (3043 lbf) at 0.75 Mach at 6096 m (20,000 ft). Cycle and performance summaries for operation in the turboshaft and turbofan modes are presented in Tables XXXI and XXXII, respectively. Comparing engine output shown with the max cruise and takeoff power requirement in Table XXVI shows the engine was sized for cruise.

Table XXXI.
Convertible fan/shaft engine performance--turboshaft mode (sea level, static).

Ambient temperature--°C (°F)	32.2 (90)
Power setting	maximum
Turbine rotor inlet temperature--K (°F)	1700 (2600)
Cycle pressure ratio	24.5:1
Shaft power--kW (shp)	5015 (6725)
Thrust specific fuel consumption--mg/N s (lbm/lbf-hr)	11.2 (0.394)
Net thrust--N (lbf)	3968 (892)
Inlet corrected airflow--kg/s (lbm/sec)	14.43 (31.82)

Since the primary purpose of the study was to identify the unique requirements of a convertible engine, such as the torque converter system, the auxiliary inlet system, and the fan axial load balance system, most of the limited resources of the effort were directed to these items for the convertible turbofan engine. The mechanical features of the engine represent 1990 technology, but

Table XXXII.
Convertible fan/shaft engine performance--turbofan mode
(0.75 M_n at 6096 m [20,000 ft]).

Ambient temperature--°C (°F)	-25 (-13)
Power setting	max continuous
Turbine rotor inlet temperature--K (°F)	1589 (2400)
Cycle pressure ratio	30.2:1
Net thrust--N (lbf)	13,536 (3043)
Thrust specific fuel consumption--mg/N.s (lbm/lbf-hr)	18.4 (0.649)
Fan pressure ratio	1.65:1
Fan inlet corrected flow--kg/s (lbm/sec)	137.89 (304.0)
Fan inlet flow--kg/s (lbm/sec)	93.94 (207.1)
Compressor pressure ratio	18.32:1
Compressor inlet corrected flow--kg/s (lbm/sec)	11.57 (25.50)
Compressor inlet flow--kg/s (lbm/sec)	11.97 (26.38)
Bypass ratio	6.85:1

such features as direct drive, rather than geared drive for the fan, were chosen in part to avoid further mechanical complexity in the front end of the the engine where the torque converter and the power takeoff shafts were located. Further, separate exhaust systems were assumed for the fan and core exhaust to simplify operation as a turboshaft engine. Neither of these choices is believed to have compromised the study in terms of identifying needed technology advances for the convertible engine.

Engine Description

Fan

The fan rotor, made from composite materials, is supported by two bearings. The thrust roller bearing is located in the fan wheel plane and is supported by the forward frame. The engine output power is transferred to the fan through a fluid torque converter during the cruise mode or to the proprotor through geared shafts during the takeoff mode.

The fan shroud is attached to the exit vane assembly and incorporates an abradable rub strip in the fan blade tip path. The exit guide vane assembly consists of high aspect ratio aluminum vanes welded into inner and outer rings. The strut support structure consists of streamlined struts welded into outer and inner forged rings. Two of the struts house the rotor power transfer shafts which transfer engine power from the power turbine to the proprotor power takeoff. The rounded splitter, separating bypass air from primary air, provides additional stiffening for the forward frame which supports the fan casing, fan rotor, HP and LP rotor thrust bearings, torque converter, and two geared power transfer shafts.

Compressor

The 10-stage advanced-technology compressor is designed for 18.32:1 R_c at 6096 m (20,000 ft), M_n = 0.75 cruise. The blades are designed with a low aspect ratio. The inlet guide vanes and the stators in the first five stages are variable to ensure optimum performance and surge margin throughout the operating range. All vane stages are inner banded for rugged construction.

The compressor rotor features an electron beam welded titanium drum spanning stages 2 through 10. The first three compressor wheels and the turbine drive shaft are piloted and bolted to this drum section. A nickel base alloy was selected for the latter stages to provide the required creep strength, hot stress corrosion properties, and oxidation resistance.

Circumferential dovetail attachments are used for stages 2 through 10, based on design optimization studies which indicate a weight and assembly advantage over blades with axial dovetails. All blades are removable from the assembled rotor and can be replaced in the engine by removal of a compressor case half.

The titanium compressor case is a machined forging with externally welded bleed manifolds at the fifth compressor stage. The internal blade tip track surfaces are coated with a chrome carbide prebond/barrier followed by an overlay of nickel graphite abradable material. This dual coating provides the abradable qualities needed to ensure low blade tip clearance operation and to prevent case damage during inadvertent heavy blade tip rub.

Diffuser/Combustor

Vortex Controlled Diffuser

In advanced gas turbine engines, a very short diffuser section is desired for minimum pressure drop. Such a diffuser becomes an integral part of the combustion system. Exploratory development programs conducted at DDA have developed the vortex-controlled diffuser (VCD) concept which reduces the diffuser pressure drop significantly. The application of the VCD results in significant engine size and weight reductions.

Combustor

An annular combustor design is used, resulting in minimum structural weight for both the combustor and associated engine structural members. This type of combustor also requires less cooling flow for a given combustion volume.

Combustor performance and endurance are significantly affected by wall cooling design. Conceptually, transpiration cooling is the ideal approach to wall cooling and is accomplished by passing cooling air through a porous combustor wall material. DDA has developeed a quasi-transpiration cooled material called Lamilloy®*, which is comprised of thin metal sheets chemically etched and diffusion-bonded together to form complex internal flow passages. Figure 40 shows the Lamilloy construction; Figure 41, the cooling effectiveness of this material as compared to a typical film cooling design.

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*Lamilloy is a registered trademark of the General Motors Corporation.

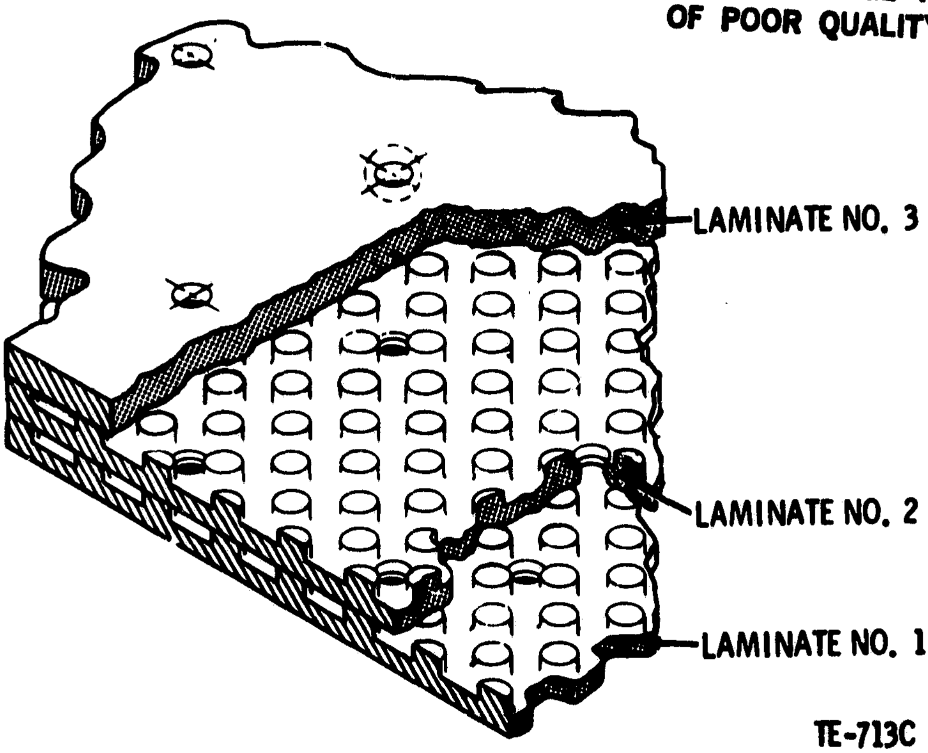

Figure 40. Lamilloy schematic.

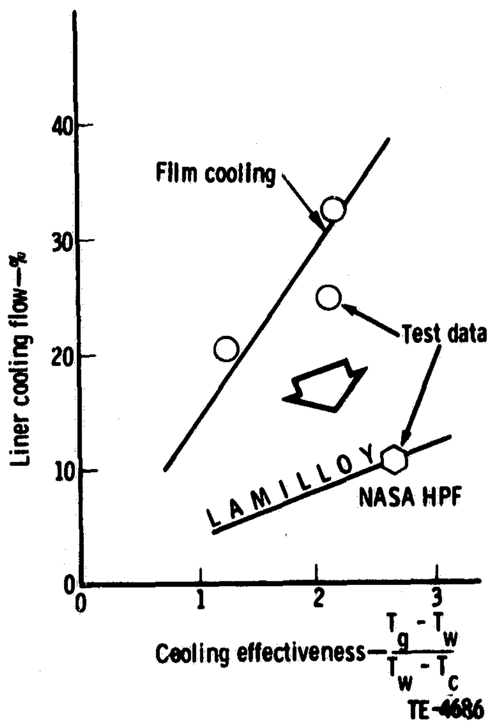

Figure 41. Advanced combustor cooling comparison.

Fuel Injectors

Traditionally, fuel injection is accomplished with pressure atomizers with resultant problems of carbon deposition, exhaust smoking, and high flame radiation. This is especially true in high pressure ratio engines. Airblast atomizers have been developed to overcome these problems.

In airblast fuel injectors, atomization is accomplished by injecting fuel at low velocity into a high velocity air stream which shatters the fuel into small droplets. The airblast process provides initial fuel/air mixing prior to the combustion zone, thus minimizing rich fuel/air ratio effects near the atomizer tip. The fuel spray distribution is controlled by the aerodynamic interaction between the airblast pattern and the combustor primary zone mixing patterns.

Turbines

The high pressure turbine is a two-stage, air-cooled design with unshrouded blades. The turbine features endwall contouring and rotor tip trenching, as well as active rotor tip clearance control for maximum efficiency.

The power, or low pressure, turbine has three stages with shrouded blades in each stage. Vane and blade platform overlapping minimizes interstage leakage.

Both turbine stages achieve a low weight through the use of reduced solidity, high aspect ratio airfoils and advanced materials.

Economic Data

Price

For the purpose of the Rotorcraft Convertible Engine Study, an original equipment manufacturer (OEM) price was established for the convertible fan/shaft engine selected for the Fold Tilt Rotor Aircraft. This price is estimated to be $847,800 using the materials index factor (MIF) method. The assumptions upon which this estimate was made are the following:

- o January 1981 economics
- o total quantity of engines--1400
- o production rate--15 engines per month

The above OEM price includes standard amounts to cover amortization of the following expenses:

- o general and administrative
- o profit
- o product liability
- o warranty

The above price is broken down approximately as shown in Table XXXIII.

Table XXXIII.
Convertible fan/shaft engine price breakdown.

Fan, forward frame, torque converter, and accessory drives	$206,000
PTO drive shaft, bearings, and gearing	54,300
Compressor	167,100
Diffuser/combustor	43,200
HP turbine	87,300
LP turbine and nozzle	159,400
Controls and fuel, oil, and electrical systems	101,700
Assembly and test	28,800
Total	$847,800

Maintenance Cost

The estimated maintenance cost for the engine was $49.94 per flight hour. This value is based upon the above assumptions plus the following:

- eight-year operating period
- 500 aircraft fleet
- aircraft delivery schedule--10, 20, 50, 75, 100, 100, 75, and 70/yr
- engine utilization--2800 hr/yr
- airframe life--30,000 hr (60,000 cycles)
- engine design life--25,000 hr, replace cold section
  --7,000 hr, replace hot section

The input data assumed to determine the above maintenance cost are summarized in Table XXXIV.

Table XXXIV.
Convertible fan/shaft engine maintenance cost input.

OEM price--$	847,800
Overhaul cost--$ (15%)	127,170
Major repair cost--$ (7%)	59,346
Minor repair cost--$ (3%)	25,434
Hot section maintenance cost--$ (10%)	84,780
Max operating time--hours	25,000
Number of hot-section maintenance actions	2
Unscheduled removals	
To overhaul--%	30
To major repair--%	50
To minor repair--%	20
Number of aircraft in fleet	500
Operational period--years	8
Unit aircraft-hours/month	200
Premature removal rate	0.6
Number unscheduled removals	2131

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Scaling Data

The engine may be resized within a thrust/power range of $\pm 20\%$. If the engine is resized, the following scaling relationships should be used where 0 = rated output as shaft power or thrust:

Airflow--varies directly with thrust or power

Weight--Scaled wt = Base wt x (Scaled 0/Base 0)^{Y},
where Y = 1.04 if scaled 0 > Base
and Y = 0.96 if scaled 0 < Base 0

Axial dimensions--Scaled dim. = Base dim. x (Scaled 0/Base 0)$^{0.4}$

Diametral dimensions--Scaled dia. = Base dia. x (Scaled 0/Base 0)$^{0.5}$

OEM price--Scaled price = Base price x (Scaled 0/Base 0)$^{0.805}$

Maintenance cost--Scaled cost = Base cost x (Scaled 0/Base 0)$^{0.805}$

sfc--Refer to Figure 42.

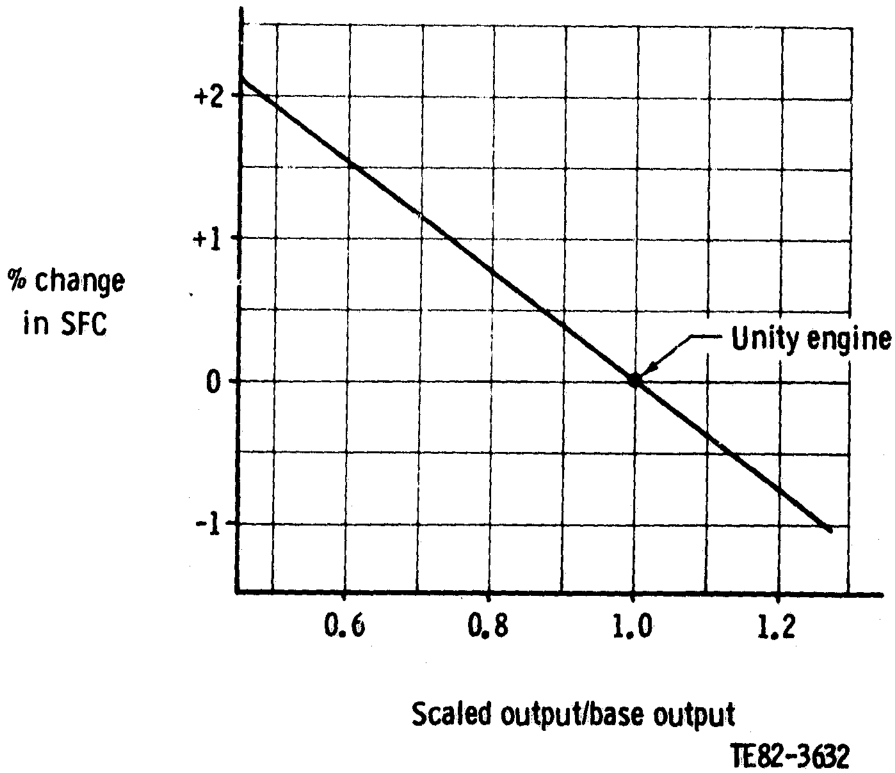

Figure 42. Sfc scaling relationship.

The following scaling relationships are applicable to the turboshaft operational mode only:

Output speed (N_{PT})--Scaled N_{PT} = Base N_{PT} x (Base power/Scaled power)$^{0.5}$

Jet thrust (F_N)--Scaled F_N = Base F_N x (Scaled power/Base power)

CONVERTIBLE PROPULSION SYSTEM FOR ABC ROTORCRAFT

Cycle Selection and Rationale

A parametric engine thermodynamic cycle study was conducted to evaluate a range of turbine rotor inlet temperatures (RIT) and compressor pressure ratios (R_c) in order to select a representative cycle for the ABC Rotorcraft.

The key flight conditions are presented in Table XXXV.

Table XXXV.
ABC Rotorcraft key flight conditions.

Design mission cruise	
Altitude--m (ft)	914.4 (3000)
Airspeed--km/h (kt)	463 (250)
Power--kW (shp)	2733 (3665)
N_{PT}--%	77
Takeoff (HOGE)	
Altitude--m (ft)	914.4 (3000)
Airspeed--km/h (kt)	0
Temperature day--°C (°F)	33.1 (91.5)
Power--kW (shp)	2237 (3000)
N_{PT}--%	100
High altitude cruise	
Altitude--m (ft)	3048 (10,000)
Airspeed--km/h (kt)	463 (250)
Power--kW (shp)	2409 (3230)
N_{PT}--%	77

The engine was matched to maximize the engine operating efficiency and, hence, minimize the engine specific fuel consumption at the 914.4 m (3000 ft) altitude, 463 km/h (250 kt) velocity, maximum continuous power, cruise flight condition with the power turbine operating speed reduced to 77%.

The matrix of engine cycle design parameters selected for the study encompassed the compressor pressure ratio (R_c) and turbine rotor inlet temperature (RIT) at the engine design point, as presented in Table XXXVI.

Engine performance data were calculated for each combination of design point parameters in the study matrix. Appropriate component performance characteristics, turbine cooling airflows, engine leakage flows, and pressure losses were assigned to each combination of design parameters and were selected to be consistent with an engine operational capability in commercial service in the 1990 time period. The resulting engine performance data were plotted, using

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Table XXXVI.
Engine design point matrix for the ABC Rotorcraft.

R_c	15:1, 20:1, 30:1
RIT--°F	1900, 2100, 2300
RIT-- K	1311, 1422, 1533

propulsion system thrust specific fuel consumption (tsfc) as the figure of merit, as shown in Figure 43. As shown in Figure 43, the minimum propulsion system tsfc is obtained with an engine having a design point compressor R_c of approximately 24:1 and a turbine RIT of approximately 1533 K (2300°F). This figure also indicates that a design point turbine RIT higher than 1533 K (2300°F) might result in an even lower propulsion system tsfc. However, the selection of a design point (maximum continuous power cruise) turbine RIT resulted in the selection of a maximum turbine RIT of 1700 K (2600°F) at the sea level static, 33.1°C (91.5°F) day, maximum power engine operation, and it was judged that a selection of turbine RIT values higher than these would not be consistent with the anticipated 1990 technology level.

Table XXXVII provides detail performance and design data for the ABC Rotorcraft convertible propulsion system operating at its altitude cruise design point.

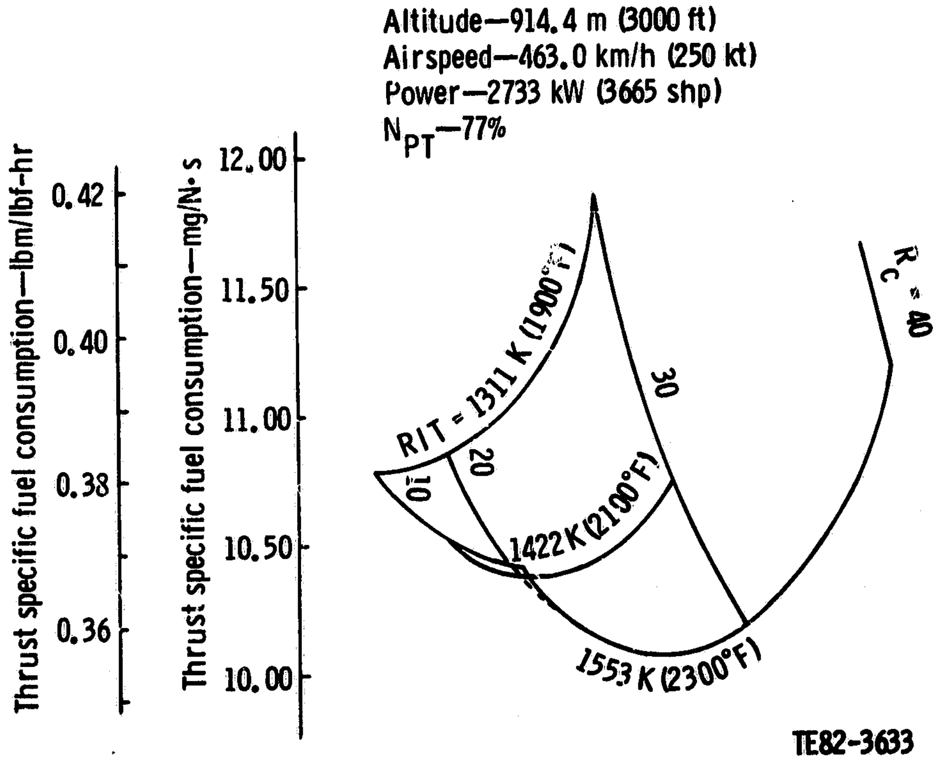

Figure 43. ABC Rotorcraft cycle study--sfc.

Table XXXVII.
ABC Rotorcraft convertible propulsion system engine data.

	SI units	Customary units
Power	2733.0 kW	3665 shp
Condition	914.4 m/0.382 Mach	3000 ft/0.382 Mach
Cycle		
R_c	24.2:1	24.2:1
RIT	1533 K	2300°F
sfc	233.6 mg/W.h	0.384 lbm/shp-hr
Corrected airflow	9.144 kg/s	20.159 lbm/sec
Inlet recovery	100%	100%
Nozzle pressure ratio	1.102:1	1.102:1
Overboard seal leakage	1.0%	1.0%
Components		
Compressor:		
η adiabatic	82.53%	82.53%
Rpm @ 100%	29,145	29,145
Axial:		
Tip speed ($U_t/\sqrt{\theta}$)	411.51 m/s	1350 ft/sec
R_c aver./stage	1.375:1	1.375:1
AR blades, aver.	1.20:1	1.20:1
Centrifugal:		
N_s	28.7 rpm $m^{0.75}/s^{0.5}$	70 rpm $ft^{0.75}/sec^{0.5}$
N_s (dimensionless)	0.545	0.545
Tip speed ($U_t/\sqrt{\theta}$)	548.6 m/s	1800 ft/sec
R_c	2.6:1	2.6:1
Blade to blade shroud loading, $\overline{LD}$	0.24	0.24
Combustor:		
η	99.9%	99.9%
$\Delta P/P$	0.04	0.04
Turbines:		
High pressure		
η adiabatic	89.0%	89.0%
Ave. stage loading coefficient ($gJ\Delta h/\bar{U}^2$ mean)	1.60	1.60
Equivalent work ($\Delta h/\theta cr$)	50.73 MJ/kg	48.08 Btu/lbm
Expansion ratio	6.017:1	6.017:1
Inlet temperature	1533 K	2300°F
Cooling airflow	6.83%	6.83%
Type of cooling (first blade)	Impingement film, cast-in	Impingement film, cast-in
Low pressure		
Rpm @ 77.5%	12,456	12,456
η adiabatic	91.0%	91.0%
Ave. stage loading coefficient ($gJ\Delta h/\bar{U}^2$ mean)	1.55	1.55
Equivalent work ($\Delta h/\theta cr$)	39.37 MJ/kg	37.32 Btu/lbm
Expansion ratio	3.848:1	3.848:1
Inlet temperature	1055 K	1440°F
Cooling airflow	0.5%	0.5%

Table XXXVII (cont).

	SI units	Customary units
Weight	251.7 kg	555 lbm
Length	1.369 m	53.90 in.
Max diameter	0.451 m	17.77 in.
Price*	$478,000	$478,000

* OEM price at 15/mo, 1400 units, 1981 economics

Engine Features

The preferred convertible propulsion system for the ABC Rotorcraft features a conventional turboshaft engine. The convertible features of this system are contained within the aircraft power transmission system and gearboxes.

This advanced, two-spool turboshaft engine has an axial/centrifugal flow compressor and an axial flow gas generator turbine on one spool and an axial flow power turbine on a separate spool. This engine is configured for front-drive power output. The general arrangement, weight, and key dimensions of this engine are shown in Figure 44.

The axial/centrifugal compressor will provide a design-point pressure ratio of 24:1. This compressor design has seven axial stages and one centrifugal stage with low aspect ratio axial blading and a low inlet hub/tip diameter ratio. The compressor inlet guide vanes and the first three vane stages are variable to ensure good compressor performance and surge margin throughout the engine operating range. The axial portion of the compressor rotor utilizes a drum-type construction. Circumferential dovetail blading is utilized in the axial portion of the compressor rotor. The centrifugal stage of the compressor is machined from a single forging and is bolted to the axial rotor drum.

The combustor of this engine has a full annular, foldback flow-path configuration to minimize combustor axial length. Two features incorporated in the combustion section are airblast-type fuel nozzles and transpiration-cooled sheet material for the liner wall. The airblast-type fuel nozzles serve to provide improved fuel atomization for optimized combustion and minimized emissions. The transpiration-cooled sheet material is Lamilloy, which requires less air to cool the liner walls while maximizing combustion liner life.

The high-pressure gas generator turbine is a two-stage, axial-flow, air-cooled design which utilizes advanced impingement and film cooling techniques. The gas generator turbine features active rotor blade tip clearance control to maintain high operating efficiencies over a wide range of engine operating conditions.

The low-pressure power turbine is a three-stage, uncooled, axial flow design which has been conceptually optimized to provide high operating efficiencies at both 100% design speed for takeoff and climb flight modes of operation and

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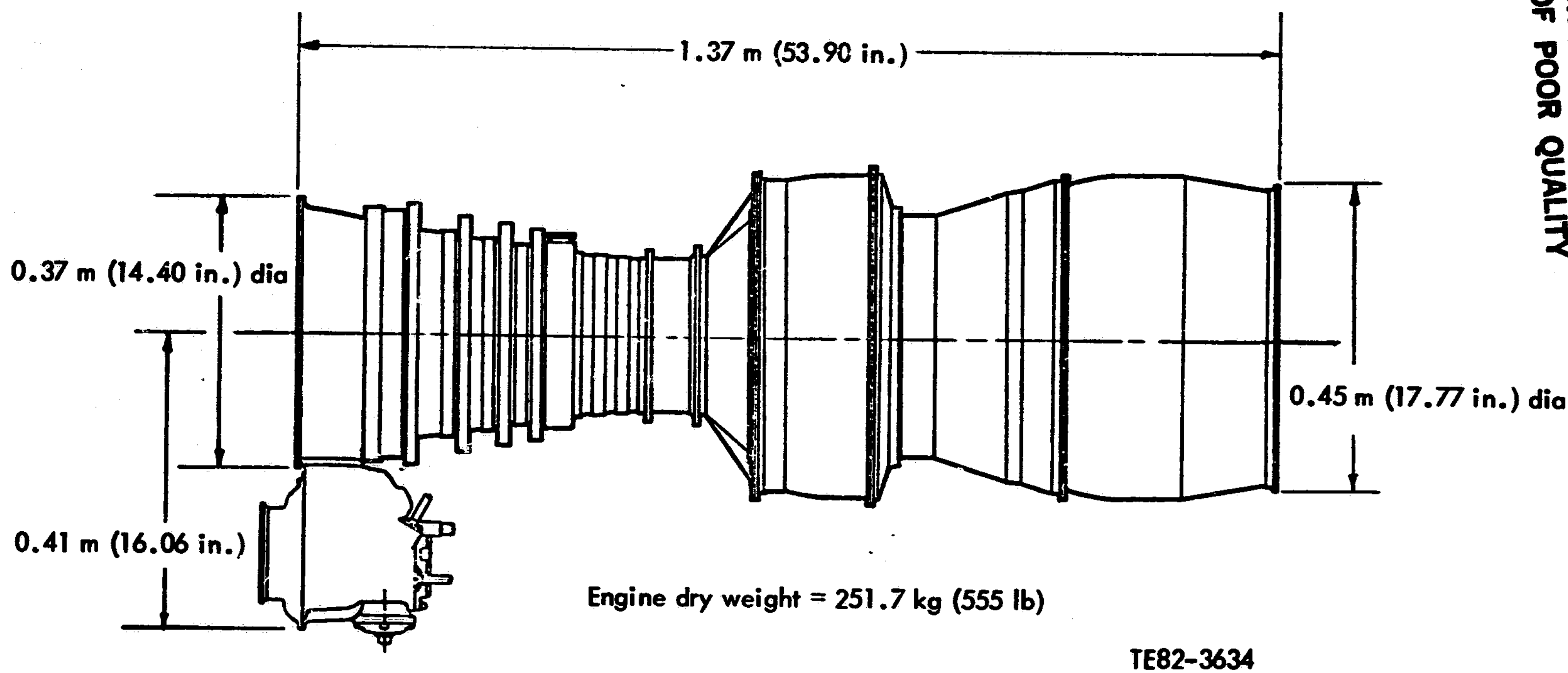

Figure 44. Preferred turboshaft engine for the ABC Rotorcraft convertible propulsion system.

77% design speed for cruise flight modes of operation. The blades in each stage of the power turbine rotor are shrouded at the blade tips to ensure maximum operating efficiency.

The accessory gearbox is mounted beneath the front of the engine on the air inlet housing. The engine and accessory gearbox utilize a fully contained lubrication system. Engine control is provided by a full-authority digital electronic control which may be integrated with the aircraft flight controls.

Primary engine mounting pads are located on the right and left sides of the air inlet housing. Auxiliary engine mounting pads are located aft of the turbine case.

Engine Performance

This engine at unity size will provide 3352 kW (4495 shp) at sea level static, 33.1°C (91.5°F), maximum power operating conditions with a turbine rotor inlet temperature of 1700 K (2600°F). The engine is flat rated at 3352 kW (4495 shp) to the sea level static, standard day 15°C (59°F), intermediate power operating condition. The 100% mechanical speed output of this engine is 16,072 rpm for the takeoff and climb modes of operation. The output speed is reduced to 77.5%, or 12,375 rpm, for cruise flight modes of operation. Cycle and performance summaries for takeoff and cruise modes are given in Tables XXXVIII and XXXIX, respectively.

Table XXXVIII.
ABC Rotorcraft convertible propulsion system--takeoff performance (sea level, static conditions).

Ambient temperature--°C (°F)	33.1 (91.5)
Power setting	maximum
Turbine rotor inlet temperature--K (°F)	1700 (2600)
Cycle pressure ratio	26.9:1
Shaft power--kW (shp)	3352 (4495)
Specific fuel consumption--mg/W h (lbm/shp-hr)	235.4 (0.387)
Jet thrust--N (lbf)	2104.0 (473)
Inlet corrected airflow--kg/s (lbm/sec)	9.5 (21.0)
Power turbine speed--%	100

Table XXXIX.
ABC Rotorcraft convertible propulsion system--cruise performance.

Altitude--m (ft)	914.4 (3000)
Airspeed--km/h (kt)	463 (250)
Ambient temperature--°C (°F)	9 (48)
Power setting	maximum continuous
Turbine rotor inlet temperature--K (°F)	1533 (2300)
Cycle pressure ratio	24.2:1
Shaft power--kW (shp)	2733 (3665)
Specific fuel consumption--mg/W h (lbm/shp-hr)	233.8 (0.384)
Jet thrust--N (lbf)	711.7 (160)
Inlet corrected airflow--kg/s (lbm/sec)	9.14 (20.2)
Power turbine speed--%	77.5

Although the turboshaft engine for the ABC Rotorcraft has a conventional configuration by today's standards, the operation of this engine calls for an unusual power turbine capability.

This aircraft is designed to operate with its rotor system and, hence, engine power turbine operating at 100% speed in the takeoff, climb, descend, and landing flight modes and at 77% speed in the cruise flight mode. In the typical design mission of 160.9 km (100 mi), a greater portion of the mission is spent in the cruise flight segment than in the takeoff, climb, descend, and landing segments combined. However, in a relatively short mission such as this, the takeoff, climb, descend, and landing segments contribute significantly to overall mission fuel usage and, although the cruise segment is still the major contributor, neither can be ignored. Expressed in terms of DOC sensitivities, a 5% reduction in engine sfc will yield a 3.2% reduction in the ABC Rotorcraft DOC. Of this 3.2% reduction in DOC, 2.2% is contributed by a 5% reduction in the cruise sfc and 1.0% is contributed by a 5% reduction in sfc in the remaining flight modes.

It is important, then, that the engine for the ABC Rotorcraft exhibit maximum component efficiencies and, hence, minimum engine sfc at both the 100% and the 77% power turbine operating conditions. A power turbine preliminary design study was conducted to determine if there are any unique design requirements associated with the design of a power turbine configured specifically for the ABC Rotorcraft and to evaluate any aerodynamic and mechanical problems that are anticipated in the design and development of a power turbine that will operate at high efficiency over a relatively broad range of operation and, particularly, at 100% and 77% operating speed conditions.

It is important, therefore, that the engine exhibit good component efficiencies for both the cruise and takeoff flight conditions.

A power turbine preliminary design study was conducted to identify any potential aeromechanical problems inherent in the design and development of this turbine. It is anticipated that the nearly 70% increase in rotor stress incurred when operating the turbine in the takeoff mode (compared to cruise) will play a dominant role in selection of output shaft speed. Studies have shown that takeoff AN^2 (rotor untapered stress parameter) values in the order of $3.2258 \times 10^7 m^2\ rpm^2$ ($5.0 \times 10^{10}\ in.^2\ rpm^2$) will be required to provide sufficient turbine exit area. AN^2 values of this magnitude are consistent with the engine development time frame of this study. From an aerodynamic standpoint the number of stages for a given shaft speed (consistent with maximum AN^2) will be established by desired efficiency level in conjunction with any installation constraints (maximum diameter and/or length) and/or engine weight trade-off. Preliminary design studies have shown the selection of the aerodesign point at engine cruise (100% aero equivalent speed) provides the desired efficiency characteristic between takeoff and cruise conditions. The turbine blading must operate at approximately 35 deg negative incidence at engine takeoff conditions (130% turbine equivalent speed). Power turbine performance at this condition could potentially benefit from improved off-design blade incidence technology.

The preliminary flow path for the power turbine, sized for this application, is shown by Figure 45. The three-stage axial turbine was assigned to provide an exit AN^2 value of $3.5484 \times 10^7 m^2\ rpm^2$ ($5.5 \times 10^{10}\ in^2\ rpm^2$) at takeoff

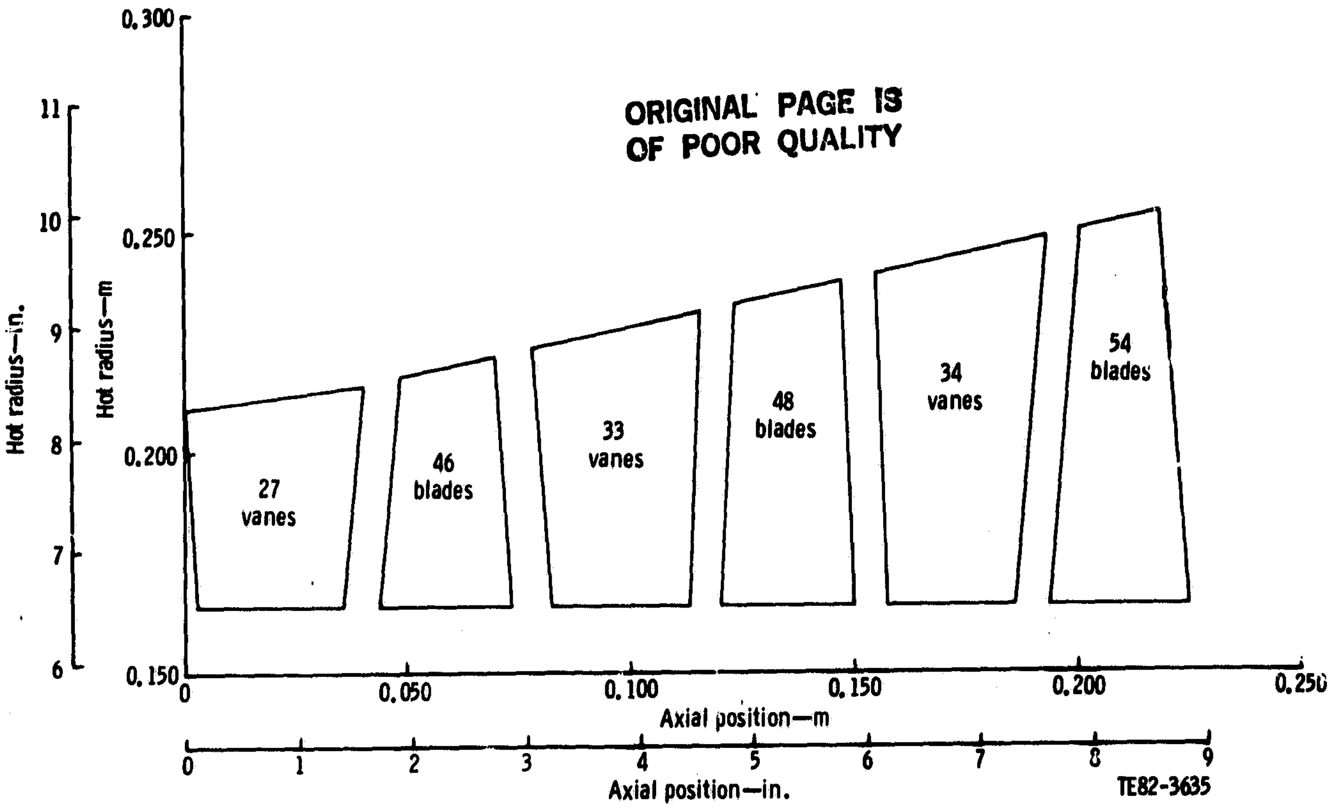

Figure 45. ABC Rotorcraft engine power turbine preliminary flow path.

speed. The engine cruise condition was selected as the turbine aerodesign point where $AN^2 = 2.0645 \times 10^7 m^2\ rpm^2$ ($3.2 \times 10^{10}\ in.^2\ rpm^2$). The turbine rotational speed was calculated to be 13,330 rpm for an assumed exit axial Mach number of 0.30. The turbine exit hub-to-tip diameter ratio was set at approximately 0.65:1. The predicted power turbine overall total-axial efficiency at the aerodesign point is 91.4%. This efficiency parameter increases to 92.1% at engine takeoff conditions. The predicted performance map illustrating these critical match points is shown by Figure 46. The turbine exit swirl varies from -9.5 deg at takeoff to +17.8 deg at engine cruise. The power turbine blading incidence swings approximately 35 deg between aerodesign and takeoff operating points.

Engine Description

Compressor

A hybrid axial/centrifugal compressor consisting of eight axial stages followed by a single centrifugal stage has been selected for this engine. The axial and centrifugal sections are separated by a bearing support.

The axial compressor has a relatively conservative low hub/tip radius ratio, low aspect ratio mechanical design. Drum construction is utilized in the rotor to minimize cost. Stages 2 through 8 will be machined from a single cylindrical forging with easy access to the inside made possible by the absence of wheel disks. Circumferential blade dovetails will be used so that slots can

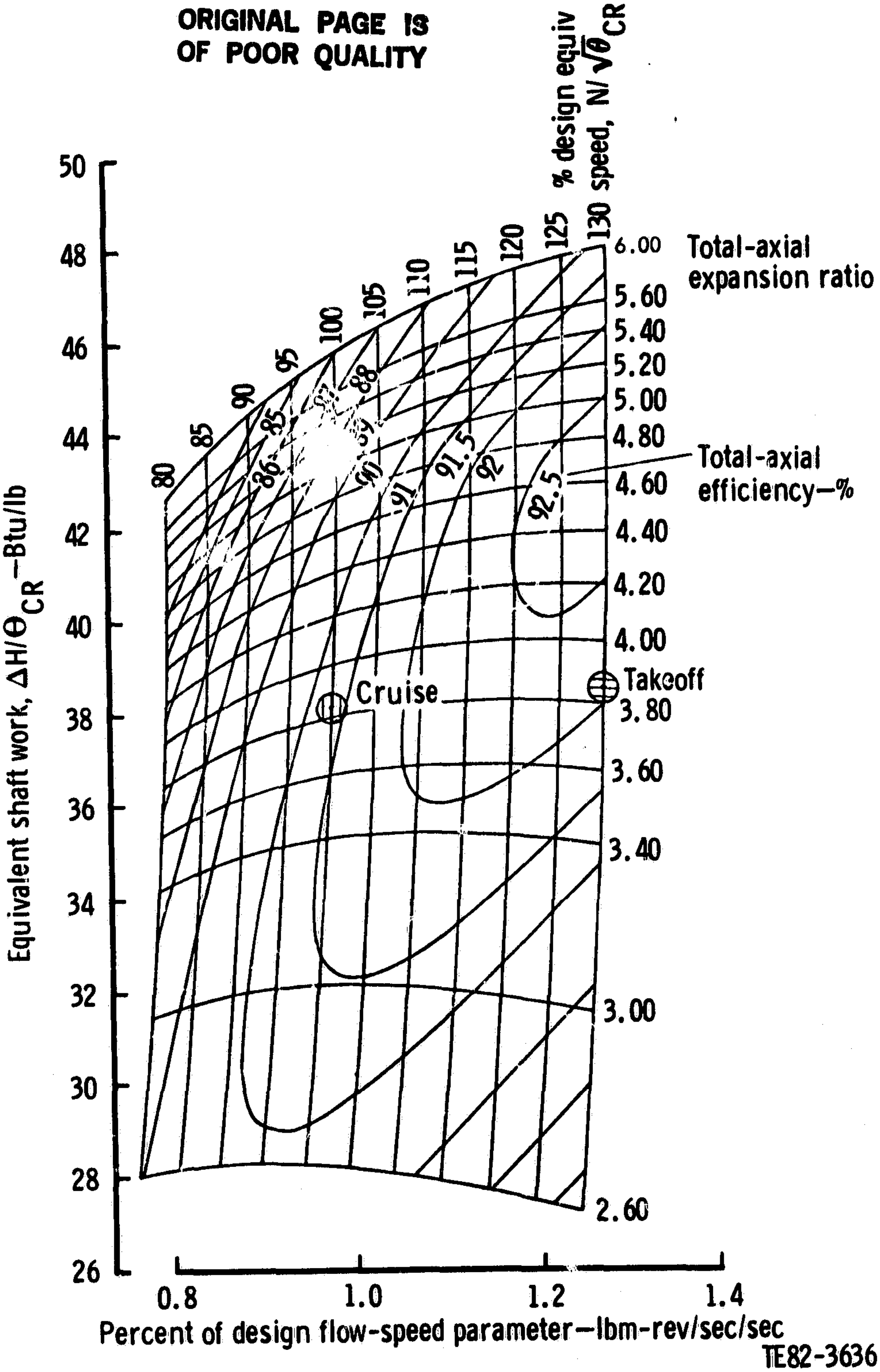

Figure 46. ABC Rotorcraft engine power turbine preliminary performance map.

be turned on one setup with basic drum contours. This eliminates the need for expensive broach bars. Since broach bar clearance need not be considered, all wheels can be integrally machined. Distortions and tolerance stacks of welded or mechanical joints between wheels are thereby avoided.

The axial compressor case will be axially split into four equal quarter cases. Two of the axial joints will be permanently bolted together while the other two remain separable for engine assembly and disassembly. Either of the two case halves can be removed from the compressor without diassembling the engine so that damage inspections can be made. Vanes will be mounted in the case halves as half-rings. Nonvariable stages will be bolted in space through the case with inner bands bayonetted together at the ends for alignment and ring rigidity.

A somewhat unconventional centrifugal compressor is incorporated in this engine. Normally, impeller inlets have a low hub/tip radius ratio wherein the inlet is crowded as close as possible to the engine axis. However, this impeller follows an axial compressor and, in order to avoid a long flow-path transition, the inlet is closely aligned with the axial compressor exit.

The centrifugal shroud is a conventional design but is mounted so as to isolate it from case structural loads. The shroud will be clamped at the outer periphery only. Case loads making a transition from the combustion outer case forward to the intermediate bearing support will pass through a structural cone-shaped member which surrounds the shroud and doubles as an aircraft service bleed manifold. Air enters the bleed manifold through slots in the compressor shroud.

Diffuser/Combustor

A full annular foldback combustor with a double-flow reversal flow path will be combined with the aft-stage centrifugal compressor to give an extremely short diffuser/combustor section. Two unique features are incorporated in the combustor: airblast-type fuel nozzles and transpiration-cooled sheet material (Lamilloy) in the combustion liner.

Fuel Nozzles

Fuel nozzles will be a simplex airblast atomizing type, which incorporate the features of fuel pressure energy and the newer air energy concept to provide highly effective fuel atomization. This type of fuel nozzle will provide

- o stable combustion over a wide range of fuel flows
- o good combustor outlet temperature profile
- o minimum exhaust smoke
- o long life
- o maximum contamination protection
- o low cost through design simplicity

The fuel nozzle consists of a holder, filter, spray tip, and internal flow director. The air swirler that provides the airblast function is integral with the combustion liner.

The flow versus pressure drop characteristic of the nozzle is established by the flow director, which also imparts a swirl component to the fuel flow. Fuel flows axially down the center passage in the flow director, radially outward at the end into a small annulus, then inward through small controlling tangential holes into the spin chamber, and finally exits the nozzle through the spray tip orifice.

Formation of internal deposits is minimized by careful proper design. Fuel flows rapidly through the nozzle without encountering dead zones. Also, fuel is isolated as much as possible from hot metal by an insulating air space between the flow director, which contains the fuel, and the spray tip casing.

Combustor

DDA has developed a method of transpiration cooling combustion liner walls that is approximately four times more effective in the use of cooling air than the conventional film cooling systems currently in use. This new concept involves the use of Lamilloy, the DDA-patented, transpiration-cooled material made by diffusion bonding photoetched sheet laminates together to form a porous structure. This is shown schematically in Figure 47.

The base laminate, or cold-side sheet (laminate No. 1 in Figure 47) is etched with a pattern of cooling air entry holes. Hole spacing is tailored to match specific air distribution requirements dictated by local heat load. A similar but offset pattern of holes is etched in the center laminate. Both the cold-side and center laminates are also etched with a pattern of posts which space the three sheets, providing internal flow passages and heat transfer surfaces. The hot-side sheet (laminate No. 3 in Figure 47) is etched only with a hole pattern and retains a full thickness over the full surface. Additional hole area may be provided in the hot-side laminate by reducing the hole spacing.

Turbines

The turbine section consists of a two-stage, air-cooled gas generator turbine and a three-stage uncooled power turbine. Mechanical simplicity and modularity are key considerations in the design. The gas generator rotor, power turbine rotor, intermediate support, and rear support are all removable as modules.

Predicted performance for this engine is based on the use of an active tip clearance control system in the gas generator turbine.

Gas Generator Turbine

The gas generator turbine rotor is a relatively simple modular assembly. It consists of two bladed wheels, an integral spacer/seal, and a rear stub shaft, all bolted together at midweb by through tie-bolts. The rotor module is clamped together by short tie-bolts, then attached as an assembly onto the compressor impeller by long tie-bolts which extend through a face spline coupling at the front of the rotor. Tie-bolt nuts will be located at the rear of the rotor for easy access during disassembly. The turbine will be replaceable as a module without having to balance the impeller and turbine as an assembly.

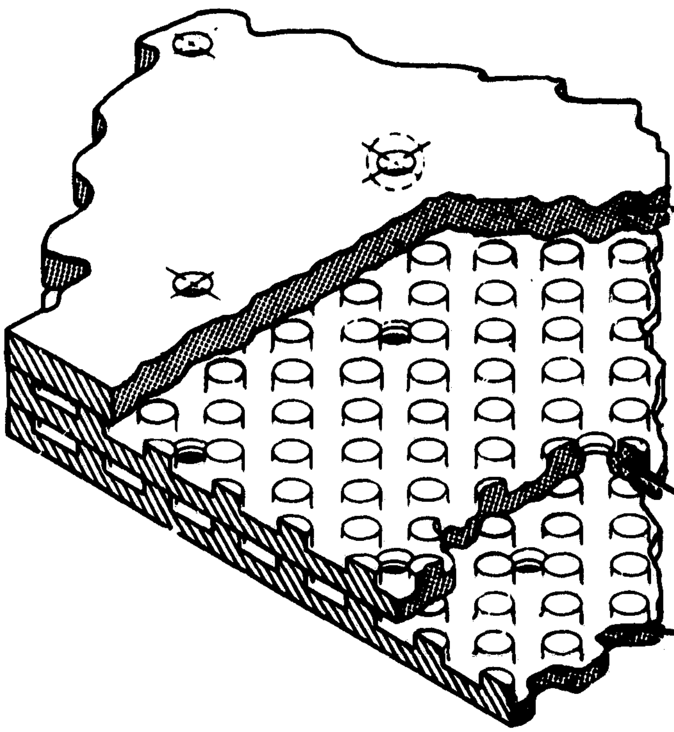

Figure 47. Lamilloy schematic.

Gas generator turbine blades and vanes are air cooled. First- and second-stage blades are single crystal castings. Single crystal blades exhibit excellent material properties and require the minimum use of cooling air. First- and second-stage blades are retained in the wheels using conventional cover plate segments. Plate segments are driven circumferentially into matching slots in blades and wheel rim and are locked in place by deforming the final small segment.

The gas generator turbine case is designed to be integral with the combustor dome cover and serves as a mounting feature for first- and second-stage vanes, first- and second-stage blade tracks, and fuel nozzles. All basic case features will be lathe turned. Then bolt holes and cooling air holes will be drilled.

By employing the foldback combustor concept, the entire gas generator turbine is buried inside the combustion section so that only the combustor dome portion of the turbine case is exposed to an ambient environment. Burying the turbine allows the combustion liner and combustor outer casing to be utilized in containing blade failures. A thinner turbine case can thus be used.

The turbine intermediate support contains the two roller bearings which support the gas generator turbine and the front of the power turbine. In order to maximize turbine performance, the intermediate support accurately controls the radial location of these two components, especially the gas generator turbine, which is unshrouded and more sensitive to clearance effects.

Both the gas generator turbine case and the power turbine case pilot directly onto the intermediate support, thus ensuring good concentricity between rotor and case elements.

Power Turbine

DDA selected a three-stage, constant hub diameter, all shrouded design for the power turbine. The rotor is a mechanically simple structure consisting of three similar wheel assemblies, two identical spacers between wheels, an aft stub shaft and balance piston labyrinth seal, the power turbine extension shaft, and central oil tube. The power turbine rotor is built up with the second- and third-stage vane assemblies trapped between blade rows and is installed in the engine as a module.

All three wheels are similar, differing only slightly in size and shape as required for the different sized blades. Wheels are free of protuberances and easily machined from simple forgings. Blades in all three stages are retained in conventional firtree attachments by cover plates driven circumferentially into matching slots in blades and wheels.

Rotor elements are clamped together by long D-head tie-bolts, which press into interference-fit holes in the extension shaft flange and extend rearward through wheels, spacers, seal, and stubshaft. This type of clamping arrangement produces a rugged rotor, which retains its clamping load under severe failure mode unbalance conditions.

A rather simple power turbine case design is utilized. It is largely finished by lathe turning a forging to produce the required wall thickness, end flanges, and vane and blade track hangers. The case is piloted directly onto the intermediate support at the forward bolt flange and directly onto the rear bearing support at the aft end. This provides minimum tolerance stack between rotor and case elements to achieve good control over blade tip seal and rotor labyrinth seal leakage.

Vane and blade track hangers and the aft bolt flange are located over the blade tips in an optimum position to contribute to blade containment.

The power turbine rear support integrates several engine functions:

- It provides the engine exhaust system flow path and includes an attaching flange for coupling with airframe exhaust system components.
- It provides radial support to the aft end of the power turbine rotor.
- It reacts the power turbine rotor thrust balance force.
- It provides oil system service lines to the rear bearing oil sump and rotor oil tube.
- It incorporates a power turbine speed monitor, which is a part of the engine control system.

The basic support structure, consisting of the exhaust shroud, struts, and inner strut support ring, is a welded assembly of machined forgings and formed sheet. Struts are arranged at a semitangential angle so that as they expand in the heat of the exhaust gas the certerbody will rotate slightly to compensate for the differential expansion.

Modular construction is achieved in the rear support as well. The entire support assembly will be built up as a module and installed [illegible] the engine simply by moving it forward into place; engaging seals, bearing rollers and race, and the rotor oil transfer tube; then bolting it onto the power turbine case.

Economic Data

Price

For the purpose of the Rotorcraft Convertible Engine Study, an OEM price has been established for the turboshaft engine selected for the ABC Rotorcraft. This price is estimated to be $478,000 using the MIF method. The assumptions upon which this estimate is made are as follows:

- o January 1981 economics
- o total quantity of engines--1400
- o production rate--15 engines per month

The above OEM price includes standard amounts to cover amortization of the following expenses:

- o general and administrative
- o profit
- o product liability
- o warranty

The above price is broken down approximately as shown in Table XL.

Table XL.
ABC Rotorcraft turboshaft engine price breakdown.

Inlet and accessory drives	$ 16,200
Compressor	118,100
Combustor	53,500
HP turbine and intermediate support	100,900
LP turbine and rear bearing support	103,700
Fuel, electrical, and control systems	58,800
Assembly and test	26,800
Total	$478,000

Maintenance Cost

The estimated maintenance cost for this engine is $24.38 per flight hour. This value is based upon the above assumptions plus the following:

- o eight-year operating period
- o 500 aircraft fleet
- o aircraft delivery schedule--10, 20, 50, 75, 100, 100, 75, and 70/yr
- o engine utilization--2800 hr/year
- o airframe life--30,000 hr (60,000 cycles)
- o engine design life--25,000 hr, replace cold section
  --7,500 hr, replace hot section

The input data assumed to determine the above maintenance cost are summarized in Table XLI.

Table XLI.
ABC Rotorcraft turboshaft engine maintenance costs input.

OEM price--$	478,000
Overhaul cost--$ (15%)	71,700
Major repair cost--$ (7%)	33,460
Minor repair cost--$ (3%)	14,340
Hot-section maintenance cost--$ (10%)	47,800
Max. operating time--hours	25,000
Number of hot-section maintenance actions	2
Unscheduled removals	
to overhaul--%	30
to major repair--%	50
to minor repair--%	20
Number aircraft in fleet	500
Operational period--years	8
Unit aircraft--hours/month	200
Premature removal rate	0.5
Number unscheduled removals	2000

Scaling Data

The engine may be resized within a power range of $\pm 20\%$. If the engine is resized, the following scaling relationships should be used:

Airflow--Varies directly with power

Weight--Scaled wt = Base wt x (Scaled power/Base power)^{Y}--
where Y = 1.04 if scaled power   base power and Y = 0.96
if scaled power   base power

Axial dimensions--Scaled dim. = Base dim. x (Scaled power/Base power)$^{0.4}$

Diametral dimensions--Scaled dia. = Base dia. x (Scaled power/Base power)$^{0.5}$

OEM price--Scaled price = Base price x (Scaled power/Base power)$^{0.805}$

Maintenance cost--Scaled cost = Base cost x (Scaled power/Base power)$^{0.805}$

Output speed (N_{PT})--Scaled N_{PT} = Base N_{PT} x (Base power/Scaled power)$^{0.5}$

Jet thrust (F_N)--Varies directly with power

sfc--Refer to Figure 48.

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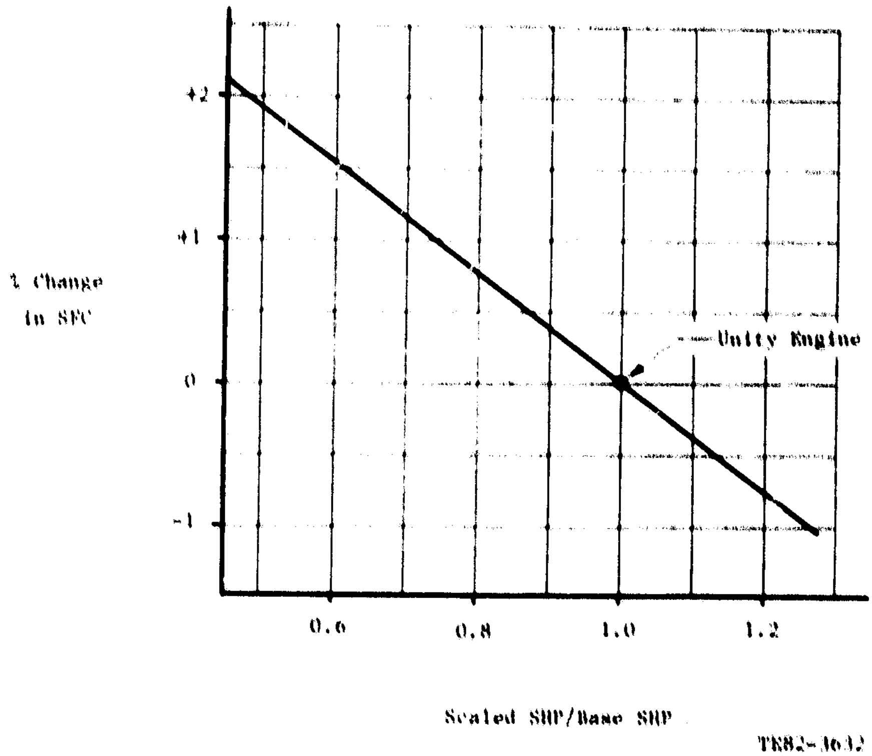

Figure 48. Sfc scaling relationship.

VI. BENEFIT ASSESSMENT

Comparative benefit analyses were conducted for each of the two types of future, unconventional civil rotorcraft. These analyses compared the initial aircraft designs using conventional propulsion systems (separate lift and cruise engines) with the same aircraft (resized as required) using convertible propulsion systems.

The benefits were calculated in each case using the baseline study missions and determining the impact of convertible systems/engines on aircraft gross weight, fuel consumption, direct operating cost, and acquisition cost. It is to be noted that in this study the aircraft characteristics and technology levels are fixed. The only changes to the aircraft, resulting from the switch to convertible engines or propulsion systems, were made as required to install the new engines.

ABC ROTORCRAFT

The ABC Rotorcraft used conventional turboshaft engines in both versions of the aircraft. In the initial mission analysis, two engines provided power to the rotor system for lift throughout the flight. Two additional engines, powering tractor propellers, provided forward thrust during the cruise portion of the flight and were entirely independent from the rotor drive system.

The baseline ABC Rotorcraft was modified for a convertible propulsion system using two conventional turboshaft engines. These engines were interconnected to the rotor system and to the tractor propellers. The conversion of power from lift only, during takeoff or landing, to lift plus cruise thrust was accomplished by the aircraft power transmission system.

The advantages of the two-engine/convertible propulsion system aircraft over the conventional four-engine aircraft are summarized in Tables XLII and XLIII.

Table XLII.
ABC Rotorcraft comparison, convertible vs. conventional propulsion systems (SI units).

	With convertible propulsion	Improvement over conventional--%
Design gross weight--kg	14,653.3	11.7
Rotor diameter--m	15.97	6.1
Design mission fuel--kg	1891.9	12.9
Typical mission fuel--kg	502.6	8.6
Acquisition cost--$	9,218,000	16.5
DOC--typical mission--¢/ASkm	13.39	12.0

FOLD TILT ROTOR AIRCRAFT

The Fold Tilt Rotor Aircraft used two conventional turboshaft engines for proprotor drive during the takeoff and landing mode and two conventional turbofan engines during the cruise mode.

Table XLIII.
ABC Rotorcraft comparison, convertible vs. conventional propulsion systems (customary units).

	With convertible propulsion	Improvement over conventional--%
Design gross weight--lbm	32,305.0	11.7
Rotor diameter--ft	52.4	6.1
Design mission fuel--lbm	4171	12.9
Typical mission fuel--lbm	1108	8.6
Acquisition cost--$	9,218,000	16.5
DOC--typical mission--¢/ASmi	21.55	12.0

In modifying the Fold Tilt Rotor Aircraft for convertible propulsion, the four original engines were replaced by two convertible fan/shaft engines. These engines were mounted in underwing pods and interconnected to each other and to the proprotors on each wing tip.

The advantages to the Fold Tilt Rotor Aircraft of the convertible propulsion system over the conventional propulsion system are shown in Tables XLIV and XLV.

Table XLIV.
Fold Tilt Rotor Aircraft comparison, convertible vs. conventional engines (SI units).

	With convertible engines	Improvement over conventional--%
Engine lift power (SLSS)--kw ea	4009.6	--
Design gross weight--kg	16,567.9	9.0
Design mission fuel--kg	2021.7	10.5
Typical mission fuel--kg	665.9	10.0
Acquisition cost--$	13,856,000	14.9
DOC--typical mission--¢/ASkm	10.58	14.7

Table XLV.
Fold Tilt Rotor Aircraft comparison, convertible vs. conventional engines (customary units).

	With convertible engines	Improvement over conventional--%
Engine lift power (SLSS)--shp ea	5377	--
Design gross weight--lbm	36,526	9.0
Design mission fuel--lbm	4457	10.5
Typical mission fuel--lbm	1467	10.0
Acquisition cost--$	13,856,000	14.9
DOC--typical mission--¢/ASSM	17.02	14.7

VII. RECOMMENDATIONS FOR FUTURE RESEARCH

NASA should address basic research and technology (R&T) needs for the near term to broaden the industry data base for design of advanced convertible propulsion systems and convertible engines for future unconventional civil rotorcraft. A general program directed toward specific areas where an investment in R&T dollars could produce critical data needed in the design of convertible gas turbine engines is presented here. These results are based on a generalized conceptual design study of two unconventional rotorcraft and their convertible propulsion systems. These 30-passenger transports are the Bell Fold Tilt Rotor Aircraft and the ABC Rotorcraft.

PROGRAM CONTENT

The overall program content is shown in Figure 49. This program includes the Rotorcraft Convertible Engine Study (RCES), a component R&D effort, and an experimental engine program. In the engine program, one of the key technology options required for convertible engines--a torque converter--may be tested in full scale under simulated aircraft operating conditions. The aircraft engine application of a torque converter is an area of high development risk which is best assessed by experimental testing of components sized to represent 1990s aircraft/technology requirements.

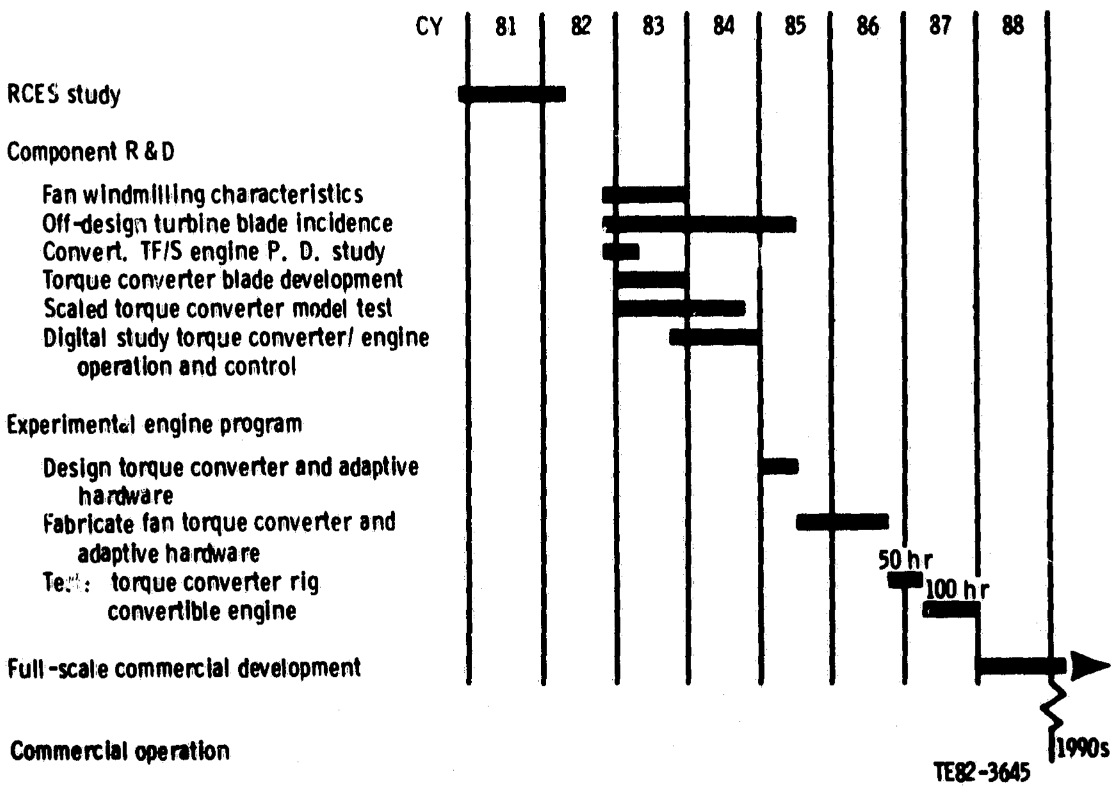

Figure 49. Rotorcraft convertible engine technology program.

Basic research and development programs which are needed to achieve the technological goals required prior to full-scale development of a convertible fan/shaft engine are given in Table XLVI. Benefit/cost ratios were based on potential reductions in development effort and/or a reduction in DOC during the service life of the engine operating in a fleet of 300 aircraft, 2800 hr/yr for 12 yr, and costs were estimated for demonstration of technology readiness. This application is a 370.7 km (200 nmi) mission using fuel priced at \$0.528/L (\$2.00/gal).

Table XLVI.
Critical technology elements for RCES R&D.

Program	Cost--\$000s(1)	Benefit--\$ million	Benefit/cost ratio	Rank(2)	Probability of success
Fan windmilling characteristics	390	43,868	113:1	2	likely
Off-design turbine blade incidence angles	700	115,300	165:1	1	likely
Convertible fan/shaft engine PD study	150	4000	26.7:1	5	likely
Torque converter blade development	160	6130	38.3:1	3	likely
Digital study of torque converter/engine operation and control	70	2000	28.6:1	4	likely
Scaled torque converter model test	610	8000	13.1:1	6	likely

(1) Budgetary estimates in 1982 economics, for planning purposes only.
(2) Ranked on basis of benefit/cost ratio.

COMPONENT RESEARCH AND DEVELOPMENT

Prior to the design of convertible engines or related new technology options, certain fundamental information applicable to high-risk technology areas should be derived from component research programs. Certain of these technology-deficient areas have been identified by this study program. They are described in the following subsection.

Compressor/Fan

The drag characteristics of a windmilling fan plus the impact of a windmilling condition on the fan bearing and lubrication requirements are relatively unknown. Current aircraft two-spool gas turbine engines have provided much experience with engine-out operation. However, this experience always occurs with a windmilling low-pressure spool including the power turbine. Convertible engines, such as the preferred configuration described elsewhere in this report, will be concerned with a windmilling fan only.

An R&D program is recommended to provide design and analysis data applicable to the entire inlet system for a convertible fan/shaft engine. This test program should provide data necessary to predict the possible requirement for a fan brake or alternate air inlet doors and to determine windmilling characteristics relative to fan lubrication and bearing requirements.

Turbine

Normally, all components of gas turbine engines are designed for one set of operating conditions, which are identified as the engine design point. The performance of the components is at a peak when they are operating at the design-point condition.

In the case of the ABC Rotorcraft, the rotors and engine power turbines operate at 100% speed during liftoff and landing and at 77.5% speed during cruise. The lower N_R speed during cruise results from a need to keep the rotor tip relative velocity subsonic as the auxiliary thrust devices accelerate the aircraft.

It is desirable, therefore, to have a power turbine for the ABC Rotorcraft engines which is as near to peak performance at both 100% and 77.5% N_{PT} as possible. One of the basic aerodynamic problems associated with such two-speed turbine operation is the resulting high negative incidence angles for the turbine blading. This is an area of little experience at present. The aim of the component R&D program proposed for this technology need is to provide cascade rig test data on different turbine blade shapes, cambers, and solidities.

Torque Converter

Torque converters have been developed to a high degree in highway and off-highway vehicles and stationary power plants. The potential new application of this hydraulic coupling device to aircraft gas turbine engines will require that considerable technical information be generated which is applicable to the special requirements of gas turbine engines. Specifically, the desired information includes the interrelationships between engine and torque converter control systems, torque converter blade shapes and flow angles, and blade tip speed and synchronization characteristics. Also desirable are computer models to simulate engines incorporating torque converters. The following research programs are recommended to reduce the development risk of aircraft engine torque converters.

Convertible Turbofan/Turboshaft Engine Preliminary Design Study

In order to initiate aircraft engine torque converter design studies, it is first essential to more thoroughly understand the dynamic relationships of the engine components to the torque converter plus their respective control requirements during the power transfer cycle. This study program will provide for analyses to establish the above characteristics and interrelationships and to document the findings for future reference.

Torque Converter Blade Development

In adapting torque converters to aircraft gas turbine engines, one of the areas in which new technology will be required is in the turbine, impeller, and reactor blade shapes due primarily to the high tip speeds involved. This program will explore blade shapes and both inlet and exit angles as they vary from hub to tip. This information will be obtained from cascade rig tests of instrumented airfoils which may be later performance tested in the scaled torque converter model.

Scaled Torque Converter Model Test

Before building full-scale engine torque converter hardware, considerable operational experience can be obtained and the development risk reduced by testing a scale version of the unit. The scale model will be used to obtain basic data such as tip speed effects, heat rejection characteristics, synchronization problems, chamber fill time requirements, and partial-fill performance.

By using a current automotive-size torque converter as the scaled aircraft unit, considerable savings may be realized in the availability of existing test equipment and test facilities.

Digital Study of Torque Converter/Engine Operation and Control

With the technical information available from the previously described research programs, accurate computer simulation models may be prepared for the convertible engine components including the torque converter. This computer model will be useful in designing the full-scale torque converter by its ability to predict the relationship of engine torque, rotor speed, torque ratios, speed ratios, fan speed, and torque converter fill time and power transfer response time.

EXPERIMENTAL ENGINE PROGRAM

The experimental engine program shown on Figure 49 is a three-year program which provides an opportunity to test a prototype gas turbine engine torque converter under simulated aircraft operating conditions. Also, the unique operational aspects for the core engine of the sudden application of ram inlet air during high-power operating conditions will be investigated.

An existing turboshaft engine and fan will be assembled with a new experimental-design torque converter. This prototype, semiconvertible engine will be tested to determine actual torque, speed, and power transfer requirements to supplement analytical data obtained on the earlier component R&D program.

A six-month design effort will be required to design the torque converter and adaptive hardware required to assemble the torque converter to the existing turboshaft engine and fan assembly. One set of new hardware, with alternate torque converter turbine, reactor, and impeller parts, will be fabricated over a 15-month period. The 100-hr test effort for the prototype semiconvertible engine will occur in the third year and provide critically needed data to enhance and reduce the development risk for the full-scale development of the true convertible engine.

VIII. CONCLUSIONS

Rotorcraft convertible engine studies indicate that future commercial rotorcraft will benefit considerably from the availability of convertible propulsion systems or convertible engines. Based upon the trade-off results of the two types of rotorcraft studied, ABC Rotorcraft and Fold Tilt Rotor Aircraft, improvements of from 15 to 16.5% in acquisition cost, 12 to 15% in DOC, 10.5% in design mission fuel required, and 9 to 12% in design gross weight are to be expected.

Convertible turboshaft propulsion systems for ABC Rotorcraft will be enhanced by optimizing the power turbines of these engines for maximum efficiency at two sets of operating conditions. This results from the need to slow down the power turbine/rotor drive system speed during high speed cruise in order to maintain high propulsive efficiency.

Convertible turbofan/shaft engines will benefit considerably from incorporating a torque converter in their fan drive systems. The availability of an input/output speed synchronizing torque converter will provide for a smooth engagement or disengagement of the fan drive with a simple positive mechanical lockup feature during engaged operation. A torque converter provides for complete disengagement of the fan when in the turboshaft operating mode. The fan may therefore be designed for use only during the turbofan mode of operation, to ensure maximum efficiency during cruise.

Research and technology development programs have been identified, through the studies of this program, which will ensure the readiness of convertible propulsion systems and convertible engines for full-scale development with acceptable risk by 1988. These programs provide for research in the following areas:

- o fan windmilling characteristics
- o off-design turbine blade incidence angles
- o convertible fan/shaft engine preliminary design study
- o torque converter blade development
- o scaled torque converter model test
- o digital study of torque converter/engine operation and control

As a follow-on to the above technology research programs, an experimental engine program is recommended to provide full-scale operational verification of the torque converter fan drive concept.

APPENDIX: LIST OF ABBREVIATIONS AND SYMBOLS

Symbol	Meaning
ABC	Advancing Blade Concept Ⓣ
A_j	Jet nozzle area
AN^2	Blade stress parameter
AR	Aspect ratio
BPR	Bypass ratio
C_t	Nozzle thrust coefficient
dB	Decibel
DDA	Detroit Diesel Allison
DGW	Design gross weight
DOC	Direct operating cost
ECS	Environmental control system
EGV	Exit guide vanes
EPNdB	Equivalent perceived noise, decibel
F_N	Jet thrust
GW	Gross weight
HOGE	Hover out of ground effect
HP	High pressure
ICAO	International Civil Aviation Organization
IFR	Instrument flight rules
IGV	Inlet guide vanes
IRP	Intermediate rated power
$\overline{LD}$	Blade-to-blade shroud loading
LP	Low pressure
MCP	Maximum continuous power
mi	Statute mile
MIF	Materials index factor
M_n	Mach number
nmi	Nautical mile
N_{PT}	Power turbine rotational speed
N_R	Rotor system rotational speed
OEI	One engine inoperative
OEM	Original equipment manufacturer
PD	Preliminary design
PT	Power turbine
PTO	Power takeoff
Prop	Propeller

APPENDIX: LIST OF ABBREVIATIONS AND SYMBOLS (cont)

Symbol	Meaning
QCSEE	Quiet Clean STOL Experimental Engine
R_c	Pressure ratio
R_{co}	Pressure ratio, overall
R_f	Pressure ratio, fan
RIT	Rotor inlet temperature (turbine)
ROC	Rate of climb
ROD	Rate of descent
rpm	Revolutions per minute
sfc	Specific fuel consumption
shp	Shaft horsepower
SL	Sea level
SLS	Sea level static
SLSS	Sea level static, standard day
TF	Turbofan
TOGW	Takeoff gross weight
TS	Turboshaft
tsfc	Thrust specific fuel consumption
V	Aircraft velocity
V_{AVER}	Aircraft velocity, average
V_{BE}	Aircraft velocity, best endurance
VCD	Vortex-controlled diffuser
VEGV	Variable exit guide vanes
VIGV	Variable inlet guide vanes
V/STOL	Vertical/short takeoff and landing
V_{TYP}	Aircraft velocity, typical
η	Efficiency
$\Delta h/\theta_{CR}$	Stage equivalent work
$\Delta H/\theta_{CR}$	Equivalent shaft work
$\Delta P/P$	Pressure change
$gJ\Delta h/\bar{U}^2$ mean	Average stage loading coefficient
$N/\sqrt{\theta}_{CR}$	Equivalent speed
$WN\epsilon/60_\delta$	Flow-speed parameter

REFERENCES

1. Cheney, M. C., Jr., The ABC Helicopter, presented at AIAA/AHS VTOL Research, Design, and Operations Meeting, Atlanta, Georgia, February 1969.

2. Ruddell, A. J., et al., Advancing Blade Concept (ABC) Technology Demonstrator, Final Report for Period January 1972-June 1980, U.S. Army Report No. USAAVRADCOM-TR-81-D-5, April 1981.

3. Ruddell, A. J., and Macrino, J. A., Advancing Blade Concept (ABC) High Speed Development, presented at the 36th Annual Forum of the American Helicopter Society, Washington, D.C., May 1980.

4. V/STOL Tilt Rotor Research Aircraft, Volumes 1 through 12, Bell Helicopter Textron Reports 301-199-001 through 012, November 1974.

5. Bilger, J., Gunderson, B., Leibensberger, R., Marr, R., and Zahedi, A., V/STOL Tilt Rotor Research Aircraft, XV-15 Interim Flight Test Data Report, Bell Helicopter Textron Report 301-189-010, 15 November 1979.

6. Final Report, Task II, Large Scale Wind Tunnel Investigation of a Folding Tilt Rotor, NASA Contract NAS2-5461, Bell Helicopter Textron Report D272-099-002, NASA CR 114464, May 1972.

7. Wernicke, Rodney K., A Tilt Rotor Design That Provides Economical Extended Range VTOL Transporation to Offshore Oil Platforms, presented at the AIAA Aircraft Systems & Technology Meeting, Anaheim, California, 4-6 August 1980.

8. Wagner, Douglas, Design and Test of a Navy V/STOL Lift Fan Clutch, Final Report for Period 30 September 1976-31 October 1978, USN N00019-76-C-0695, Report No. EDR 9626, 1 November 1978.

9. Helms, H. E., Quiet Clean STOL Experimental Engine Study Program, NASA-LRC Contract NAS3-16727; Task I, EDR 7543, September 1972; Task II, EDR 7610, November 1972; Task III, EDR 7620, November 1972; Task IV, EDR 7738, February 1973.

10. Design Practices--Passenger Car Automatic Transmissions, Advances in Engineering, Series No. 5, SAE 1973, Chapter 18, "Application of Hydrodynamic Drive Units to Passenger Car Automatic Transmissions," by E. W. Upton, Engineering Staff, General Motors Corporation.

11. Preliminary Design Study of Convertible Fan/Shaft Engines, USAAVLABS Technical Report 68-26.

12. Part-Span Variable Inlet Guide Vanes for V/STOL Fan Thrust Modulation, AIAA-80-1248.