Turboprop Engine Propulsion for the 1990's

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Continuing interest in fuel-efficient prop-fan propulsion has highlighted the need for a large horsepower advanced technology turboprop engine. The initial application could be in a 100-150 passenger short/medium-range aircraft. An engine concept which could provide from 9,000 to 25,000 SHP for commercial and military applications, and could be available for introduction to service by 1990, is described. Results of engineering studies which support the preliminary design of the power unit and the approach being taken to define the reduction gear are presented. Key technology issues related specifically to the propulsion system are identified.

Introduction

PROPELLER-driven propulsion dominated aviation through the 1950's, but propeller-driven aircraft eventually were superseded by turbojets, which provided superior productivity as well as improved passenger comfort. The fact that the turboject was less fuel efficient was of little concern in an era when aviation fuel cost 10¢/gal. In the 1960's and 1970's, the emergence of turbofan propulsion, coupled with progressive improvements in technology, recaptured the lost fuel efficiency and offset the ensuing increases in fuel prices. As the rate of improvement in fuel efficiency has slowed and fuel costs have skyrocketed, it now appears that turbofan propulsion systems may not be totally satisfactory for the transport aircraft of the 1990's and beyond.

However, there is a new propulsion system which promises significant improvement in fuel consumption without compromising productivity or passenger comfort. A new advanced single rotation high-speed propeller, the prop-fan, in combination with an advanced turboprop engine, offers comparable productivity and a potential 15-20% reduction in fuel consumption relative to advanced turbofan engines. This new system will allow propeller-driven propulsion to once again contribute significantly to commercial and military air transport.

The prop-fan is an advanced multibladed propeller featuring thin, swept airfoils operating at high power loading. Initial aerodynamic/acoustic model tests conducted by NASA and Hamilton Standard have demonstrated the potential for full-size prop-fans to extend the flight speed capability of advanced propeller-powered aircraft up to Mach number 0.8 with the same high propulsive efficiency conventional propellers currently exhibit at lower speeds.[1,2]

NASA is pushing forward to establish complete technology readiness.[3] However, considerable work remains before industry would be able to initiate a development program with acceptable risk. This work involves the prop-fan itself, noise generation and attenuation, aerodynamic integration including both the prop-fan/nacelle/wing and prop-fan/inlet/compression system, and the overall power system.

This paper focuses on the turboprop engine and the reduction gear through which the prop-fan is driven. The prop-fan itself will not be described in detail. Current design study status is described, and areas in which technology verification is required are identified.

Applications for Prop-Fan Propulsion

Potential Market

The most promising application for prop-fan propulsion is the short/medium-range 100-120 passenger replacement aircraft market, starting as early as 1990. This initial application will require an advanced turboprop engine producing 10,000-12,000 hp.

Market projections are based on the fact that more than half of the short/medium-range aircraft in the free world are now over 9 yrs old (Fig. 1). The 4000 aircraft in this market, mostly Boeing 727's and 737's and Douglas DC9's, will be replaced with more fuel-efficient aircraft by the year 2000. The replacement process has been initiated already with the introduction of the 140 passenger stretched DC9-80 and the recently announced 120 passenger re-engined Boeing 737-300, scheduled to begin service in late 1984. The 175 passenger Boeing 757-200, which started service in 1983, also may draw on this replacement market.

Figure 2 shows a short/medium-range commercial transport aircraft scenario for the 1980's and 1990's. As already mentioned, the replacement process has begun, but beyond 1985 new aircraft definition is still wide open. Aircraft and engine companies currently are studying new 120 and 150 passenger turbofan-powered aircraft for possible introduction into service in the mid to late 1980's.

Prop-fan-powered aircraft could emerge as a significant factor in the commercial market in the early 1990's if technology readiness can be established by the mid-1980's. Market studies confirm this potential: a new prop-fan-powered aircraft family, introduced into service in the early 1990's, could capture more than 2000 aircraft, including one-half of the replacement market. This family of aircraft is initially expected to seat 100-120 passengers, with growth capability up to approximately 150 passengers. The power requirements for the 100-120 passenger aircraft fall in the 10,000-12,000 hp range (Fig. 3), with growth versions requiring approximately 15,000 hp. The confidence to develop such a powerplant must start with prop-fan/engine/aircraft studies and technology verification.

Benefits

Prop-fan power provides direct benefits, in terms of improved fuel efficiency, as well as several indirect benefits. By the year 2000, 6 billion gallons of fuel could be saved with prop-fan power compared to advanced technology turbofans. Over their entire life, prop-fan powered aircraft delivered by the year 2000 would save a total of 20 billion gallons of fuel.[4] These figures are based on introduction into service of a new 100-120 passenger prop-fan twin short/medium-range air-

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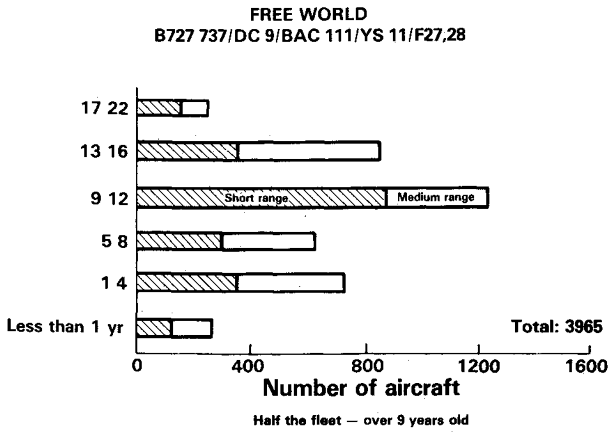

Fig 1 Age of existing narrow body fleet

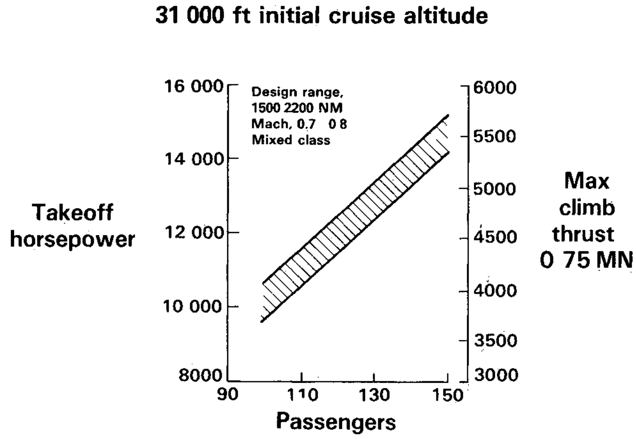

Fig 3 Power requirements for twin engine transports

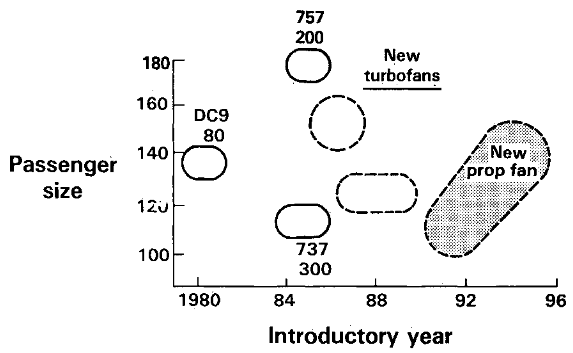

Fig 2 Potential prop-fan scenario

plane by 1990 1991 followed by a growth version ap proximately 5 yr later For comparison, U S airlines used 11 billion gallons of fuel in 1980 The benefits of improved fuel efficiency also would be available to the military which is increasingly active in pursuing proven commercial technology in transport aircraft

Other indirect benefits would accrue from the attainment of prop fan capability These include reduction of U S. dependence on foreign oil improved service to small and medium sized communities through reduced airline operating costs retention of the U S aircraft technology lead in the world enhancement of the U S balance of payments and creation of new jobs in the manufacture of prop fan aircraft [4]

Engine Concept

In order to realize the benefits of prop fan propulsion eventually new engine and aircraft studies must be conducted first To assist in this iterative process when the required engine size is unknown an advanced turboprop concept which could cover requirements from 9 000 to above 15 000 hp was developed The first step in the engine design process was selection of a thermodynamic cycle Parametric studies then were conducted to understand the effect of ther modynamic cycle on aircraft fuel burn and direct operating cost In selecting the configuration, derivative technology was considered but a scaled version of the energy efficient engine eventually was selected This advanced turboprop study engine designated STS 589 [5] provides the required horse power flexibility for engine/aircraft studies

Cycle Selection

The 36 000-lb thrust energy efficient engine (E^3) is the focus for technology development aimed at providing more efficient turbofan engines in the late 1980's and 1990's At its aerodynamic design point, Mach number 0 8, 35 000 ft the overall pressure ratio of the energy efficient engine is 38 and the combustor exit temperature is 2700 R The level of gas turbine performance efficiency in the advanced turboprop engine which is considerably smaller in thrust size will affect the optimum cycle pressure ratio and turbine temperature

Cycle studies covering a range of pressure ratios from 20 to 40 and combustor exit temperatures from 2500 to 2800 R were conducted for the turboprop engine Typical results of these studies are shown in Fig 4 Relative cruise fuel con sumption and gas generator weight are shown as functions of overall pressure ratio and combustor exit temperature at constant shaft horsepower Along each line of constant combustor exit temperature, the engine core gets smaller and compressor and turbine efficiency are reduced as overall pressure ratio increases In addition, turbine cooling air temperature increases with overall pressure ratio causing a further reduction in turbine efficiency The difference in minimum fuel consumption for the range of combustor exit temperatures studied is only 0 5% at an overall pressure ratio of 30 to 35. The variation in gas generator weight at constant temperature is 5 8% Since there are fewer stages of com pression, weight is reduced as overall pressure ratio decreases The best cruise fuel consumption for this size engine is available at a pressure ratio of 30-35 and a combustor exit temperature of 2600 2800 R However selection of these parameters must take into consideration the evaluation of aircraft economics and fuel burned

A 120 passenger twin engine airplane was used in the parameteric studies Technology was consistent with aircraft currently being developed for introduction into service in the mid 1980's, such as the Boeing 757 Design range and speed were 1800 n mi and Mach number 0 8 at 31,000 ft respec tively. Engines were sized for an initial cruise altitude capability of 31,000 ft

At takeoff a turboprop engine sized for this aircraft would develop about 12,000 hp The prop fan was sized for a power loading equal to 37 5 SHP/D^2 at maximum climb and 800 ft/s tip speed Reduction gear and prop fan weight were held constant.

Fuel burn and direct operating cost trends were evaluated for an average flight of 400 n mi at 60% load factor In Fig 5a, at a constant pressure ratio of 30 fuel burn shows a respectable improvement of 0.6% from 2500 to 2600 R and one-half of this rate above 2600 R In Fig 5b at constant combustor exit temperatures of 2600 and 2700 R the op timum overall pressure ratio is 28 32

The effect of variations in overall pressure ratio and combustor exit temperature on airline economics was studied briefly Direct operating cost plus interest was calculated assuming constant maintenance cost and propulsion price a fuel price of $1 50/gal (1980), and 15% interest The trend of

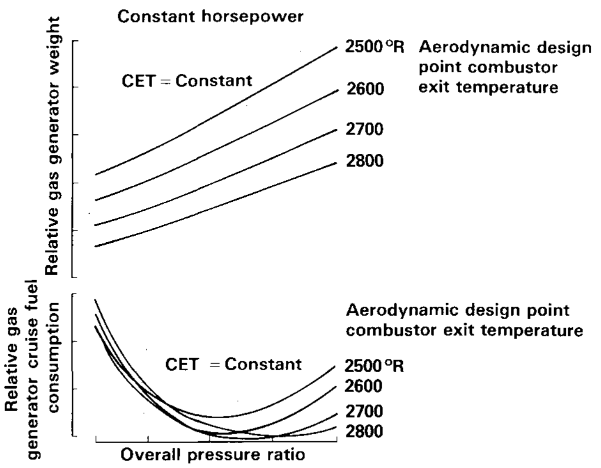

Fig. 4 Engine cycle study results.

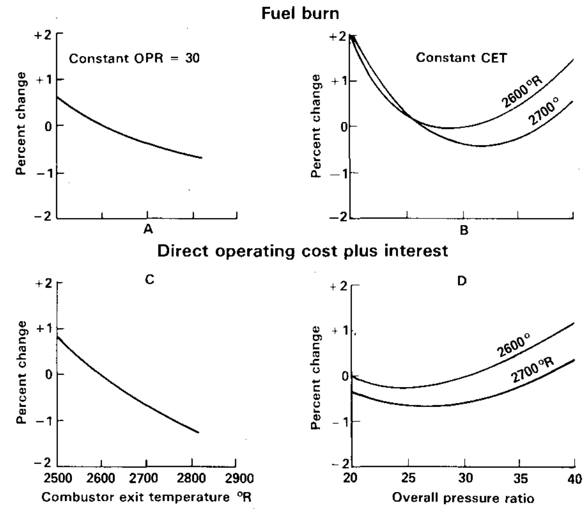

Fig. 5 Aircraft parametric study results.

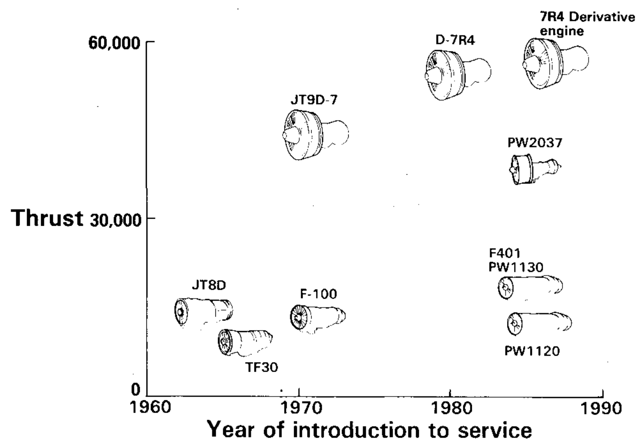

Fig. 6 Commercial and military engines.

direct operating cost plus interest at constant overall pressure ratio, Fig. 5c, follows the fuel burn trend. However, in Fig. 5d, at constant temperature, minimum cost occurs at an overall pressure ratio of 23-28, reflecting the importance of reduced gas generator weight. At higher overall pressure ratio, the fuel burn improvement is not large enough to counter increased weight. It should be noted that the reduced maintenance cost and price resulting from operation at low temperature and pressure tends to drive the optimum cycle in the direction of even lower overall pressure ratio.

These studies clearly show that optimizing on fuel burn drives the optimum cycle to a higher overall pressure ratio while optimizing on direct operating cost drives the cycle pressure ratio down. Biasing the judgment in favor of fuel burn, an overall pressure ratio of 30 and combustor exit temperature of 2700°R was selected for the study engine. However, the influence of maintenance cost and engine price eventually must be considered carefully. Certainly much fine tuning needs to be done in the area of cycle/airframe optimization in the future.

Derivative Approach

Once the thermodynamic cycle has been established a turboprop engine can be designed. One approach is to derive the turboprop from an existing engine. The Pratt & Whitney spectrum of engines from which a large horsepower derivative turboprop engine might be developed include 14,000-60,000 lb thrust commerical turbofan engines and the 12,000-17,000 lb thrust (intermediate power) military engines (Fig. 6). The F-100 (early 1970's military technology) and PW2037 (early 1980's commercial technology) high-pressure compressors are closest in flow size to the advanced turboprop requirements; thus, these engines are the most likely choices.

The relative fuel consumption of turboprop engines designed around these compressors and sized for a 120 passenger twin-engine airplane is compared to an optimized turboprop in Table 1. First, note that the PW2037 and F-100 high-pressure compressor flow sizes are 65 and 85% larger than required. The new engine operates at optimum pressure ratio at altitude cruise conditions. The derivative engines would develop excess thrust at their design pressure ratio and must be desupercharged. Therefore, as a result of poor cycle efficiency, the PW2037 derivative has 5% higher fuel consumption relative to an all new engine. Fuel consumption of the F-100 derivative is 12% higher due to poor cycle efficiency and lower component efficiency. In addition, when installed, the new engine will enjoy lower weight and drag compared to the derivatives. It is clear that unless the prop-fan is powered by an engine with an optimum size compression system, much of the advantage of the prop-fan over the turbofan will be lost.

All New Engine

To meet turboprop thrust requirements with optimum fuel consumption and weight, the energy efficient engine core flow size was scaled down. For example, starting with the energy efficient engine at point A in Fig. 7, which is the base for performance and thrust size comparison, the mixer is removed at point B. The engine is then scaled down at constant pressure ratio to approximately 0.6 size and desupercharged to an overall pressure ratio of 30 at point C. The turbofan defined by point C has 8% higher fuel consumption and is about one-half smaller in thrust size than the energy efficient engine. Replacing the fan with the prop-fan and introducing a reduction gear gives the advanced technology turboprop at point D. In this example, the turboprop exhibits provement and 12% lower fuel consumption than the energy efficient engine. The turbofan at point E is discussed in the next section.

The advanced turboprop engine concept, designated STS 589, is shown in Fig. 8. It is a two-spool engine with a scaled 14:1 pressure ratio energy efficient engine high spool and a new short single-stage aerating burner. The compressor operating line is lowered approximately 5% compared to the energy efficient engine size in order to maintain surge margin. The new burner is designed to minimize engine length and maximize rotor speeds within the allowable critical speed.

The low spool, which is supported on three bearings, consists of a four-stage power turbine driving a four-stage low-pressure compressor and prop-fan through the 8.5 gear

Table 1 Turboprop engine performance comparison 120 passenger twin constant maximum climb thrust prop fan power loading 37 5 SHP/D^2

	New engine	Derivative engines	
High pressure compressor	New	PW2037	F100
HPC exit corrected flow at 30 OPR lb/s	5 0	8 3	9 3
Pressure ratio			
HPC	13 7	14 2	8 7
LPC	2 2	1 4	2 5
Overall pressure ratio	30	20	22
Relative TSFC %	Base	5 2	+ 11 8

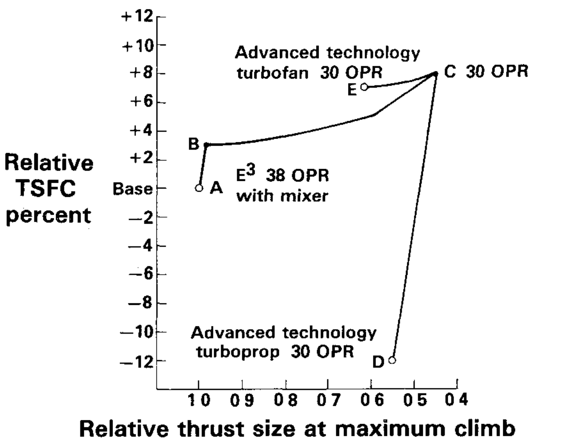

Fig 7 Performance of advanced turboprop vs advanced turbofan engine

ratio reduction gear The need for variable guide vanes to optimize low pressure compressor performance and stability will be determined during full scale inlet/compressor tests

The study engine can be scaled over a wide range of power for aircraft studies The maximum climb thrust range with a prop fan power loading equal to 37 5 SHP/D^2 is 3000 to over 5500 lb The base engine with a high pressure compressor exit corrected flow of 5 0 lb/s is rated at 15 000 hp at sea level and develops 4700 lb climb thrust At 4000 lb climb thrust the compressor exit corrected flow is 4 2 lb/s and the sea level rating is 12 000 hp

New Engine Performance Advantage

Compared to an equivalent technology turbofan the turboprop engine with the prop fan always will enjoy the propulsion efficiency advantage illustrated in Fig 9 The size of the advantage depends on flight condition with lower speed and altitude generally favoring the advanced turboprop A second order influence is engine core size The turbofan core flow which is sized by takeoff thrust tends to be larger than the turboprop which is sized by altitude cruise thrust For this reason, the optimum turbofan cycle and component efficiency will be somewhat better for the same aircraft design payload and range

As discussed previously (see Fig 7), the prop fan concept is derived by scaling the energy efficient engine core and desupercharging An equivalent technology turbofan is derived from point C by scaling up at constant cycle to point E where the advanced turbofan provides the same takeoff thrust as the turboprop At the same turbine temperature it then has excess climb thrust capability compared to the turboprop at point D In this example the turboprop exhibits approximately 20% lower cruise fuel consumption and also enjoys the benefit of lower gas generator weight

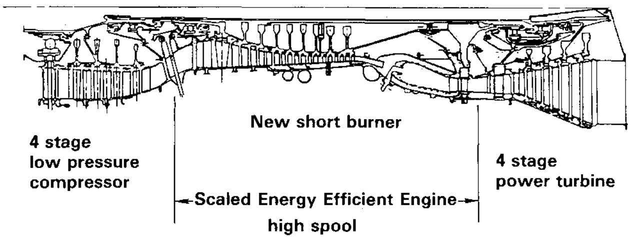

Fig 8 Turboprop engine concept

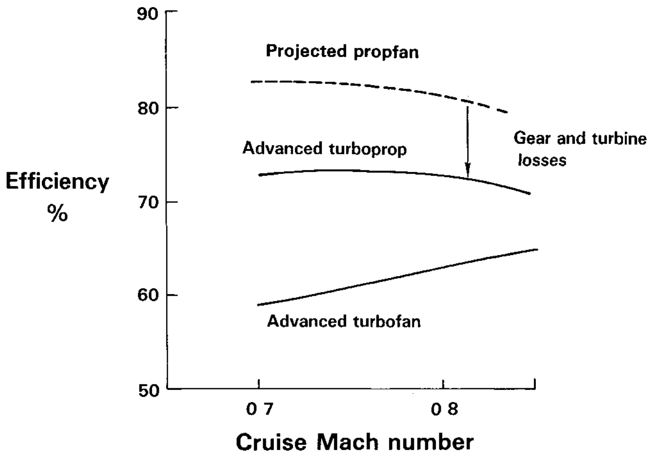

Fig 9 Turboprop engine efficiency advantage with prop fan

Reduction Gear

Aircraft industry experience with large turboprop reduction gear technology is relatively limited However studies indicate that compound idler offset and split path in line planetary systems can provide the high reliability and low weight required for effective prop fan propulsion These systems are being evaluated in current integrated prop fan/engine/airframe studies

Current Experience

United States aircraft industry experience is illustrated in Fig 10 where current reduction gears are compared in terms of output speed torque, and horsepower There is considerable high technology experience in the helicopter industry Main rotor gearboxes have been developed for a variety of power requirements ranging up to 13,000 hp CH53E (Sea Stallion) These reduction gears are characterized by high output torque low output speed and a high gear ratio (30 35)

At the high output speed end of the spectrum some experimental work has been done on NASA supported turbofan engine programs Experimental reduction gears have been designed and tested at 13,000 (QCSEE) and 50,000 hp (ATEGG)

Current high power turboprop experience is limited primarily to designs from the 1950's ranging from the 3100 hp T64 to the 4900 hp T56 engine The 6800 hp T34 is no longer in production The proposed STS 589 reduction gear falls in the region between 9,000 and 25,000 hp well beyond the range of current turboprop experience

Design Approach

A successful reduction gear for a commercial transport must combine high reliability and efficiency with low weight and maintenance cost Durability is also a crucial factor in the commercial environment, where 2500 3000 h of service per year is common A long life bearing system is fundamental to achieving the desired overall reliability and durability. High bearing system life, in conjunction with modular maintenance capability and gear stress limits consistent with very high cyclic life, are expected to allow a reliability goal of 30,000 h mean time between removal.

Based on conceptual design screening studies, the offset compound idler and in-line split path systems shown in Fig. 11 were selected for continuing propulsion studies. Final selection will depend on detailed evaluation of installed performance and weight as well as total system maintenance.

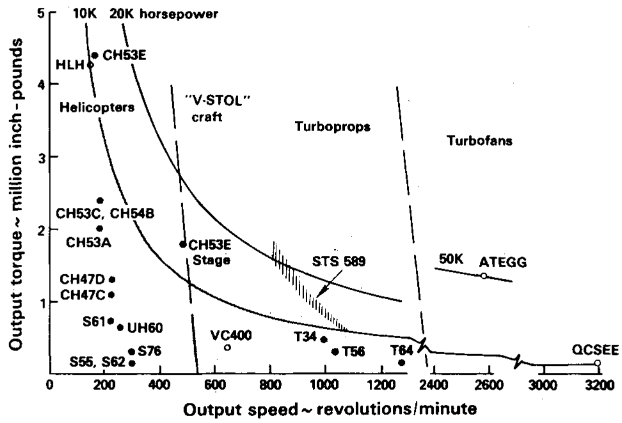

Fig. 10 Aircraft reduction gear experience (U.S.A.)

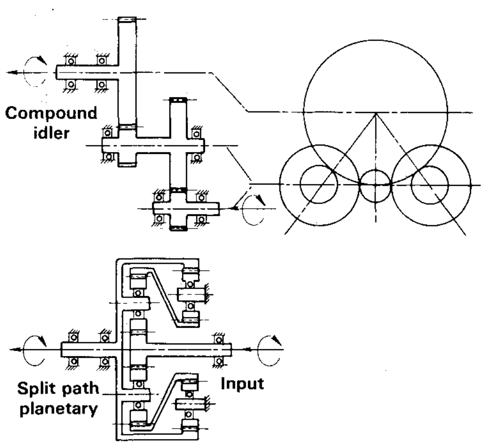

Fig. 11 Reduction gear concepts.

Technology

The engine studies have highlighted specific technology work at both the component level, where isolated effects must be evaluated, and the system level, where interactive effects must be evaluated. Technology verification for the reduction gear, the prop-fan/inlet/compression system, the turboprop power unit, and the overall power system is discussed in this section. Before discussing technology verification the engine development process is put in perspective; the aim is to reinforce the view that full systems technology verification will be required to increase confidence to proceed with final development.

Engine Development and Support Cycle

We begin by examining the typical development and support cycle required to bring a new engine into service. Figure 12 shows the relative cost of the three phases in this process: technology verification, final development, and engineering support after the engine enters service.

Before development commitment, new component and system technologies for the engine must be verified. This is a very critical phase because understanding and resolution of component and systems concerns ensures that technical problems encountered during the development will be manageable.

The costs of developing an engine are many times greater than the costs incurred before development go-ahead. The development process requires a large-scale commitment of capital and manpower for at least 4 yr in order to complete the design, engine testing, flight testing, and FAA certification tests. Thus, the engine manufacturer must be satisfied that the new venture represents an acceptable risk before development is initiated.

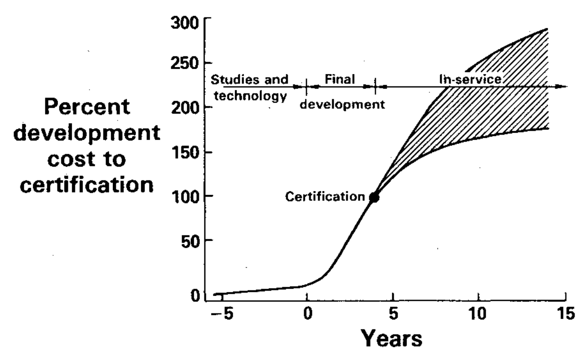

Fig. 12 Typical technology development service cycle.

Table 2 Power system technology requirements

	Component or model test	Power system ground test	Remaining areas
Prop-fan aero/acoustics and structural integrity	8-ft diameter	No	15-ft diameter
Reduction gear structural integrity and efficiency	Yes	Yes	—
Prop-fan/inlet aerodynamics	Yes	Yes—sea level	Altitude
Compressor/inlet performance and stability prop-fan/compressor	Yes	Yes—sea level	Altitude
Engine (approximately 0.5 flow scale turbofan high spool)	Yes	Yes	Cruise performance
Heat rejection system	—	Yes	—
Secondary power system	—	Yes	—
High spool and high-speed low spool performance and transient characteristics	—	Yes—sea level	Altitude
Prop-fan/reduction gear/pitch mechanism structural integrity and control	—	Yes	—
Power system operation, stability and control	—	Yes—sea level	Altitude

Reduction Gear

Since there is no experience with turboprop reduction gears in the 15 000 hp class a technology base must be established Current design methods and technology must be applied to bearings and seals gears materials, structures, and lubrication in order to design a reduction gearbox which provides reliability, efficiency low cost and light weight The capability of this design to meet commercial performance and service goals then must be verified by full scale rig tests

Once a base has been established, the benefits of improvements in technology can be identified and quantified by design studies The most cost effective ideas then must be addressed in suitable component level technology programs Major areas of interest are bearings and seals with increased life high D_N bearings gears with increased strength and tooth contact higher strength housing materials with adequate stiffness and improved lubrication systems with low churning losses

Prop Fan/Inlet/Compression System

The high flight speed and unique prop fan configuration create an all new turboprop engine inlet environment Consequently current design methodology must be extended in order to produce an efficient installation First the inlet conditions behind the prop fan must be defined Model tests of candidate prop fan/inlet nacelle configurations must be conducted Existing analytical design methods must be modified to include transonic flow and axisymmetric shapes in order to ensure a successful integrated inlet design Using this data the inlet can be designed to capture expected transonic flow from the prop fan which has a swirl component and channel this flow to an annular compressor entrance without high distortion and with maximum pressure recovery Second analytical procedures must be developed to shape the inlet in a manner which delivers air to the compressor efficiently If the reduction gear is an offset configuration, air entering the compressor must be channeled around the engine shaft efficiently Finally conditions during thrust reverse operation are unknown; these conditions may constitute a fundamental integration consideration

The compressor system must be capable of stable operation over a wide range of airflow rates with good distortion attenuation and high aerodynamic performance It is expected that distortion at the compressor face will be greater than distortion encountered in turbofan installations

Finally, full scale compressor/inlet tests using an inlet configuration and distortion level obtained from model tests, must be conducted to verify the design of the inlet/compression system

Turboprop Power Unit

Within limits the well established turbofan core engine compressor and turbine technology base is directly applicable to the turboprop by scaling However the energy efficient engine airflow size must be scaled down by a factor of about 0 5 too large a change to make without affecting component efficiency cooling effectiveness and combustion parameters Of particular concern are rotor tip clearance clearance to span ratio turbine blade cooling trailing edge thickness and burner mixing effectiveness cooling and pattern factor

Power System

The various power system technology issues as viewed by the engine manufacturer are listed in Table 2 As noted in the table, component model and power system ground tests can address all areas of concern within the capability of a static environment The reduction gear heat rejection secondary power and prop fan/reduction gear/pitch mechanism system could be completely verified In addition sea level verification of prop fan/inlet/compression and engine systems would reduce industry risk to an acceptable level The engine manufacturer would still have to bear the considerable risk associated with the ability to project sea level performance and operational characteristics to altitude

Concluding Remarks

Prop fan propulsion can play a significant role in reducing fuel consumption in short/medium range commercial and military air transports in the early 1990's The study engine STS 589 provides the aircraft designer with realistic advanced turboprop engine data on which to base aircraft propulsion integration studies for applications requiring from 9 000 to over 15,000 hp Assuming timely technology verification a new turboprop engine could start service as early as 1990 The cost of missing the early 1990's with a new prop fan powered transport can be measured in billions of gallons of jet fuel in this century in short/medium range commercial operations alone

Acknowledgments

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