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POTENTIAL APPLICATION OF ADVANCED PROPULSION SYSTEMS TO CIVIL AIRCRAFT

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ABSTRACT

This paper identifies powerplant options for the 1990's and relates them to Airliner categories. The influence of safety, efficiency, economy and noise is discussed in relation to obtaining the most suitable powerplant for a given application. The Advanced Feederliner is used as an example to examine effects of the introduction of open rotors on aircraft efficiency and economics.

1. INTRODUCTION

Evolution has been a major factor in the development of airframes and of powerplants. Wing design has progressed from the early empiracal sections to todays fully optimised aft-loaded supercritical sections. Civil turbine engines have progressed from turbojets through low by-pass ratio turbofans to the current high by-pass ratio turbofans. Propellers have advanced from fixed pitch to variable pitch and are now evolving from unswept single-rotation to counter-rotation Propfans. All these evolutionary processes have been beneficial in increasing aircraft efficiency, but the task of integrating the powerplant with the airframe has become more and more complex.

The last few years have seen a proliferation of proposals for aircraft propulsion systems which must be evaluated against aircraft requirements in order to arrive at the right choice of airframe/powerplant configuration. The choices made during the latter part of this decade will be crucial to the way in which civil transports evolve for service extending well into the next century.

In view of the vast finanical investment required for any new major aircraft development, aircraft companies tend to build upon what they know rather than innovate. Aircraft configurations develop along similar lines. The rear-engine jet installation of the Caravelle was the forerunner for the BAe 111, DC9 and Fokker F28/F100. The Trident engine configuration set the style for the Boeing 727. In more recent years, wing mounted turbofans have dominated the civil market. There is remarkable similarity between the configurations of the Boeing 757 and 767 and the A300, A310, A320 and A330 Family and further configurational similarity between the A340 and the Boeing 747. Only Douglas and Fokker have stayed with the rear-engined configuration. New developments in the propulsion scene may lead to reassessment of aircraft configurations in the 1990's. Even so, the majority of commercial aircraft in service at the end of the century will have wing-mounted engines.

The major factors influencing aircraft development are safety, efficiency, economy and noise. Safety must be paramount and, like community noise, is covered by legislation. Within these constraints aircraft designers have the task of integrating aircraft and propulsion systems to create efficient, economic and competitive aircraft.

2. POWERPLANT OPTIONS

Figure 1 shows schematically the categories of advanced powerplants that are under development for service in the 1990's. "Open rotor" is a generic term to cover all non-contained rotors whether they are advanced propellers, swept Propfans or unducted fans.

For a given standard of core engine technology, the geared counter-rotation open rotor provides the most efficient means of propulsion.

The component parts of the geared open rotor-the core engine, gearbox and propeller assembly can be configured to provide a pusher or a

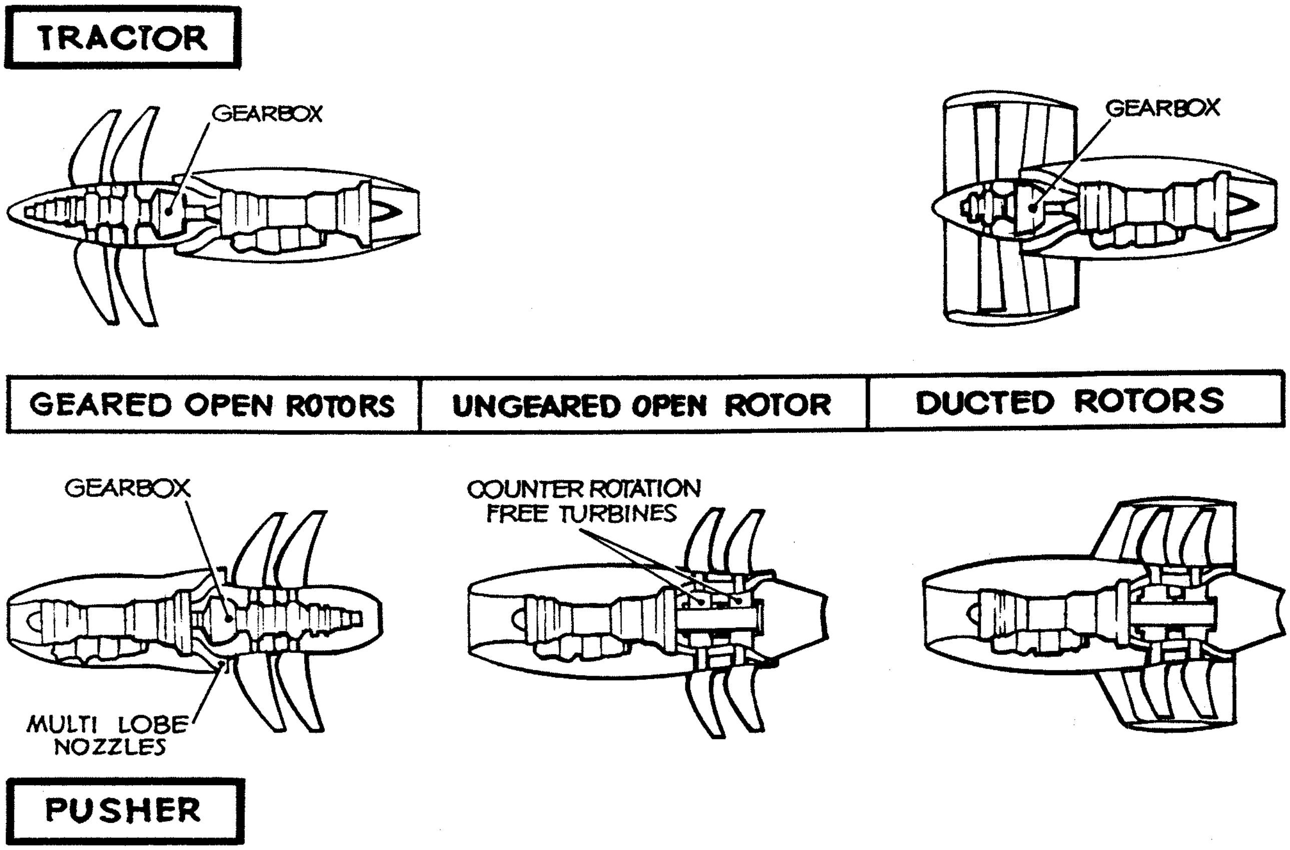


FIGURE 1. Advanced Powerplant Categories

tractor installation. In the pusher configuration the gearbox lies inside the engine exhaust system and in most configurations the exhaust is discharged across the blade roots. Multilobe exhausts alleviate both these problems to some extent. A tractor installation avoids these problems but requires a longer overhang on a wing installation.

The <u>ungeared</u> open rotor or unducted fan (UDF) has the advantage of eliminating the gearbox, but looses some efficiency because rotor rpm has to match turbine rpm. Rotor rpm is limited for noise reasons, so that turbine rpm becomes sub-optimum. Some of this lost efficiency is retrieved through the counter rotation of the turbines. The ungeared open rotor concept is based on a free turbine arrangement which leads naturally to a pusher configuration.

Engine manufacturers are now studying advanced propulsion systems with ultra-high by-pass (UHBR) ratio ducted fans. The presence of the large diameter duct results in a weight and drag penalty which at low speeds is offset by a thrust increase due to the duct. The powerplant can be configured as a pusher installation with a free turbine system similar to that of the ungeared open rotor or with a geared front fan.

3. SAFETY

Doubts have been expressed with regard to the safety of highly loaded open rotors operating at high cruising speeds.

The safety record of modern propeller blades has been good. Dowty Rotol propellers have not experienced any loss of propeller blades or debris due to the propeller design, manufacture or material faults during 420 million blade flight hours. Hamilton Standard propellers have not experienced any in-flight blade separations during more than 350 million blade flight hours.

Modern propellers are designed with metal or carbon fibre spars with a composite blade in the form of a sheath. With this kind of construction, detachment is generally limited to the blade sheath which weighs only a few pounds. During an early run on the test bed, the prototype UDF engine shed a blade sheath without damage to any other blade and without any failure of the unit or mounting due to out-of-balance forces. Service experience has shown that foreign objects cause only a shredding of blade materials.

The most severe trajectories of propeller debris release can be predicted and qualitative assessments of likely damage to the aeroplane predicted. By positioning of powerplants, provision of structural redundancy and careful layout of control systems, the effects of such damage may be alleviated such that the risk of catastrophic failure is reduced to an acceptable level.

Ultra-high by-pass ratio ducted rotors can be designed for rotor containment if tip speeds are limited to open rotor values.

4. INFLUENCE OF NOISE

The main parameters determining propeller source noise are power loading and helical tip speed, both of which increase as flight speed increases (see figure 2). Using a typical current turboprop Feederliner as datum, a Mach 0.7 advanced Feederliner would require a doubling of power loading, whereas a Mach 0.8 Airliner would require power loadings to be increased by a factor of 4 or 5. Limiting propeller tip speeds to around 650 ft/sec enables helical tip speed of the advanced Feederliner to be kept subsonic whereas the Mach 0.8 Airliner would produce helical tip Mach Nos of 1.1 to 1.15. This shows that the task of designing a Mach 0.7 aircraft with wing-mounted open rotors is significantly easier than for a Mach 0.8 Airliner where cabin noise requirements may preclude the location of open rotors on the wing.

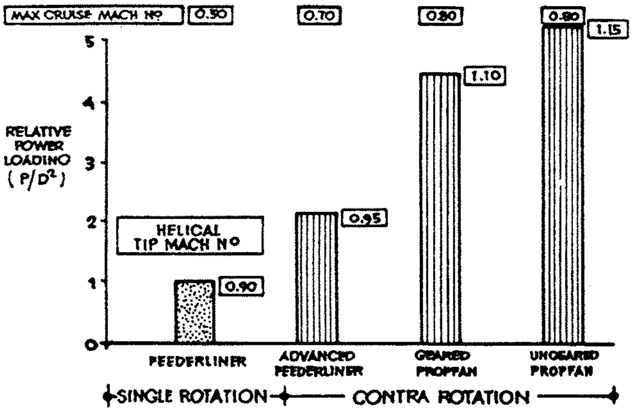


FIGURE 2. Propeller Power Loading

British Aerospace are involved in a comprehensive acoustic research programme, including flight research, to investigate cabin noise and to demonstrate means of providing an acceptable cabin environment for Mach 0.7 airliners with wing-mounted open rotors.

Placing a duct around the rotor to provide source noise containment would enable wing-mounted powerplants to be used on aircraft operating at Mach Nos of 0.8 or higher.

5. AIRFRAME/POWERPLANT MATCHING

Table 1 divides Airliners into categories and identifies the most suitable advanced powerplant configurations for next new generation of developed aircraft.

Small Feederliners with operating speeds up to Mach 0.5 have traditionally been propelled by open rotors and this trend is continued with aircraft such as the BAe ATP, the Fokker F50 and the Aerospatiale ATR 42. These aircraft have relatively low blade loadings and slipstream swirl is not a major problem, consequently the additional complexity of counter-rotation is not justified. Blade sweep is not required at these operating speeds.

Larger, faster Feederliners/Regional Airliners currently typified by the turbofan powered BAe 146 may lead in the 1990's to family developments powered by open rotors or ultra-high by-pass ratio (UHBR) ducted fans. At these speeds counter-rotation begins to show significant benefits in terms of propeller efficiency and lower interference losses due to the virtual elimination of slipstream swirl. Gearboxes become more compact lighter and more efficient with reduced cooling requirements. However blade pitch control systems become more complex.

Short/Medium haul Airliners and high capacity medium haul airliners with cruise Mach Nos up to 0.8 require either open rotor powerplants with swept counter-rotation Propfans or advanced turbofans such as the ultra-high by-pass ratio ducted fan. Cabin noise considerations lead to a natural division between rear-engined pusher open rotors and wing-mounted advanced turbofans in this aircraft category. The high capacity airliners require larger engines where escalation of gearbox size and weight may begin to make geared engines less attractive.

The Mach 0.85 long range Airliner poses a more severe set of propulsion requirements resulting from the combination of high speed and high weight due to the large amount of fuel carried. This tends to lead to four engined solutions which have of necessity to have wing-mounted engines. At Mach 0.85 wing-mounted Propfans become even less viable due to cabin noise constraints and the propulsion field becomes limited to advanced turbofans, unless acceptable three-engined aircraft configurations can be found.

Figure 3 illustrates some of the possible aircraft configurations

AIRCRAFT CATEGORY	NO OF PASS	TYPICAL DESIGN MACH NO	TYPICAL DESIGN RANGE NM	PREFERRED FUTURE POWERPLANT OPTION	
				WING-MOUNTED	REAR FUSE MOUNTED
SMALL FEEDERLINERS	30-70	0.5	700	SINGLE ROTATION OPEN ROTORS.	
LARGE FEEDERLINERS/ REGIONAL AIRLINERS	80-120	0.7	1200	COUNTER-ROTATION OPEN ROTORS OR ADVANCED DUCTED ROTORS (UHBR).	COUNTER-ROTATION OPEN ROTORS.
SHORT/MEDIUM HAUL AIRLINERS	150-200	0.8	2000	ADVANCED DUCTED ROTORS (UHBR)	COUNTER-ROTATION OPEN ROTORS.
HIGH CAPACITY MEDIUM HAUL AIRLINERS	300-500	0.8	4000		
LONG RANGE AIRLINERS	250 UPWARDS	0.85	5000-7000+	ADVANCED DUCTED ROTORS (UHBR)	

TABLE I. Airframe/Powerplant Matching

	Wing-Mounted Open Rotors	Rear Fuselage Mounted Open Rotors
Preferred Wing Location	High	Low
Preferred Propeller Configuration	Tractor Contra-rotating	Pusher Contra-rotating
Propeller Environment	Clean air entering Props but high upwash at high incidence	Props in wing downwash and pylon wake fields. High probability of F.O.D.
Thrust Line/Trim Drag	Thrust line on centre of drag - No trim drag penalty	High thrust line required To provide Prop/Ground Clearance - trim drag penalty
Cabin Noise & Vibration	Need to minimise source noise and provide additional cabin soundproofing or Active Noise Control	Alleviation of airborne transmitted cabin noise. Structural-borne noise and vibration at rear of cabin could be worse
Community Noise	Measures to limit source noise should avoid a community Noise Problem	Could be a community noise problem particularly with high tip speeds required by gearless option.
Wing Design	Design constrained due to presence of engines	Clean wing with more design flexibility
Flexibility for Other Roles	Suitable for 2 or 4 engine layouts. Same powerplant could be used for Military applications requiring 4 Engines.	Rear fuselage installation limits configuration To 2 (or 3) engines-precludes 4 Engined solution

TABLE II. Wing v Rear Fuselage Mounted Rotors under study for service in the 1990's.

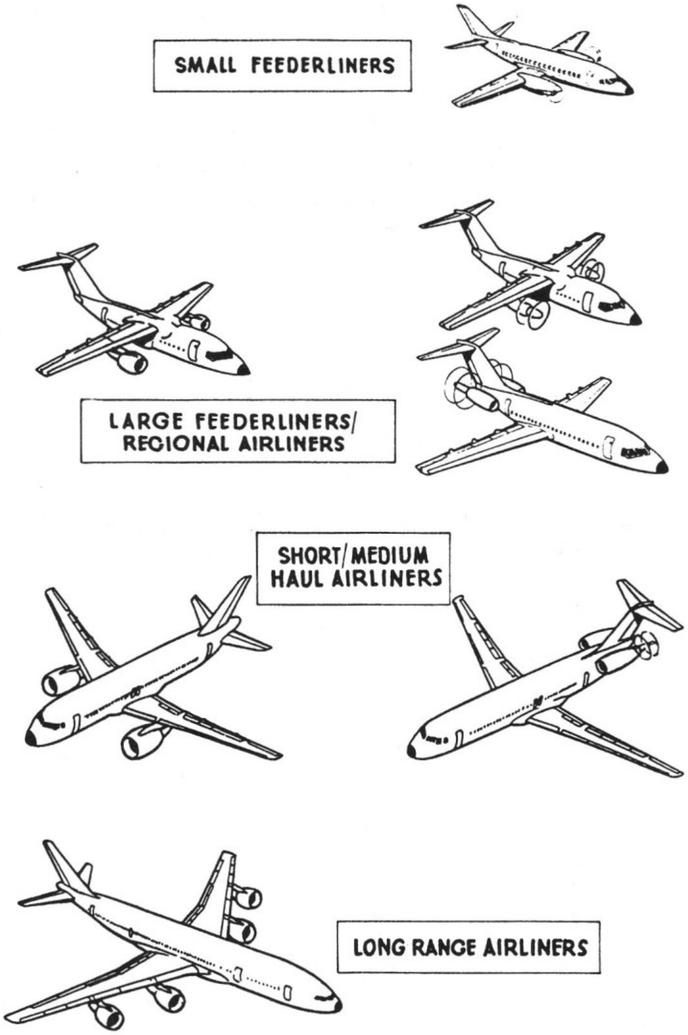


FIGURE 3. Likely Powerplant Airframe Options the 1990's

6. THE ADVANCED FEEDERLINER

Each category of aircraft generates it own set of powerplant requirements. For the purpose of this paper we will examine one category in more detail - that of the advanced Feederliner/Regional Airliner. For this kind of operation, field performance is an important parameter. With stage lengths averaging 200 nm, a high proportion of flying time is spent in climb and descent. This obviously has a bearing on powerplant characteristics as well as the aircraft configuration.

It is worth examining the design philosophy behind the BAe 146 (see figure 4) which was designed specifically to fulfill this role.

The high wing location is beneficial in providing good field performance. Continuity of the lifting surface across the fuselage coupled with continuous flaps extending out to 70% of the span accounts for the high $C_L$max (3.4) achieved by the BAe 146 without leading edge devices. The high wing enables engines to be mounted under the wing with a good ground clearance. Location of the fuselage close to the ground facilitates quick loading and unloading of passengers or freight with good access to aircraft services for a quick turnround.

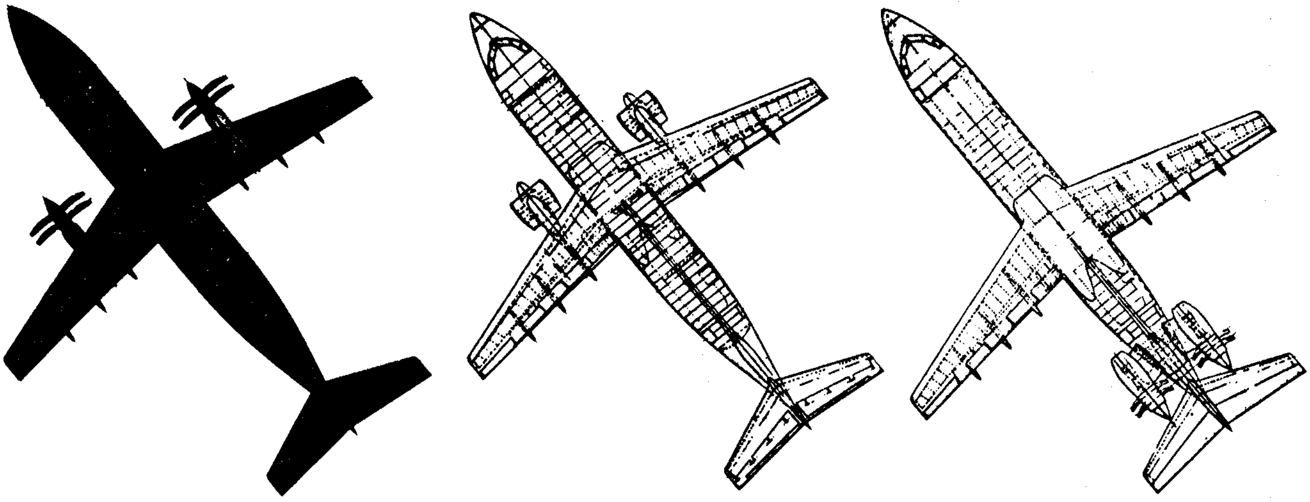
FIGURE 4. BAe 146

The BAe 146 is powered by four high by-pass ratio turbofan engines. Development of the turbofan engines and further aircraft stretch will enable the 146 to remain competitive well into the 1990's. The high wing and high tail combination enables the installation of ultra-high by-pass turbofan or open rotor powerplants to provide further improvements in fuel efficiency in the longer term.

Figure 5 shows some of the aircraft configuration options suitable for an Advanced Feederliner/Regional Airliner. The first two powerplant options suit the characteristics of the BAe 146 airframe. The pusher open rotor powerplant is more suited to a rear engined installation as shown in the figure.

For this class of aircraft the building blocks will be available to develop tractor or pusher open rotor powerplants for service in the early 1990's. There is currently no firm proposal for an ultra-high by-pass turbofan at this size. Table II compares the characteristics of aircraft configured with wing-mounted open rotors with aircraft configured with rear-mounted open rotors.

Figure 6 (1) shows an aircraft development with wing-mounted counter-rotating open rotors based



Wing-mounted geared tractor contra-rotating propellers

VHBPR ducted fan

Fuselage-mounted unducted fan

FIGURE 5. New Propulsion Options for Mid 1990's

upon a BAe 146 Airframe. The engine installation is illustrated in figure 7.

Co-axial counter rotating open rotors offer significant advantage to the airframe designer compared with single rotation:-

- Higher rotor propulsive efficiency.
- Reduction in disc diameter with less loss of efficiency.
- Lighter, more compact, more efficient gearbox.
- Reduction in gearbox oil cooling requirements.

In, the particular case of a wing-mounted, tractor engine installation for a derivative aircraft cruising at M0.65 there are three further advantages.

- Fewer blades per disc - less intake blockage.
- Elimination of need to contour the wing to remove slipstream swirl. No requirement for handing gearboxes.
- Possibility of lowering tip speed to reduce source noise without loss of propeller efficiency.

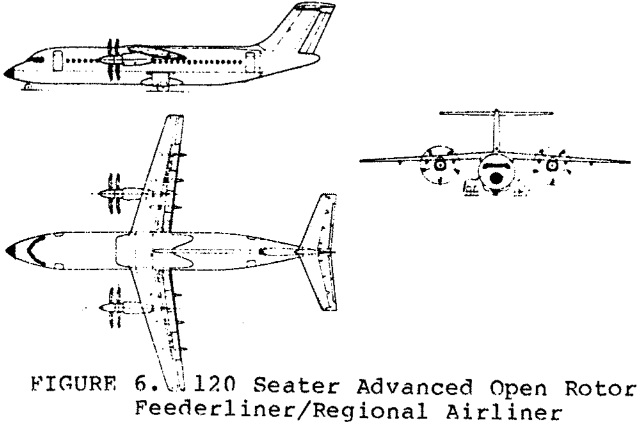


FIGURE 6. 120 Seater Advanced Open Rotor Feederliner/Regional Airliner

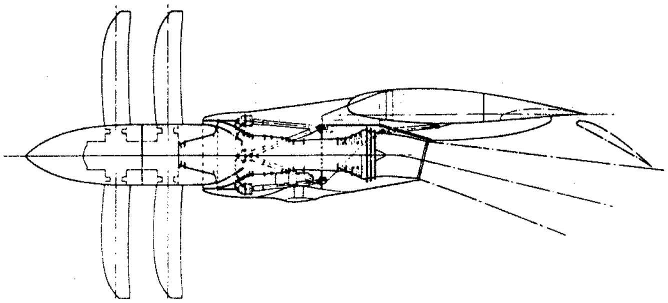


FIGURE 7. Wing-Mounted Open Rotor Powerplant Installation

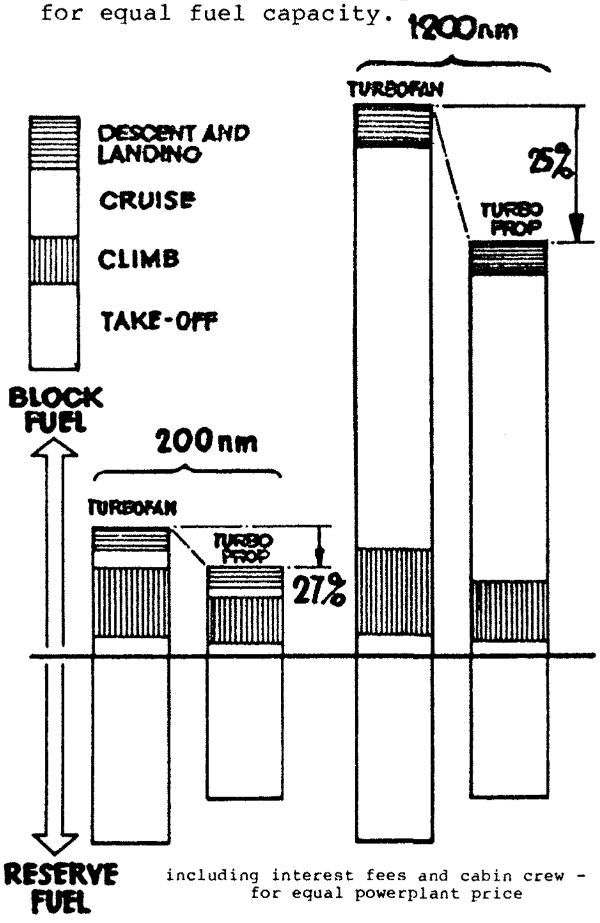
7. THE INCENTIVES

What then are the incentives which might extend the domain of the open rotor up to cruise speeds of M0.7 and beyond and to seating capacities of 120 and what are the implications on the aircraft design to achieve this?

Aeronautical engineers are continually striving for improvements in efficiency. The performance of the powerplant is the largest single factor contributing to aircraft efficiency. Powerplant efficiency relates directly to fuel that needs to be carried. Improved powerplant efficiency not only reduces fuel consumption but results in a lighter aircraft to perform the same task or in increased range for the same fuel capacity.

The main incentive is fuel economy. Figure 8 compares fuel breakdowns for the Feederliner shown in figure 6 powered by unswept contra-props driven by derivative turboshaft engines with a similar airframe powered by the best proposed turbofan derivatives. Block fuel savings of 27% are predicted over a typical stage length of 200nm. Currently this class of aircraft makes the equivalent of 3,500 such flights a year. With fuel at $1.0 per US gallon, this would represent a saving of $4.5 million per year for an operator with a fleet of 10 aircraft.

For a derivative aircraft, savings in block fuel and reserve fuel can be used to increase payload or to increase range. The fuel savings shown in figure 8 would enable design range to be increased by around 45% for equal fuel capacity.



including interest fees and cabin crew - for equal powerplant price

FIGURE 8. High Speed Feederliners Fuel Breakdowns

8. ECONOMICS OF CHANGE

The trade-off between efficiency and cost is the determining factor influencing the economics of change.

Fuel price is a key factor. 1986 is a year which has seen a dramatic fall in the price of oil due to the collective failure of the World's oil producers to conserve their resources and balance supply and demand. This situation is unlikely to continue indefinitely. Figure 9 (2) indicates that fuel prices are likely to return to around $1.0 per US gallon in real terms by 1995. From then on, fuel prices might be expected to rise again due to increased cost of obtaining oil from less accessible fields or from resorting to synthetic fuels. Oil demand for non-aeronautical purposes appears to be on the decline which may place a premium on the small proportion of the barrel suitable for aero-engines. However, predictions can be upset if there are more oil crises similar to those which forced oil prices through the roof in the late 1970's.

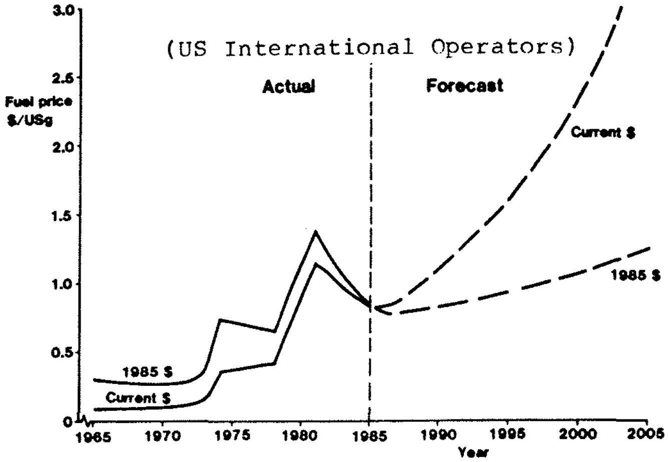


FIGURE 9. Jet Kerosene Prices

If an economic case can be made for aircraft entering service in the mid 1990's powered by new fuel efficient propulsion systems with fuel at $1.0 per US gallon, the economic advantage can be expected to increase during the service life which will extend into the next century.

Studies have shown that for short/ medium haul aircraft, a 20% change in fuel consumption has the same effect on operating cost as a 10% change in aircraft price or a 40% change in powerplant cost if engine price comprises 25% of aircraft cost.

Figure 10 compares the DOC breakdown over a typical 200 nm stage for turboprop and the turbofan powered Feederliners using the fuel savings shown in figure 8. the effects of interest, fees and cabin crew are included and the total powerplant cost per aircraft is assumed to be equal. On this basis a DOC saving of 6.5% is predicted with fuel at $1 per US gallon rising to 9% with fuel at $1.5 per US gallon.

Powerplant depreciation can account for as much as 11% of the aircraft

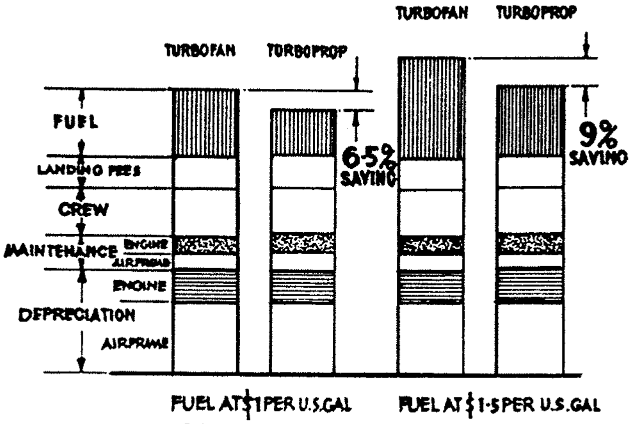


FIGURE 10. 120 Seat Feederliner DOC Breakdowns 200nm Stage

DOC on a 200 nm stage. Figure 11 shows sensitivity of DOC to fuel price and powerplant price.

A 20% increase in turboprop price relative to the turbofan would result in the DOC advantage being reduced by around 3%. For study purposes it has been assumed that half the maintenance costs are proportional to first cost, and half proportional to engine size, with maintenance costs for the turboprop increased by 10% relative to the turbofan. A 20% change in maintenance costs changes DOC by 1%.

For this class of aircraft a lower engine price resulting from the saving in development costs consequent upon using an existing engine core could outweight the DOC advantage resulting from the greater fuel efficiency of a higher priced all-new powerplant. Development costs of all new powerplants might however be alleviated by the use of a new engine core having multiple applications.

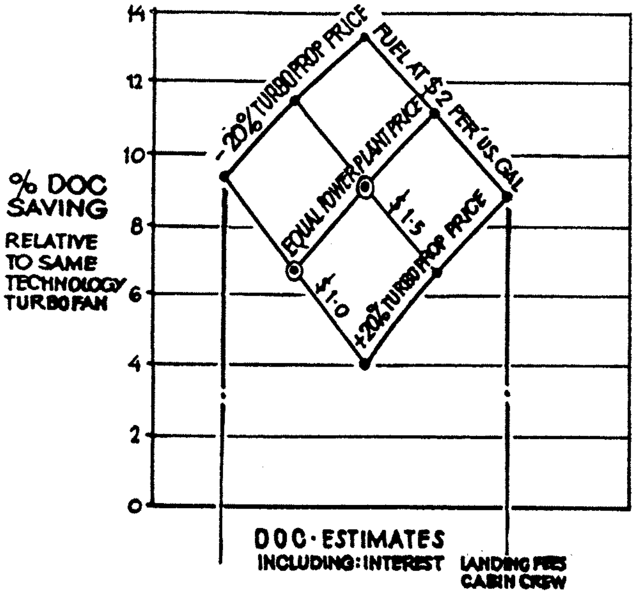


FIGURE 11. 120 Seat Feederliner/Regional Airliner DOC Sensitivity over 200nm Stage

9. CONCLUSIONS

- Contra-rotating open rotors provide the most efficient known means of propulsion for aircraft cruising at Mach Nos between 0.6 and 0.8.
- Considerations of safety, efficiency, economy and noise determine the best match of powerplant and airframe for a given aircraft configuration. There is no universal powerplant configuration which will suit all needs.
- An Advanced Feederliner can show a block fuel advantage of 27% and a range increase of 45% by replacing turbofan engines with counter-rotating open rotor powerplants. DOC savings of 6.5% are predicted for equal powerplant costs and fuel at $1.0 per US gallon.
- Efficiency has to be balanced against cost. The DOC advantage of a 20% reduction is fuel usage can be cancelled out by at 10% increase in aircraft price or a 40% increase in powerplant price.

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