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MODERN TURBOPROP ENGINES

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Abstract—The turboprop engine has played a major role in short haul commuter aircraft and military transport and patrol aircraft where speed is not critical. In recent years NASA have proposed the application of turboprops, coupled to advanced propellers usually referred to as 'propfans', at conventional turbofan speeds. The achievement of this goal would provide significant savings in fuel without sacrifice of flight speed. The paper reviews the past history and current state of development of modern turboprops, noting that there has been very little recent development of high power units. Current trends suggest a shift from the NASA goal away from turboprops to a new breed of engine using the generic name Ultra High Bypass systems. Although the future of the turboprop for high speed transportation may appear dubious, there is no doubt that the turboprop is going to continue to play an increasingly important role in the short haul commuter aircraft market.

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1. INTRODUCTION

For many years the turboprop has filled a very important, but relatively inconspicuous, role in aircraft propulsion. In recent years, because of increasing concerns about fuel availability and costs, a great deal of attention has been focussed on advanced turboprops for use at higher speeds than were possible in the past. NASA have done a great deal of work on advanced propellers, generally referred to as propfans, for use at a flight Mach number of 0.8, the ultimate goal being to achieve the fuel economy of the turboprop at the cruise speed of the turbofan. The first flight tests of propfans are scheduled to take place in 1987, and there are still many problems to be solved with regard to structural integrity, aeroelasticity, acoustics and transmission design. One major manufacturer, General Electric, has proposed the elimination of the transmission and the use of a direct drive turbine, resulting in the concept of the UnDucted Fan (UDF); other manufacturers challenge this idea and are convinced that a reduction gearbox is essential. At the time of writing, the final outcome of the application of propfans at $M=0.8$ is not clear. What is clear, however, is that conventional turboprops are opening up new and significant markets in short haul, commuter operations following in the wake of airline deregulation in the U.S. The business aircraft market, although currently depressed, has spawned several revolutionary new designs which will use turboprops up to $M=0.6$, which is comparable to the highest commercial turboprop speeds achieved in the West.

This paper will concentrate on the design and development of modern turboprop engines, without reference to current developments in propellers which are widely reported on in the open literature.

2. THE ROLE OF THE TURBOPROP

It is a well known fact that propeller efficiency falls off dramatically at high flight speeds due to compressibility effects at the blade tips. In the past this effectively limited flight speeds to Mach 0.6, and for higher flight speeds the pure jet engine was initially used. The propulsive efficiency was substantially lower than that of the turboprop, leading to a decrease of passenger miles per gallon which was compensated for by the increased productivity due to the increased flight speed and the improved passenger appeal. As gas turbine technology improved, the turbofan superseded the pure jet and demonstrated both an improved propulsive efficiency and a significant decrease in noise compared with the jet. Typical variations of propulsive efficiency with speed are shown in Fig. 1, which also shows the projected efficiencies of propfans at turbofan cruise speeds. The productivity of early gas turbine aircraft is shown in Fig. 2, from Ref. (1), which shows the initial decrease

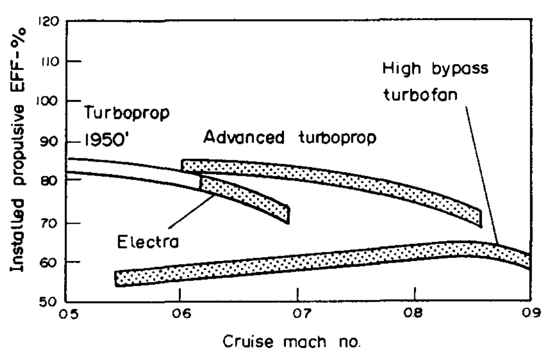


FIG 1. Propulsive efficiency.

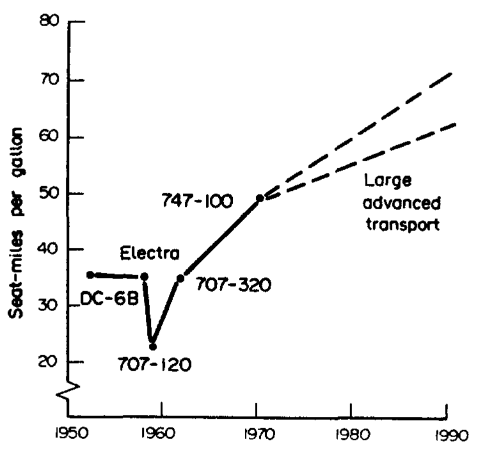


FIG. 2. Productivitiy improvement.

due to the introduction of jets which was then reversed by the advent of the turbofan and greatly improved with the introduction of the combination of the wide body aircraft with high bypass ratio turbofans.

The limitation on cruise speed resulted in turboprop penetration of the long haul market being minimal. At shorter ranges, however, and for military transport applications, lower cruise speeds are quite acceptable and the turboprop has been very widely used. In the case of business aircraft, the turboprop was so attractive compared to the piston engine that it opened up entirely new markets leading to very large sales of small turboprops in the range of 500–1000 SHP. The Viscount and the Fokker F-27 were the most successful airline applications, with the F-27 remaining in production for over 25 yr. In the military field the most successful applications have been the Lockheed C-130 Hercules and the P-3 Orion, both of which still remain in production; these aircraft represent the vast majority of operational experience with high power turboprops in the West. It should be noted, however, that a very significant amount of Russian experience has been accumulated with over 700 Il-18's and 900 AN12 built, both using 4–4000 SHP engines; the TU 95 (Bear) has remained in production in various versions for over 30 yr using 4–15,000 SHP engines and counter-rotating propellers.

3. HISTORICAL BACKGROUND

When considering the potential gains in fuel economy with turboprops, especially for high flight speeds, it is educational to look at previous experience which may provide historical lessons. Civil turboprop experience covers both long haul and short haul operations, while military experience is dominated by transport and long range patrol operations.

Turboprops were first introduced to airline service in April 1953, when the Vickers Viscount entered service with British European Airways, powered by four Rolls Royce Darts. The passenger appeal of the Viscount proved to be very high, because of its low noise and vibration levels relative to existing piston engined aircraft; this was particularly apparent on routes where BEA's competitors had long claimed the major portion of the traffic. As an example, between the summer of 1952 and 1954 BEA's share of the traffic from London–Copenhagen–Stockholm increased from 26.7 % to 46.2 %.[2] It is interesting to note from Ref. (2) that Viscounts were used on non-stop sectors as long as London–Rome and London–Lisbon. Air Canada (then Trans-Canada Airlines) was the first North American user of the Viscount, and operated one of the largest fleets of Viscounts anywhere in the world for many years; while primarily used on routes such as Toronto–New York and Toronto–Montreal, sectors as long as Toronto–Winnipeg (3 hr 50 min) were flown.

The Lockheed Electra, powered by four Allison 501 turboprops, entered service with Eastern Airlines in January 1959. The Electra had a much higher cruise speed than the Viscount, being capable of continuous cruise at Mach 0.6 with a range of over 2500 miles. It is interesting to recall that in the post-World War II piston engined airline market, the dominant manufacturers were Lockheed and Douglas with Boeing lying a distant third. Unfortunately for Lockheed the major U.S. airlines decided that the fuel economy of the turboprop could not compensate for the lack of passenger appeal when compared with the pure jet aircraft on offer. The Electra also suffered from critical aeroelastic problems associated with the nacelle-wing combination, resulting in several accidents. In its civil form the Electra was certainly not a success, and Lockheed dropped out of the civil transport market until they re-entered with the L-1011 in 1970 only to drop out of the civil field around 1980. The Electra, however, spawned the extremely successful P-3 Orion Anti Submarine Warfare (ASW) aircraft which achieved huge sales around the world and is still in production with the T56 turboprop, which was the military version of the Allison 501. Lockheed also achieved major success with the ubiquitous Hercules military transport, also using the T56. The Hercules has remained in production for over 30 yr and both

Hercules and Orions will remain in service well into the 21st century. It is particularly important to note that Hercules and Orion applications represent a very large proportion of Western experience with large turboprops.

There was a major controversy in the mid 1950's regarding the most appropriate propulsion systems for long haul, inter continental aircraft required to replace the existing piston engined aircraft such as the super Constellation and DC-7C. One school of thought favoured the turboprop because of its better fuel economy, and this led to the development of the Bristol Brittania powered by Bristol Proteus turboprops. The Brittania was large and comfortable for its day and was well known for its low noise; it was the only inter continental turboprop developed in the Western World. The Brittania's entry into service was disappointingly delayed partially due to icing problems with the reverse flow engines, and it had only a very short period of superiority before it was superseded by the faster and more productive pure jets. It is amusing to recall, however, that when the 707-120 first entered service and had to make technical stops at both Boston and Iceland, it was in fact faster to cross non-stop on the slower turboprop. The Brittania was used on routes as long as Vancouver–Tokyo (Canadian Pacific) and New York–Tel Aviv (El Al). The only other transatlantic turboprop to be used was the Russian TU-114, a civil counterpart of the Bear bomber. This was a truly remarkable aircraft, and it is unfortunate that so little is known of Aeroflot's commercial operations. The TU-114 was notable for its extremely high speed, extremely powerful engines and contra-rotating propellers. Jane's quoted the TU-114 as having a maximum speed of 590 mph ($M=0.88$) and a maximum cruising speed of 497 mph at 32,800 ft ($M=0.74$). If these seem hardly credible, a world record for carrying a 25,000 kg payload over a 5000 km circuit at a speed of 545 mph was established in April 1962. The power was supplied by four Kuznetsov NK-12 turboprops of approximately 12,000 ESHP, driving eight-bladed contra-rotating propellers of 18.3 ft diameter. Despite the remarkable performance, the TU-114 did not remain in service for very long before being superseded by jet aircraft such as the Il-62; there may well be a lesson to be learned from history.

Perhaps the most interesting of all the turboprops, however, was the Vickers Vanguard. The Vanguard was probably the first real attempt to design an 'airbus' type aircraft, with a capacity of 139 passengers, a maximum payload range capability of 1830 miles and a cruise speed of 425 mph at 20,000 ft ($M=0.61$). The Vanguard was powered by four Rolls Royce Tyne turboprops of about 5500 ESHP. A paper by Dyment of TCA[(3)] on the selection of the Vanguard makes very interesting reading in the light of current interest in fuel economy, as fuel burn was hardly even mentioned for a very fuel efficient aircraft. The sad fact remains that only BEA and Trans-Canada Airlines bought a total of about 40 Vanguards. The author always enjoyed flying in Vanguards and was of the opinion that a unique solution to the noise problem was achieved, with all the noise transferred to the passenger cabin! Despite its commercial failure, the Vanguard was a good workhorse with an excellent safety record, and it too provides a useful lesson in history.

Salient data for the faster turboprops are given in Table 1. Data extracted from Air Canada timetables (1961 and current) compare the scheduled times for Viscount, Vanguard and modern jets of sectors on varying lengths; even at a stage length of around 1000 miles the Vanguard was only 27 min slower than current schedules, as shown in Table 2.

The picture for long range, high speed turboprops is very discouraging; the only 'commercial' operator still using high power turboprops in large numbers is Aeroflot and

TABLE 1.

Aircraft	Max TOW (lb)	Power Plant (ESHP)	Max Cruise (mph/alt)	Range (miles)	Passengers
Britannia	185.000	4 Proteus × 4450	357/30,000	5300	139
Electra	116.000	4 Allison × 4050	405/22,000	2770	74–98
TU-114	396.800	4 NK12 × 12.000	497/32.800	6200	120–220
Vanguard	146.500	4 Tyne × 5500	425/20.000	3100	139

TABLE 2.

	Viscount	Vanguard	DC-9/727
Toronto–Winnipeg	3 hr 50 min	2 hr 55 min	2 hr 28 min
Toronto–Chicago	1 hr 55 min	1 hr 35 min	1 hr 28 min
Montreal–Toronto	1 hr 30 min	1 hr 15 min	1 hr 05 min

its various satellites. In the case of the short haul aircraft, however, the picture is very different. Notable successes have been achieved by the Fokker F-27, Viscount, HS-748* and YS-11, all powered by the Rolls Royce Dart. The F-27 and HS-748 both remained in production until 1986 and many are still in service. The F-27 is being replaced by a substantially upgraded derivative, the Fokker 50, maintaining much of the basic structure but using new engines and avionics. Similarly the HS-748 is being replaced by the B.Ac-ATP with an extended fuselage and new engines. In both cases the Dart has been superseded by a modern technology engine, the Pratt and Whitney Canada PW-124. In the commuter market a very large number of turboprops have been sold, including the DHC-6 Twin Otter, Short 330 and 360, Fairchild-Swearingen Merlin, Beech 99 and Embraer Bandeirante. The most widely used engine has been the P&WC PT6, followed by the Garrett 331. There is now a high degree of activity in the turboprop market for commuter aircraft in the 30–50 seat range; aircraft now in service or development include the Saab 340, DHC-Dash 8, ATR 42 and 72 and the CN-235. The two engine contenders for this market are the PW100 series and GE CT7, based on the highly successful T700 turboshaft.

Another major market for the turboprop has been business aircraft, with many examples by Beech, Cessna and Piper in service using the PT6 and Garrett 331. Despite the current depressed state of the business aircraft market, manufacturers such as Beech, Piaggio and Embraer are offering revolutionary designs such as the Starship and Avanti with rear mounted pusher installations. New designs offer significantly higher flight speeds, approaching those of small turbofans, with much better fuel economy; these are still based on conventional, but advanced, propeller designs. It should be recognized that flying hours in this market are quite low, perhaps about 20 percent of those in an airline operation. While fuel efficiency is obviously desirable, first cost is even more important leading to somewhat simpler designs than might appear from the thermodynamic optimum.

4. REVIEW OF POWER REQUIREMENTS

The NASA goal of using turboprops at conventional turbofan flight conditions requires a cruise speed of $M = 0.8$ at altitudes of 30,000 ft and above, and lead immediately to some major problems with regard to availability of suitable engines. Studies by many independent sources have all shown that the potential fuel gains of the propfan compared with an equivalent technology turbofan are of the order of 20–30 percent. While there are still many aerodynamic, acoustic, structural and installation problems to be overcome, the potential gains are so large that even if they are not fully realized, significant gains can still be expected. Figure 3 from Ref. (4) shows the gains predicted by several different studies over a range of stage lengths; perhaps the most significant feature is that at *lower* Mach numbers the advantage of the propfan is even more marked. Figure 4 shows the cruise power required at Mach numbers of 0.8 and 0.6 at an altitude of 30,000 ft, showing the effect of reduced propeller efficiency below the target value of 80 percent. It is clear that the risks of lower than expected propeller efficiency are much higher at Mach 0.8, and combined with the already high power required may result in a significant power increase, fuel demand and increase in structural weight. The very nature of the propfan means that

*Now B.Ac-748.

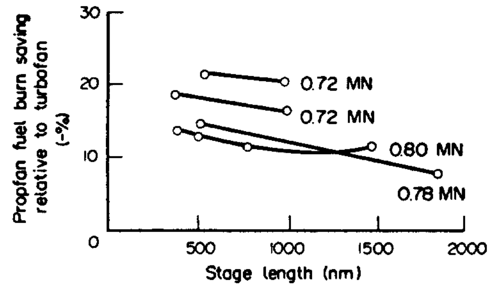


FIG. 3. Propfan savings.

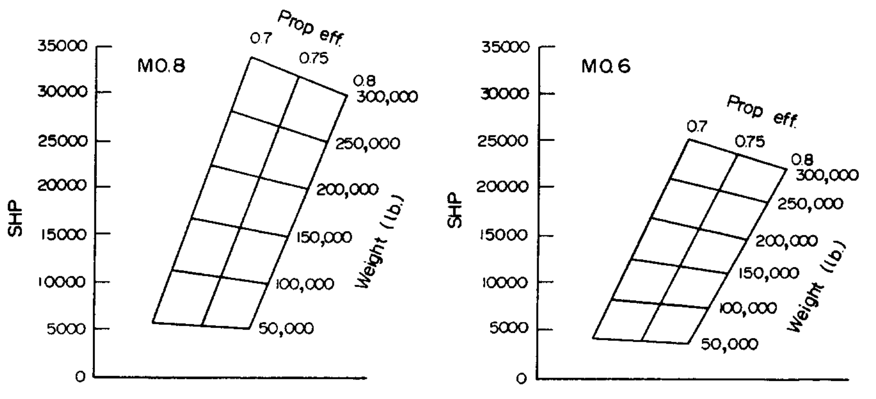


FIG. 4. Cruise power requirement.

the aircraft will use either two or four engines, and three engine installations appear to be impractical. With the current trend towards twin-engine aircraft, it appears likely that a twin-propfan aircraft would be desirable for most civil transport applications.

It is appropriate at this point to briefly consider the concept of *equivalent* shaft horsepower (ESHP) which used to be widely used in discussing turboprop performance, although it is less common today and some manufacturers quote only shaft horsepower. The designer of a turboprop has a prescribed enthalpy drop available from the combustor exit conditions and this is required firstly to drive the compressor, with the remainder available for useful output. The designer has some choice in how to divide this between shaft power and jet thrust; in practice this has led to most of the output appearing at the propeller with some residual (but by no means negligible) jet thrust. The *thrust* shaft horsepower (TSHP) can be expressed as

$$\text{TSHP} = (\text{SHP})\eta_{\text{PR}} + F\,C_a,$$

where η_{PR} is the propeller efficiency, F the jet thrust and C_a the aircraft speed. The thrust power is thus largely dependent on the propeller efficiency.

It is desirable to find some way of expressing power so that it is not so heavily dependent on propeller efficiency, as the engine may be used with a variety of different propellers and users are basically interested in the engine performance itself. This led to the concept of equivalent shaft horsepower, defined as

$$\text{ESHP} = \frac{\text{TSHP}}{\eta_{\text{PR}}} = \text{SHP} + \frac{F\,C_a}{\eta_{\text{PR}}},$$

where only the smaller term is affected by the propeller efficiency. The equivalent shaft horsepower is an arbitrarily defined quantity which should not be quoted without reference to the flight speed. Note that by definition the ESHP and SHP are equal at static conditions, although there is some beneficial jet thrust. To make allowance for this it has been the convention to assume that 1 SHP gives 2.5 lb_f thrust and values of ESHP at take-off conditions are given by $SHP+(F/2.5)$ where F is the jet thrust in lb_f. Most early engines quoted SHP, F and ESHP but modern engines seldom quote F. As a typical example of an engine with a relatively high jet thrust, the Rolls Royce Tyne RTy12 at take-off showed 5305 SHP, 1110 lb_f thrust and 5730 ESHP.

For detailed design it is clear that the aircraft manufacturer must know both the power available to the propeller and the jet thrust, particularly for higher speed applications. Most widely published information on engines tends to stress take-off performance, however, and some manufacturers now quote only shaft horsepower where others quote equivalent horsepower as well, but thrust is seldom quoted. In this paper either SHP or ESHP will be used, depending on what was presented in the source material. It should also be noted that virtually all data published by manufacturers is given in terms of British rather than SI units and British units will be quoted throughout this paper.

It is not always appreciated how large the power requirements are, especially when compared to the 6000 ESHP which is about the largest value in use. Goldsmith and Bowles[5] investigated the design of a propfan-powered version of a DC-9-80, and the power required per engine came to about 16,500 ESHP. A Boeing study by Davenport[6] for an $M=0.8$, 1800 mile range, 180 percent passenger aircraft resulted in a requirement of 31,000 ESHP per engine. This study, in fact, showed only about a 10 percent saving in fuel and the author concluded that the drag and weight uncertainties were great enough to have a decisive influence on the propfan's economic potential. Egglestone[7] studied the requirements for a propfan-powered STOL aircraft operating up to $M=0.7$; even for a twin-engined aircraft with a maximum TOW of 51,000 lb capable of carrying 50 passengers for 345 miles from 2000 ft strips, the take-off power was no less than 9500 SHP per engine.

Goldsmith and Bowles[5] pointed out that current aircraft such as the DC-9-80 (MD80) cruise substantially slower than $M=0.8$ and Fig. 5 shows the effects of Mach number on both fuel burn and range, showing clearly the greater advantage at reduced Mach number.

It seems probable that the propfan may best be aimed at relatively small (100–150 seat) transports with cruise speeds in the range of $M=0.7$, close to current operational speeds of B-737/DC-9. Aircraft of this class may require engine powers in the range of 10,000 ESHP, which represents a considerable increase in the power capability of turboprops but one which does not present huge risks. The power requirements for twin engine transports are shown in Fig. 6 from Ref. (8). The long endurance ASW mission represents a considerable market for advanced turboprops; an increase in cruise Mach number from 0.6 to 0.7 would permit faster transit times and more time on station. Even without propfans, using conventional propellers, a new version of the T56 currently under development could give an increase in time-on-station of 2.3 hr.[9]

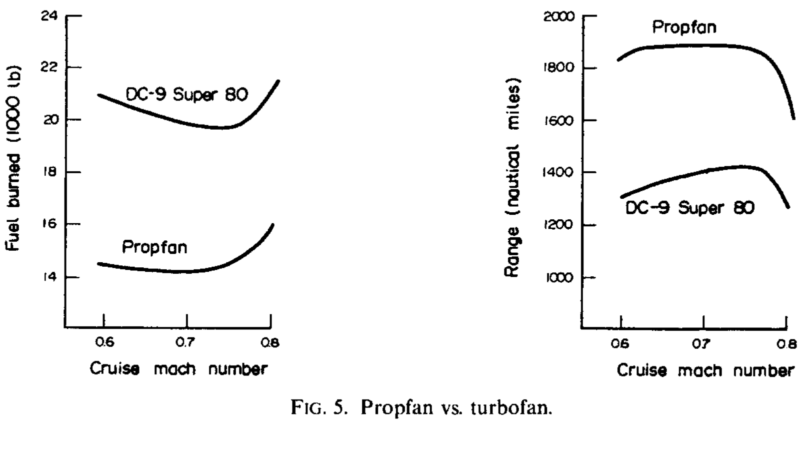


FIG. 5. Propfan vs. turbofan.

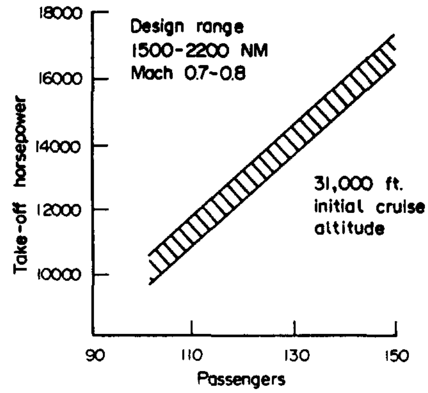


FIG. 6. Power requirements for twin-engine transports.

5. CYCLE CONSIDERATIONS

In the past 20 yr a high proportion of the aero engine industry's Research and Development expenditures have been devoted to large civil turbofans and high performance military turbofans. Examples include the continuous development of the RB211, CF6 and JT9D family of engines and the introduction of the F100, F404 and RB199 into service; there has been no similar infusion of funds or effort into any turboprop program. The PW100 appears to be the only totally new turboprop to have entered service in the last twenty years. The Allison T56 is the only high power turboprop that has been built in large numbers (around 14,000) and remains in production in the West. There was virtually no performance development done on this engine from 1968 on, because the US Congress directed industry to restrict Component Improvement Program (CIP) to reliability and maintenance improvements and consequently all performance related improvements for engines in the military inventory were halted.[10] It is against this background that the development of advanced turboprops must be considered.

Realizing that the turboprop was never developed to the same level of aerodynamic sophistication as the turbofan it should be apparent that current turboprop cycles are quite modest in terms of both pressure ratio and maximum cycle temperature. Considerable gains could readily be achieved using current technology.

It must be remembered, however, that propfans and turboprops operate at extremely high bypass ratios, say from 30 to 50, and it immediately follows that for a given cruise thrust the gas generator flow will be much smaller than would be required for the equivalent turbofan. While new turbofans such as the V2500 use pressure ratios of around 36, these would be very difficult to achieve in a propfan gas generator because of the very small size of the rear stages if axial compressors were used. This could be overcome by the use of a centrifugal compressor at the high pressure end, a method widely used in small turboprops and turboshafts. The relatively small high pressure turbine blades could not use the same sophisticated cooling techniques currently in use in large turbofans, so it would be necessary to operate at somewhat lower maximum cycle temperature.

Quite apart from the reduction in cycle parameters due to the effects of size, the designer is also faced with aerodynamic penalties due to relatively large clearances, relatively thick compressor leading edges and turbine trailing edges and the use of lower aspect ratios because of blade strength considerations resulting in increased secondary flow losses. Thus, in performing detailed cycle calculations it is very important to make appropriate allowances for the penalties resulting from small size.

These effects were clearly illustrated by Morris[11] describing the evolution of the design of the PW100. Figure 7 from Ref. (11) shows that if size effects are ignored the optimum cycle conditions for low specific fuel consumption would be a pressure ratio in excess of 30 and a turbine inlet temperature of 2600°F (1700 K). If the engine were sized for a cruise

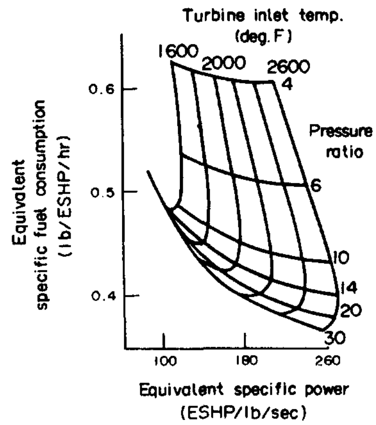


FIG. 7. Engine performance; size effect ignored.

power of 1300 ESHP at 25,000 ft and 350 mph, however, an optimum pressure ratio of 20 at 2600°F is shown (Fig. 8), with a pressure ratio of 30 showing a considerable degradation of both specific fuel consumption and specific power. In fact, at a pressure ratio of 15 and a turbine inlet temperature of 2000°F (1365 K) there is a negligible penalty on sfc and this was chosen as the design point for the PW100. Brooks and Hirschkron[12] of GE reviewed advanced turboprops for commuter aircraft in the 30 and 50 passenger size class and arrived at values of 17 and 2300°F (1535 K) for the smaller aircraft and 20 and 2400°F (1590 K) for the larger aircraft. Hirschkron and Davis[13] of GE, under contract to Lockheed, carried out a study of advanced turboprops for long endurance ASW aircraft and proposed a pressure ratio of 22 and a turbine inlet temperature of 2400°F (1590 K), presumably for an engine in the 5–6000 SHP class suitable as a T56 replacement. Banach and Reynolds[8] of PW investigated gas generators for an $M = 0.8$, 120 passenger twin with 12,000 SHP engines, where size effects would be much less critical, and suggested values of 30 and 2240°F (1500 K). The studies referred to were carried out by different design teams from Pratt and Whitney Canada, GE and Pratt and Whitney and the results obtained are quite consistent; it should be noted that the pressure ratios are significantly lower than those of large turbofans. It appears that GE are rather more aggressive with regard to turbine inlet temperature; a balance has to be struck between performance, durability and manufacturing cost.

It is clear that there is no inherent difficulty in producing a fully acceptable gas generator. In view of the very high development costs of a totally new engine program, it is worth considering whether an existing core may provide a suitable gas generator. Both the CF6 and RB211 cores have been used with notable success as generators for industrial and

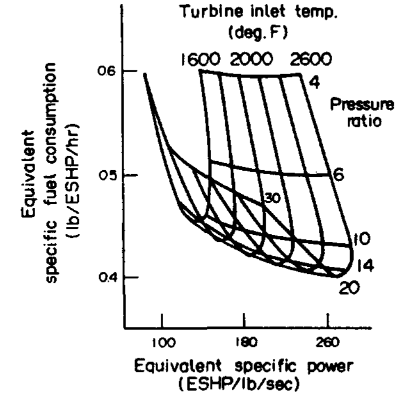


FIG. 8. Engine performance; size effect included.

marine engines in the 25–30,000 SHP class, but this power level would be too high for a propfan of much higher bypass ratio. Banach and Reynolds[8] considered the possibility of using the HP compressors from the F100 and PW2037 programs, but found the resulting sfc to be 11.8 and 5.2 percent worse than for the optimized turboprop. The core of the V2500 has a pressure ratio of 20 on a single spool and this could provide an attractive gas generator for a turboprop of around 12–14,000 SHP.

Another alternative which should be considered is the use of more complex cycles involving heat exchange and intercooling, and these ideas have been examined at regular intervals during the last thirty years. The Bristol Theseus, built before the Proteus, was the first turboprop to use a heat exchanger, but it never went into service. The heat exchanger, although offering gains in fuel economy, leads to a heavier and bulkier installation. The US Navy investigated the use of a regenerative cycle engine based on the T56, the T78, as far back as 1964, intended for long endurance patrol aircraft;[14] the heat exchanger was built by Garrett and fitted quite neatly in the rear of the nacelle.[15] This engine was successfully tested, showing over 35 percent improvement in sfc at the design condition[14] but did not go into service. More recently GE, under contract to Lockheed, re-examined cycles for a similar long endurance mission.[13] It was concluded yet again that a simple cycle turboprop of advanced design (22, 1590 K) was superior to both a regenerative turboprop (13, 1590 K) and a regenerative/intercooled turboprop (22, 1590 K). Using the conventional turboprop as a base, the mission engine and fuel weight was 9.5 percent higher for the regenerative cycle and 18.7 percent higher for the regenerative/intercooled cycle, combined with an increase in nacelle drag. It seems clear that if these more complex cycles cannot show a gain on this long duration mission they are unlikely to be competitive for higher speed commercial transports.

6. CURRENT TURBOPROPS

It is important to examine the design of turboprops which have achieved widespread use, to see whether previous experience can provide the design concept for a new development program. As mentioned earlier, the PW100 is the only all new design to emerge in many years and the T56 is the only high power unit still in production. One particularly notable feature of the turboprop scene is the widespread use of the centrifugal compressor, the only all axial turboprops still in production being the T56 and the T64 (GE). The development of larger and more efficient jet and turbofan engines required axial flow compressors to provide the large flow per unit frontal area for high speed flight and also very high overall pressure ratios. Thus, for many years the centrifugal compressor was ignored by large sectors of the industry. The designers of small turboprops and turboshafts were forced to develop centrifugal compressors to achieve reasonable pressure ratios at small flows and the centrifugal machine has been developed to a remarkable degree. Small turbofans also gained from this development and centrifugals are now used in engines up to 6000 lb_f thrust for business aircraft.

Design aspects of six turboprops will be reviewed. The Rolls Royce Dart and Allison T56 represent engines which were the earliest into service, with the T56 still being developed after a hiatus of nearly 10 yr. The Pratt and Whitney Canada PT6 and the Garrett 331 are representative of engines which created a new market and have undergone continuous development for over 20 yr. The Pratt and Whitney Canada PW100 and the GE CT7 are the newest engines in service.

6.1. Rolls Royce Dart

The Dart was the first successful turboprop and remained in production for over 30 yr, the last production engine being delivered for the last Fokker F-27 in the summer of 1986. It is perhaps worth mentioning that the design of the Dart started in 1945 and the first

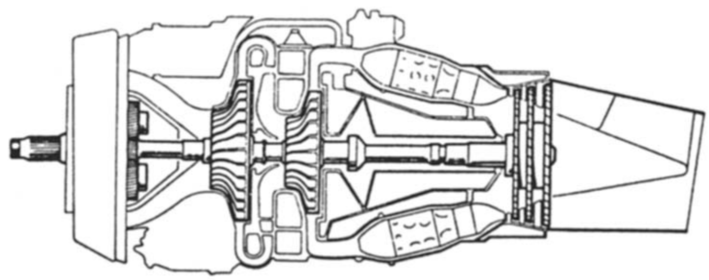


FIG. 9. Rolls Royce Dart.

type test was completed in December 1948 with entry into service with the Viscount in April 1953. This, it should be noted, was long before the introduction of computers and the entire design would have been done using slide rules and mechanical desk calculators; and this engine will undoubtedly remain in service until the end of the century!

The general arrangement of the Dart is shown in Fig. 9, remaining unchanged throughout with the exception of a change from a two stage to three stage turbine early in the development. The two stage centrifugal compressor was an extension of Rolls Royce experience on two stage superchargers for the Merlin piston engine, and proved highly successful and rugged. During its development the Dart grew from 1,400 SHP (1540 ESHP) in the early Viscount to 2970 SHP (3245 ESHP) in the HS Andover military transport, with the sfc at 345 mph/20,000 ft reduced from 0.645 to 0.556 lb/EHP hr. A modification kit using a modern centrifugal compressor, using the lastest aerodynamic design techniques, and other detail improvements can be fitted at overhaul offering substantial performance improvements at low cost and risk. Thus a very old but reliable design can be updated to considerably extend its useful life.

6.2. Allison T56

The T56 was designed originally for military transport applications, with a commercial derivative known as the Allison 501. With a power level of around 3500 SHP an all-axial single-shaft configuration was selected, this basic configuration being retained to this day. The principal impact was in the military role, powering the C-130 Hercules, the P-3 Orion, the E-2 Hawkeye and C-2 Greyhound; in the civilian field the only new aircraft application was the Electra, but a considerable number of Convair 340/440 were converted from piston engines and they were also used for the conversion of the Boeing Stratocruiser to the Super Guppy. The general layout of the T56 is shown in Fig. 10. A new and significant feature of the T56 was the use of a remotely mounted gearbox, one of the first successful uses of the modular concept so widely used today. This approach was used

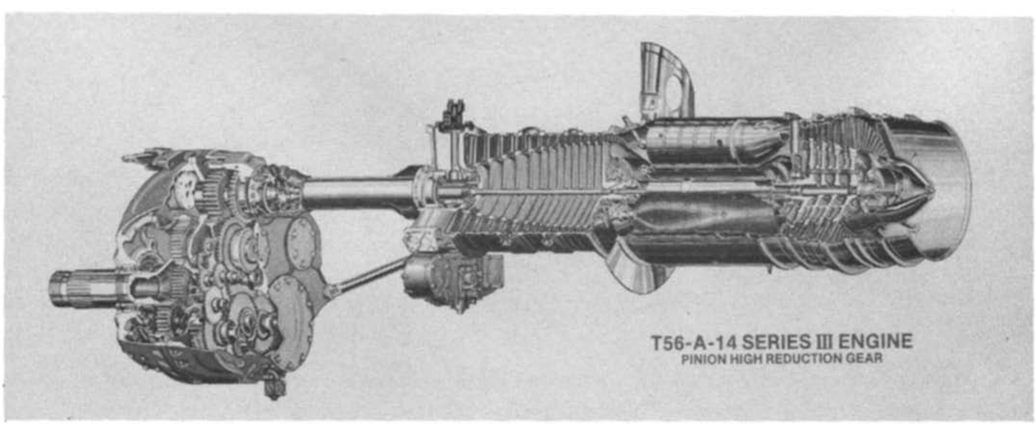


FIG. 10. Allison T56.

TABLE 3. ALLISON T56 (ISA/SLS)

	1954	1958	1964	1986
Series	I	II	III	IV
SHP	3460	3755	4591	5912

primarily for installation flexibility, with provision to mount the gearbox offset up or down. The configuration shown (pinion up, gearbox down) is used in the P-3, with the engine mounted above the wing and the propeller centre line in line with the wing; the opposite arrangement is used on the Hercules.

Table 3 from Refs (16, 10) shows the performance growth of the T56, with no performance development after 1968. This means that there is nearly 20 yr worth of technology improvements that can be implemented. The requirement for the E-2C aircraft was 4600 SHP at 103°F, and the Series IV T56 is thermodynamically capable of 5912 SHP at 59°F requiring torque limiting to a maximum of 5250 SHP. At maximum continuous cruise (25,000 ft, $M = 0.5$) the power is increased from 2560 to 3180 SHP with a reduction in sfc from 0.486 to 0.420 lb/HP hr.

It is interesting to note that although T56 development stagnated for over a decade, a two-shaft version of significantly higher power (over 8000 SHP) was developed for the U.S. Army Heavy Lift Helicopter, which was abandoned. This, however, led to industrial and marine versions known as the Allison 570 and 571 with substantially higher power than the aircraft engine. These developments proved fruitful for Allison when the 501-M80C, based on the 570 development program, was selected to power the V-22 Osprey tilt wing aircraft. The Allison engine was chosen over the PW and GE contenders for the Modern Technology Demonstrator Engine (MTDE) program because it offered less technical risk and was available with less development cost. The MTDE engines, offering an improved level of performance, may eventually be available for re-engining the P-3/C-130 fleet but this is far from certain. The 501-M78 two-shaft engine is being used for flight test development of the Hamilton Standard Propfan, using a Gulfstream II test bed aircraft.[17]

6.3. Pratt and Whitney Canada PT6

The PT6 started its development in the late 1950's and has been the most widely sold of all turboprops. The design and early development of the PT6 is discussed in Refs (18–20) and a cross section of one version is shown in Fig. 11. The use of a free turbine in such a

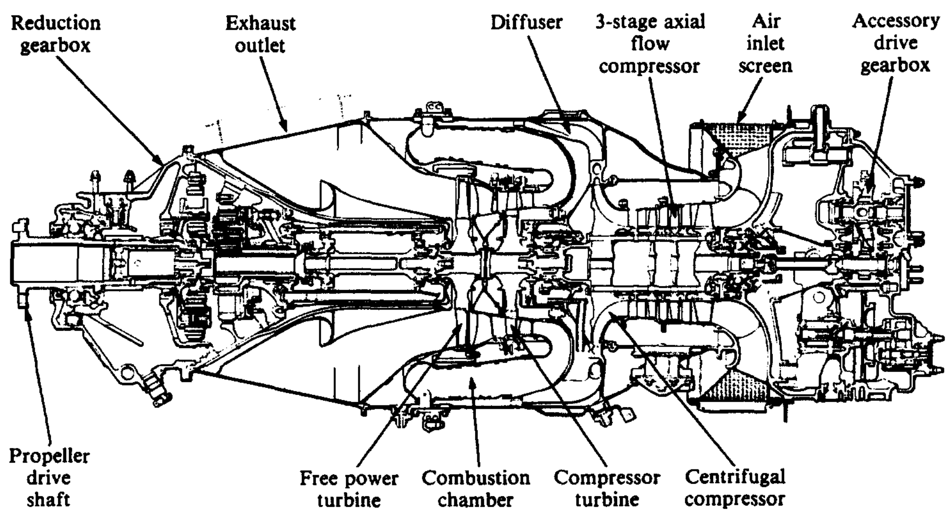


FIG. 11. Pratt and Whitney Canada PT6.

small engine led to considerable difficulty in using the common arrangement of concentric shafts, resulting in the choice of the unconventional but highly successful reverse flow arrangement selected. At the time the PT6 was designed there was no market for small turboprops, but it was felt that if a small turboprop superior to existing engines could be delivered it would create a new market.[21] This proved to be the case and a wide variety of business aircraft such as the Beech King Air family were sold in large numbers.

The PT6 design used a three stage axial compressor followed by a single stage centrifugal compressor, driven by a single stage turbine, with a single stage power turbine (Fig. 11). The 'pipe' diffuser was a very successful innovation, offering both high performance and low manufacturing cost.[22] Since its introduction to the market at 600 ESHP the engine has been continually developed to provide ratings up to 1700 ESHP; this highest rating is restricted in service by gearbox limitations, but is evidence of the power growth. The larger versions (over 750 SHP) use a two stage power turbine, and the latest series use an additional axial compressor stage. Power growth is primarily due to aerodynamic development giving higher mass flows and pressure ratios, with only modest increases in turbine temperature; because of the small size of the first stage rotor blades they have remained uncooled, although the first stage stators are cooled on many models. The growth in power led to applications in commuter aircraft such as the Short 330/360, Embraer Bandeirante, DHC-6 Twin Otter, DHC Dash 7, and Beech 1900. Parallel development led to lower cost versions for use in markets where first cost was critical, such as agricultural aircraft.

The power capabilities of the various PT6 versions are shown in Fig. 12, while the improvements in specific fuel consumption and specific weight are shown in Fig. 13; particular attention should be paid to the A50. This version was designed specifically for the Dash 7, with very low speed propellers resulting in high torque loads and a large reduction gearbox. The A45 and A50 engines are essentially identical other than the gearbox, and it is immediately apparent that a large penalty is paid for low noise. The steady improvement in power and sfc is shown in Fig. 14.

The PT6 layout offers great flexibility in the design of nacelle installations, and can readily be used for either tractor or pusher applications. Radical new aircraft designs such as the Beech Starship and Piaggio Avanti use the PT6 in the pusher configuration. The PT6 is an excellent example of how a good basic design can be continually developed over a 20 yr period, opening up several new markets.

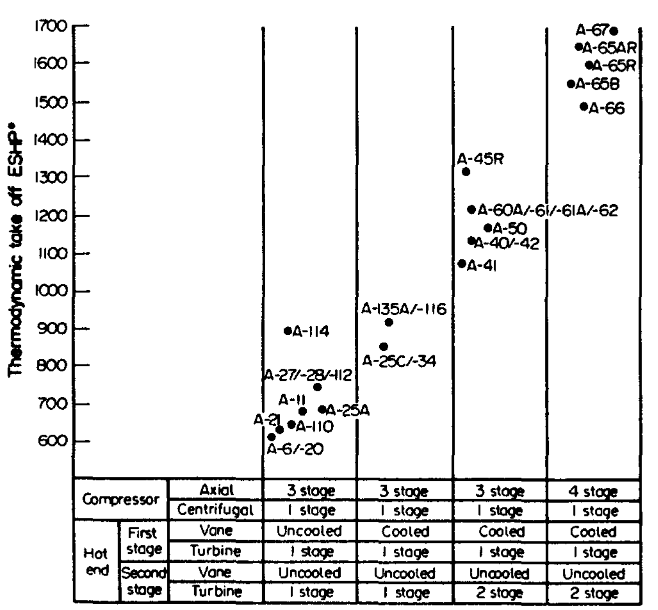


FIG. 12. PT6 power capability.

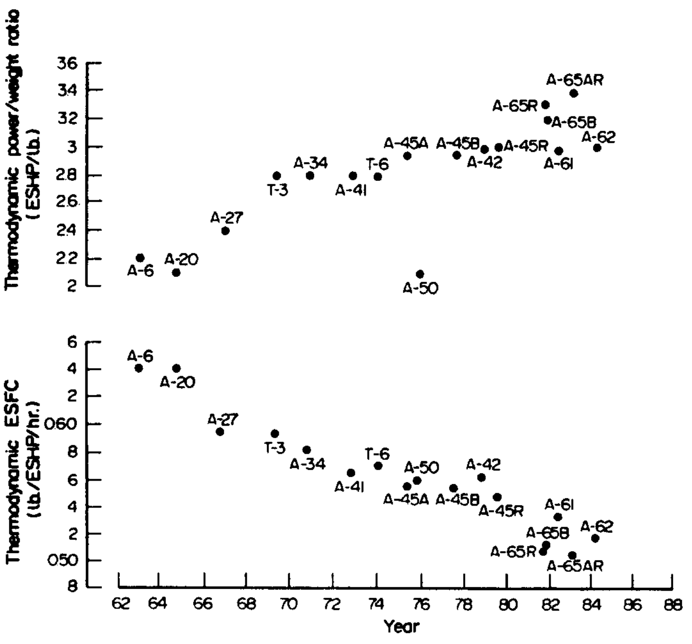


FIG. 13. PT6 product improvement.

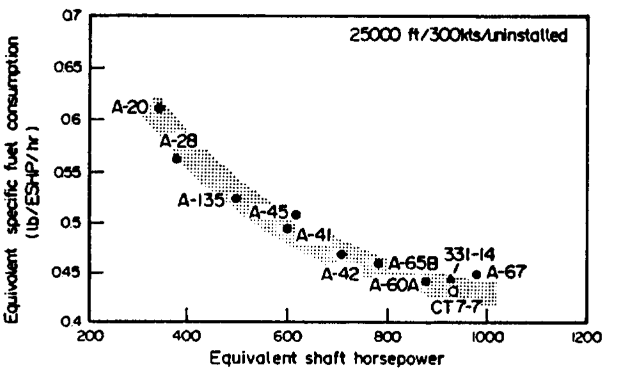
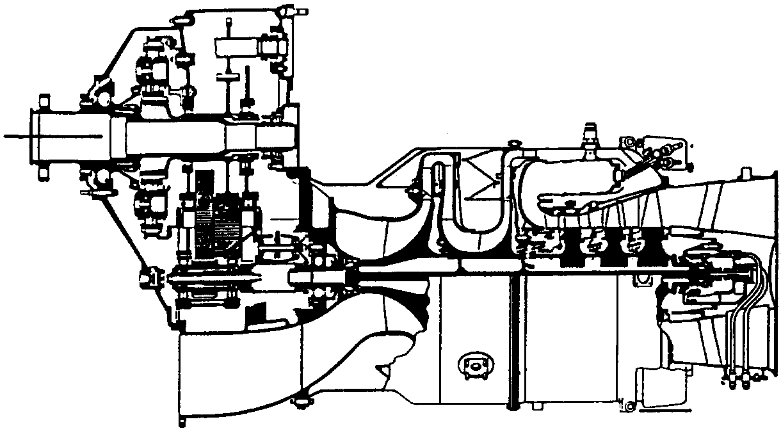


FIG. 14. PT6 cruise performance improvement.

6.4. GARRETT 331

The Garrett 331 is a direct competitor of the PT6, covering a power range from 575–1645 SHP at ISA conditions (SLS). This engine was first certified in 1965 and its first application was in the North American OV-10A Bronco Counter Insurgency (COIN) aircraft. The configuration of the 331 is shown in Fig. 15, having remained unchanged throughout the development cycle. A two stage centrifugal compressor is driven by a three stage axial turbine, using a single-shaft arrangement. The gearbox is offset and can be mounted either up or down depending on the aircraft application, giving a clean air intake with high ram recovery. The growth in power and improvement in sfc with time is shown in Table 4. Note that for several models the ISA shaft horsepower is greater than the gearbox power limit; this means that the engine can produce the limiting power of the gearbox in very hot temperatures. The -14, for example, can maintain the gearbox limit of 1250 SHP up to an ambient temperature of 109°F. A choice of propeller speeds is available, the most common speeds being 2000 and 1591 rpm, with a speed for 1390 rpm also available for the -15 which has both a thermodynamic rating and a gearbox limit of 1645 SHP.



TPE331-14 TURBOPROP ENGINE

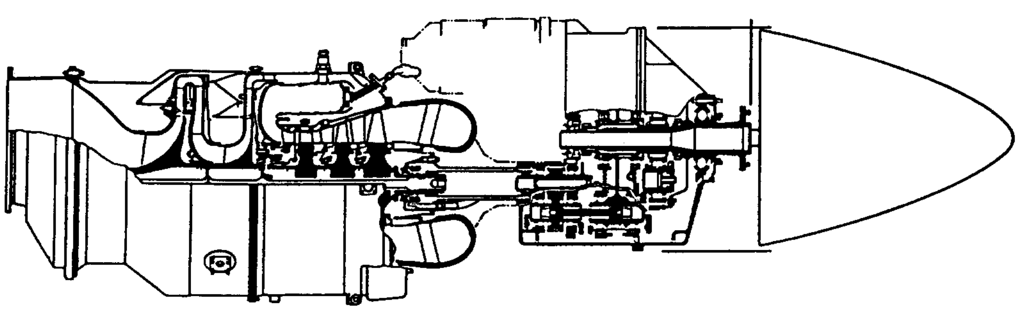
FIG. 15. Garrett 331.

TABLE 4. GARRETT 331 (ISA/SLS).

Model	Pre Century	−1 Century	−3	−10	−14
Year certified	1965	1967	1970	1978	1984
SHP (thermo)	575	715	840	1000	1645
Gearbox SHP Limit	575	665	840	900	1250
sfc (lb/HP hr)	0.665	0.633	0.590	0.558	0.515
Airflow (lb/s)	5.8	6.2	7.7	7.6	11.4
Pressure ratio	8.2	8.5	10.4	10.6	10.8

To date the 331 has been used in tractor installations only, but the engine is also suitable for pusher installations. The 331-14RD is on offer for rear drive applications, as shown in Fig. 16; in this case the reduction gearbox is driven from the rear end of the engine and a bifurcated exhaust is used. Note that there is much less offset to the propeller shaft, to keep the total frontal area down for higher flight speeds.

The 331 has been used in a variety of business aircraft such as the Mitsubishi MU-2 and commuter aircraft such as the Swearingen Merlin, BAC Jetstream and Dornier Do 229. The 331 also shows the continuous development of a good basic design over two decades.



TPE 331-14RD TURBOPROP ENGINE

FIG. 16. Garrett 331-RD proposal.

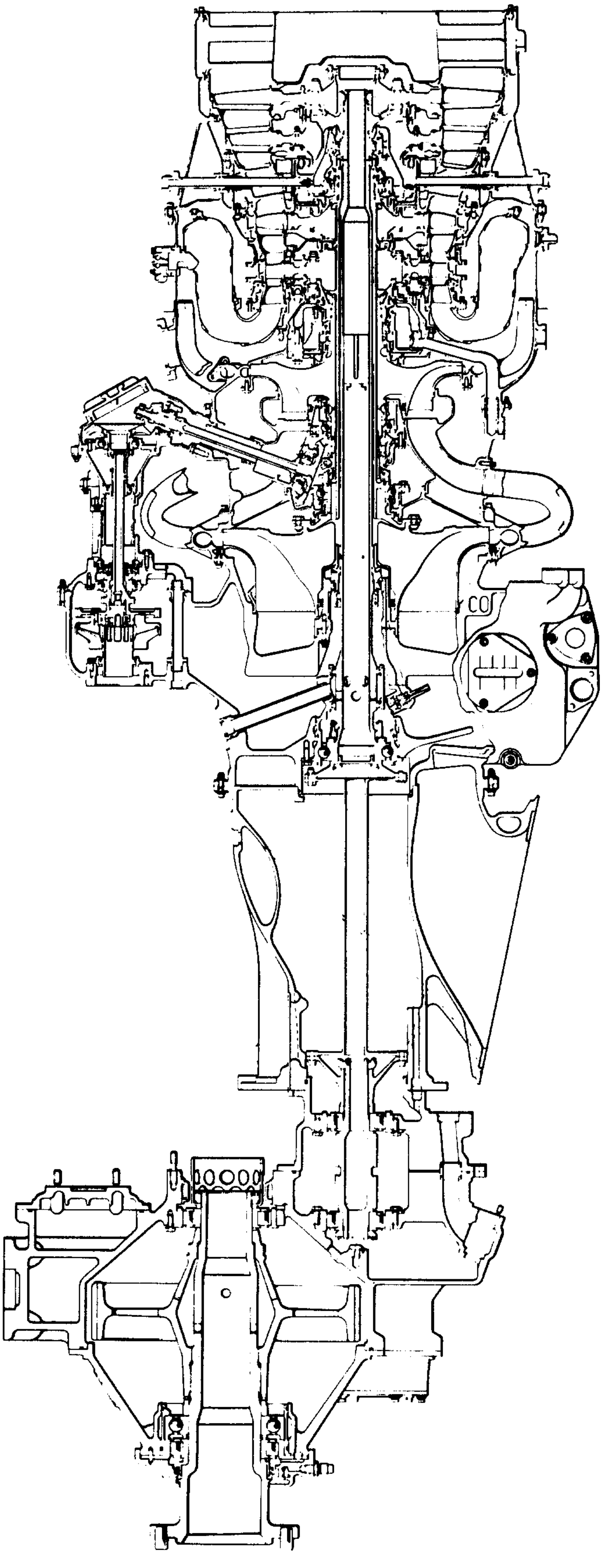


FIG. 17. Pratt and Whitney Canada PW100.

6.5. Pratt and Whitney Canada PW100

The design and development of the PW100 is described by Morris[11] and Cook.[23] With the advent of airline deregulation in the U.S. a market for 30–50 seat commuter airlines opened up, filling a gap between aircraft such as the Beech 99 and Twin Otter (up to 19 seats) and the F-27/HS748 (40–50 seats). It appeared that these aircraft would require the ability to operate at 350 mph and 20,000 ft, resulting in a cruise power of 1300 ESHP. This requirement resulted in a totally new engine design, with a twin-spool gas generator and a free power turbine. Two centrifugal compressors are used, each driven by a single stage turbine with a two stage power turbine driving a remote mounted gearbox at the front (Fig. 17). The reverse flow arrangement of the PT6, although highly successful, was not considered to be optimal for the higher flight speeds where ram recovery is more important. The twin-spool centrifugal compressor arrangement is unique and provides a pressure ratio of around 15 without the need for variable geometry. The design was chosen to provide adequate power growth and rapidly spawned three different versions, the PW115, 120 and 124 (nominally 1500, 2000 and 2400 SHP using the PW numbering system). The PW115 was selected for the Embraer 120 Brasilia, the PW120 for the DHC-Dash 8 and ATR-42 and the PW124 for the B.Ac-ATP, Fokker 50 and ATR-72. The PW115 and 120 are now in service, starting in late 1984, and the aircraft using the 124 are not yet in service. In the B.Ac-ATP advanced 6-bladed propellers are used; the free power turbine permits propeller speeds of 1200 rpm for take-off and 1020 rpm for cruise, giving high efficiency at both conditions and low cabin noise at cruise.

6.6. General Electric CT7

General Electric also perceived the needs of the rapidly expanding commuter market, but based their contender on a highly successful T700 turboshaft, which had achieved a dominant position in the military helicopter market. The design of the CT7 is discussed by Stewart in Ref. (24). The CT7 uses a combined axial-centrifugal compressor, with variable geometry stators on several stages, driven by a two stage gas generator turbine with a free power turbine, also with two stages as shown in Fig. 18. The gearbox is remote and offset up. The CT7 can be used to provide the requirements normally met by an APU, by running with the propeller (and hence power turbine) locked, as described by Stewart.[25] (This feature can also be provided by the PW100.) The CT7 has been selected for the SAAB 340 and the CN-235, the latter not yet being in service. Performance data from Ref. (12) is given in Table 5; uprated versions are not yet in service. The CT7 operates at higher turbine inlet temperatures than other engines in its class, probably reflecting

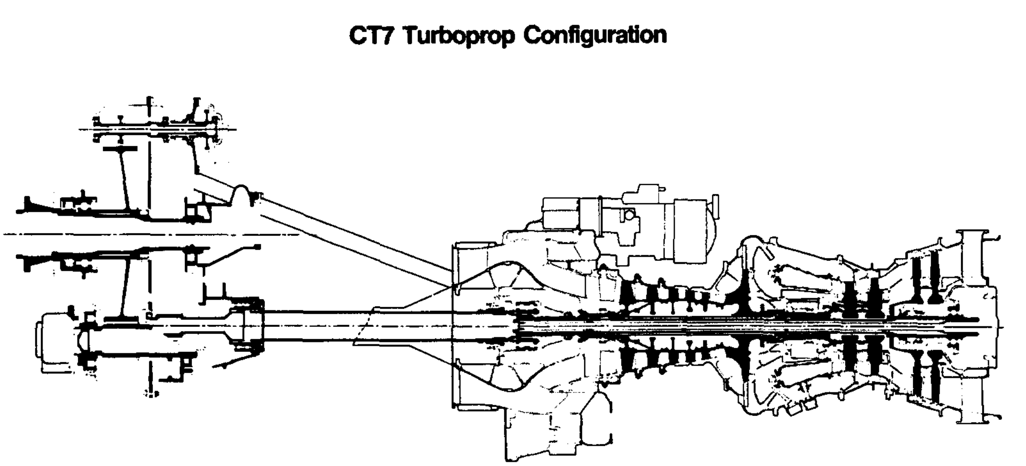


Fig. 18. General Electric CT7.

TABLE 5. GENERAL ELECTRIC CT7 (ISA SLS)

	CT7-5a	CT7-7
ESHP, Take-off	1699	1756
sfc (lb/EHP hr)	0.456	0.455

fallout from its military origins. Proposals have been made[12] for a considerable uprating by introducing an extra compressor stage forward of the front frame, driven by the power turbine; these do not appear to have progressed beyond the study phase and uprating will continue in the conventional manner by improving cycle conditions.

Having reviewed the status of the more successful turboprops it becomes clear that the only high power turboprop available is the T56, which is more than thirty years old; even at its Series IV rating of 5912 SHP it is too small for aircraft to meet the original NASA goals. The 501-M78 being used for the propfan assessment program shows a considerable power increase but is still not adequate. An engine to meet the NASA goals would therefore have to be an entirely new development or a spin-off from some other program such as the V2500.

7. CANDIDATE CONFIGURATIONS

At the period when the earlier large turboprops were designed, pressure ratios available on a single-spool compressor were limited to about 10, and the Tyne achieved the highest pressure ratio in service of 14 using a twin-spool compressor with no variable geometry. Modern developments in compressor aerodynamics using multiple rows of variable stators, pioneered by GE on the J79, permit much higher pressure ratios on a single spool. The LM2500 industrial derivative of the CF6 demonstrated a pressure ratio in excess of 16, and the inner core of the V2500 is capable of a pressure ratio of 20 in 10 stages. These advances in compressor design give the engine designer much more flexibility than in the past, and an advanced turboprop with a pressure ratio of 15–25 could be laid out in four basic configurations as shown in Fig. 19.

7.1. FIXED TURBINE

This approach has been very widely used on the T56, 331, Dart and Astazou and also on virtually all Russian turboprops. The fixed shaft engine is essentially intended for fixed speed operation, but some minor change in rotational speed for fuel economy is possible; a lower speed may also be used for ground idle and taxiing. As an example, the latest development of the T56 (Series IV) can increase rotational speed by 3 percent to improve hot day take-off performance;[26] the operating characteristics of the single shaft unit permit this speed increase without an increase in turbine inlet temperature. For low altitude loiter in the ASW role, at 500 ft and 210 knots, the rotational speed can be reduced 5 percent to save fuel. The mechanical design is simplified, but at very high

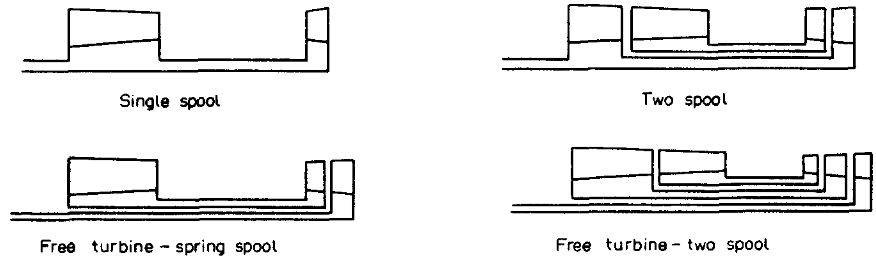


FIG. 19. Candidate configurations.

pressure ratios efficiency penalties may result from the restriction that the propeller and compressor speeds are coupled. This configuration provides excellent transient response on approach because the compressor need not be accelerated to increase power.

7.2. Free Turbine, Single-Spool Compressor

This configuration is also very widely used on the PT6, T700 and T64 and was pioneered on the Proteus. The use of a free turbine opens up the market to both turboprop and turboshaft versions, which is important in widening the sales base. It should be noted, however, that the requirements for aircraft flying at 20–30,000 ft and a helicopter operating at low altitudes are so widely different that history shows engines have tended to be much more successful in their primary role. Power setting is controlled by fuel flow to the gas generator and the propeller speed can be set independently of the compressor speed. This has the important advantage of allowing variation of propeller rpm with flight speed, which is attractive both from fuel economy and internal noise points of view. Reduction in power requires reduced compressor speed, so that compressor must be accelerated to restore power; this has not proved to be a problem in practice, and is dependent on the compressor surge margin and the flight idle speed.

7.3. Twin-Spool Compressor, Propeller Driven by LP Turbine

The Tyne is the only turboprop to have entered service in this configuration, but this approach has been proposed by both P&W[27] and GE[28] for advanced turboprops. The LP compressor is coupled to the propeller, and it would almost certainly be necessary to incorporate variable stators to accommodate variable propeller speeds. This compressor arrangement would suffer less penalty from propeller speed restrictions than the single-shaft engine, as only part of the compression system is affected.

7.4. Twin-Spool Compressor with Free Turbine

At the present time the PW100 is the only turboprop using this configuration, although it is also used in the Gem turboshaft and a variety of industrial derivatives of aero engines. In many ways this seems the ideal situation regarding design and operational flexibility, as compressor and propeller speeds are completely independent and variable geometry (other than blow-off at low power) may be dispensed with. The mechanical design, however, becomes more complex with the introduction of three shafts rather than two. It is worth noting that the Tyne has been produced as a marine engine with a free turbine and rear drive; this configuration would be ideally suited to a pusher type arrangement. The PW contender for the Modern Technology Demonstrator Engine (MTDE) program used this arrangement, as both turboprop and turboshaft applications were considered.

It is not possible to make categorical statements regarding the best arrangement, and this would clearly depend on the past experience of the design team and the power rating. It does appear, however, that all four configurations are quite viable; as the pressure ratio increases the twin-spool compressor becomes more likely.

8. TRANSMISSION CONSIDERATIONS

The development of suitable high power transmissions is a major requirement for the introduction of the propfan into airline service. In the early days of turboprop development for high power, the gearbox was a critical item which could prove to be an Achilles heel. There are surprisingly few engineers, including gearbox specialists, aware of the loss of the second prototype Britannia due to gearbox failure.[29] The effect of the gearbox failure was to separate the free power turbine from its driven load, allowing a catastrophic overspeed, destruction of the turbine and an uncontrollable fire; it was fortunate that the pilot was able to make an emergency landing on the mud flats of the Severn River. The aircraft was a total loss but the engine was saved for post mortem investigation. It is possible now to design free turbines so that in the event of an overspeed the blades will fail before the disc, and the blades can be retained within the engine casing. The episode of the Britannia, however, is a cautionary tale which should be remembered.

The T56 and Tyne represent the highest power turboprops built in the western world, and by far the most experience has been gained on the more than 14,000 T56 engines which have accumulated over 100 million flight hours. Experience with these high power gearboxes has been good, but considerably higher powers will be required in the future. These successful gearboxes were designed more than twenty years ago, and there have been major advances in stress analysis and design technology which will have a major impact on the design of new gearboxes. From the airline point of view it is clear that the propeller/gearbox combination should not present any significantly different maintenance cost or problem compared with the fan and thrust reverser on conventional turbofans. Studies(14) have shown that this goal can be achieved, but there is no doubt that there will be airline scepticism until this has actually been demonstrated. It is worth noting that a high proportion of gearbox removals are due to problems with accessories rather than the main gear train, which is generally extremely reliable. The design of gearboxes for small turboprops is discussed in Ref. (30), outlining current 3D Finite Element methods for examining both complex surface to surface interactions and the loading experienced between dynamically active teeth meshing at high speed. This paper compares the design of the in-line epicyclic gearboxes used in the PT6 family with the offset gearboxes used in the PW100 family and concludes that the weight characteristics are similar.

The design of the gearbox will be heavily dependent on whether single rotation or counter-rotating propellers are used. There seems to be general agreement that counter-rotation gives significant gains in propulsion efficiency, by reducing the swirl leaving the rotor system. The use of counter-rotation is said to ease the gearbox design; with the exception of the input driving gear, the power input is split between the two output trains. A comparison of proposed arrangements for a counter-rotating propfan and the Rolls Royce Tyne are compared in Fig. 20 from Ref. (31). A 12,000 SHP gearbox of this type would require 6000 SHP per train, which is equivalent to the power of a Tyne. Allison(32) have tested a 12,000 SHP gearbox driven by a pair of T56 gearboxes. They suggest that at high powers the specific weight of the gearbox may increase from about 0.1 lb/HP for the T56 to about 0.15 lb/HP at 30,000 SHP. The next generation of gearboxes will be designed to achieve a life in regular operation of 25,000 hr or more.

Another interesting possibility comes from history, the concept of torque limiting at

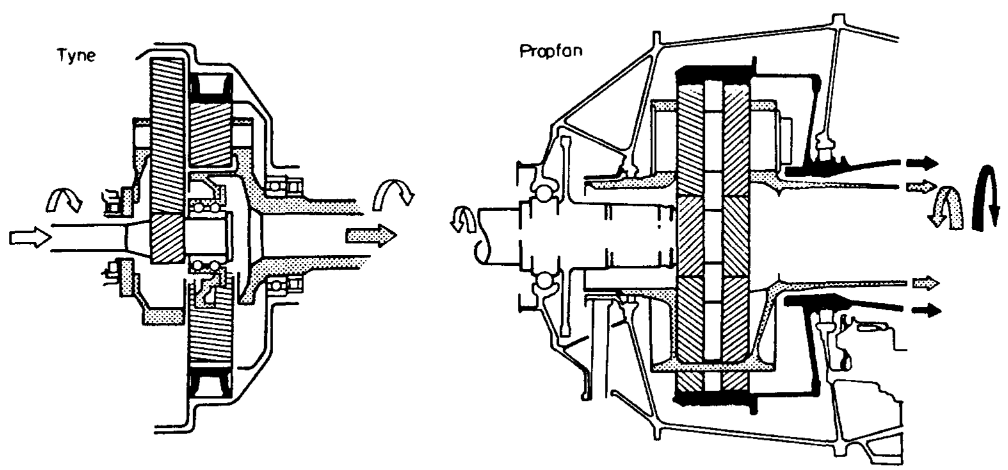


Fig. 20. Gearbox arrangements.

take-off conditions, with the power limited to the maximum cruise rating at altitude. As the aircraft climbs the throttle is opened to maintain constant power. This was proposed as far back as 1956 on the Bristol Orion, designed for later versions of the Brittania; with a cruising power of 3500 ESHP at 30,000 ft the power available at SLS was 8000 ESHP.[33] The Orion was torque limited to maintain constant power with altitude, a notable feature being the ability to offer the SLS/ISA rating for all airfield elevations and temperatures. Financial restrictions in the mid 1950's resulted in the U.K. Government only supporting the development of one large turboprop, and the Orion was dropped in favour of the Tyne. There is no doubt that this approach would be valuable today in tackling the problem of excessive gearbox powers.

The layout of the gearbox also has a major impact on the design of the air intake and the nacelle installation. All British turboprop designs (Dart, Proteus, Tyne etc.) used an in-line epicyclic gearbox as shown in Fig. 9. This arrangement has a number of disadvantages, including restricted flexibility of installation; in addition, at smaller sizes the hydraulic diameter becomes small and the resulting narrow annular duct would produce a thick boundary layer which could affect the compressor performance. The use of the offset gearbox has been favoured by most North American manufacturers, with the notable exception of the PT6. Morris,[11] in discussing the gearbox arrangement for the PW100, points out that even though the offset inlet duct is unsymmetrical, it has a better cross section than a narrow annular duct. It also has greater potential for avoiding Foreign Object Damage (FOD) by inertial separation. This point of view would appear to be shared by Allison, Garrett and GE (see Figs 10, 15, 17 and 18). According to Morris the offset gearbox gives much better freedom in location of accessories, improving maintenance. While the offset gearbox may now appear favourable for conventional turboprops, the in-line epicyclic gear train is clearly more favourable for counter-rotating propfans.

As power requirements increase, especially if twin-engined aircraft are favoured, the transmission problem becomes so severe that consideration must be given to alternative configurations which can dispense with a reduction gearbox, leading to unconventional arrangements which are becoming known as Ultra High Bypass (UHB) engines.

9. ULTRA HIGH BYPASS CONCEPTS

The turboprop, of course, is the ultimate high bypass engine with extremely high bypass ratio and very low 'fan' pressure ratio, i.e. across the propeller. The problems associated with very high power gearboxes and concern with possible noise problems in the passenger cabin made designers consider other concepts to raise the bypass ratio beyond that achievable with conventional turbofans.

GE were the first to move away from the propfan concept with the revolutionary UnDucted Fan (UDF).[34] This arrangement dispenses with the gearbox and uses a gas generator providing power to a pair of counter-rotating turbines each driving a variable pitch unducted fan; the machinery arrangement is shown in Fig. 21. The turbines have no stators. Some industry observers believe that the turbine and fan speeds cannot be made compatible without the use of a gearbox, but GE appear confident of the design. During early testing a number of problems arose, including a turbine blade failure and the loss of a fan blade at full power. These problems were overcome and flight testing on a modified Boeing 727 started in mid 1986. As a result of the test program, it appears that different numbers of blades will be used on the front and rear fans and they will also have slightly different diameters to avoid interference of tip vortices. McDonnell Douglas plan to fly this engine on an MD80 in 1987 and Boeing studies for the so called 7J7 plan on using a production version of the UDF. The UDF is basically suitable for rear mounting, with the fans behind the passenger cabin, for aircraft up to about 150 seats. The concept of the UDF is very bold and the aircraft industry is keenly awaiting the results of trials. At this stage GE have not committed to production, but are designing a high performance gas

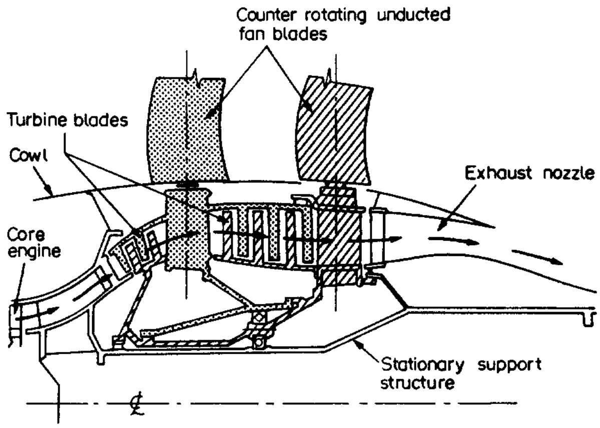


FIG. 21. UDF machinery arrangement.

generator for the UDF; for proof of concept a standard F404 was used as the gas generator.

International Aero Engines (IAE) have proposed a UHB concept using the V2500 core, with a geared variable pitch fan of bypass ratio of around 20:1 in a conventional duct.[35] Their proposal is called Super Fan and their studies indicated that it would be able to operate at higher flight speeds and longer ranges than the UnDucted Fan. Fan concepts investigated included single rotation, fixed and variable pitch and variable pitch counter-rotation; all used a gearbox. Initial results suggest the use of a geared, variable pitch, single rotation fan. The development cost was estimated to be 60 percent less than the cost of a completely new development program.

Rolls Royce announced several proposals for UHB systems at the 1986 Farnborough show; very little technical detail was available at the time of writing. The RB509 is an unducted, counter-rotating aft propfan in the same thrust range as the GE UDF; both geared and ungeared versions are being considered, although earlier Rolls Royce statements[36] suggested the geared configuration would be superior. Another possibility is the variable pitch fan referred to by IAE. Perhaps the most interesting concept goes by the name of Contrafan; this uses a ducted, ungeared, counter-rotating aft fan system suitable for under wing mounting. This concept is claimed to be capable of thrusts up to 65,000 lb for use in a new generation 747.[37] Pratt and Whitney are also considering a concept known as the Advanced Ducted Propeller, which uses a front drive and is also suitable for underwing mounting.[37] It appears that unducted systems are considered unsuitable for under wing mounting because of certification problems with blade containment, and these are likely to be restricted to rear locations.

Pratt and Rolls feel that flight speed cannot be compromised for long haul aircraft and consider a duct essential for flight at $M=0.85$; the duct allows diffusion of the free stream before entry to the fan, reducing critical Mach numbers as well as providing containment. The duct, of course, adds weight and drag.

It can be seen that there are a variety of UHB concepts under consideration, but none have got beyond the drawing board with the exception of the UDF which has been successfully flight tested. The financial risk in all these concepts is high and it will be several more years before the outcome is shown.

10. CONCLUSIONS

In the relatively short period since NASA redirected attention to the possibility of using turboprops at turbofan speeds, a considerable change in technical direction has become apparent. The NASA effort was driven by fuel costs, but the bottom line to the aircraft operator is Direct Operating Cost (DOC). With the current stability of fuel prices (which is almost certainly not going to last for long) there has been less pressure to get the ultimate fuel efficiency, especially if the first cost of doing so is too high. This period has given both airframe and engine manufacturers some time to consider further options.

The trend now seems to be in favour of ultra high bypass propulsors, which may be ducted or unducted, for civil transport applications. The high speed turboprop may find applications in military transports or patrol aircraft, where cruise speed would be lower than the NASA goal of $M=0.8$. It is remarkable that the revolutionary GE concept of the UDF, starting several years later than propfan projects, achieved flight testing before any propfan took to the air and this engine type may play an important role for medium range aircraft. Significantly modified turbofans of greatly increased bypass ratio may yet prove to be superior for flight speeds of $M=0.85$ for long haul transportation.

It is quite clear, however, that the conventional turboprop will continue to play a major role in the commuter market and considerable technological advances are taking place. Revolutionary new designs of business aircraft are also based on advanced turboprops operating with conventional propellers at speeds up to $M=0.6$.

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