THE DANIEL AND FLORENCE GUGGENHEIM MEMORIAL LECTURE
CIVIL PROPULSION; THE LAST 50 YEARS

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Introduction

This paper covers propulsion developments in the civil field over the last five decades. It is notable that aircraft have displaced ships and railways for long distance passenger travel, and this could not have been achieved without the continuous development of the aircraft gas turbine. The paper traces propulsion developments from the end of the piston era through the early turboprops and turbojets to the high bypass ratio turbofans of the present.

Travel Situation in 1952

It is instructive to consider the situation in 1952 before embarking on a study of propulsion developments over the last 50 years. Younger readers may be surprised to know that aviation played only a very minor role in passenger transportation at that time.

At the end of World War II Europe was reduced to a very poor economic state and much effort was required to rebuild the infrastructure. Pre-war passenger liners were returned to service, but the market now shifted from luxury travel for the wealthy to large scale emigration from Europe to countries such as the US, Canada, Australia and South Africa. Many new ships were built in the decade following the end of WW II and the building of passenger ships was a major industry; the rapid and total decline of this industry certainly could not have been predicted. Emigrants crossing the Atlantic would not even have thought of flying and the very limited airline services were restricted to the very wealthy; it was common in newspaper offices to see photographs of the celebrities arriving by aircraft. When immigrants arrived in North. America they would immediately get on a train to get to that final destination; one of the common derogatory terms was “just off the boat”.

Train travel in North America was well developed with all major cities connected by rail. The railway station was in the centre of all big cities and was surrounded by the business district; this is still the norm in Europe but has not been true in North America for many years. Transcontinental trains were widely used and crossing the continent took several days. Distances of 500-600 miles were often covered by overnight express trains. The idea of a one day business trip from, say, Toronto to Montreal, was out of the question.

Internal air transport in North America was in its infancy and was virtually non existent in other parts of the world. Aircraft such as the DC-3 and Convair 240 were in use, with passenger capacities of about 20-40 and very limited range. A few airlines operated Constellations, Stratocruisers and DC-6 on the Atlantic; the major airlines were Pan American and TWA.

Noting that Pan American have disappeared and TWA are bankrupt, it is also interesting to consider who were the major players in the aircraft industry. In terms of long haul aircraft the dominant companies were Lockheed and Douglas, and for short haul Douglas, Martin and Convair. The principal engine manufacturers were Pratt and Whitney and Wright. It will readily be recognised that a few key names are missing, including Boeing, Airbus, General Electric and Rolls-Royce, giving some indication of the enormous changes that have occurred.

Travel times between continents were measured in terms of days or weeks and there was very little business or vacation travel as we know it today. Typical times by ship were London to Montreal 8-10 days, London to Colombo 18-21 days, and London to Sydney 30-40 days. In the 1950s it was common to meet immigrants who had spent 20-30 years working in North America saving up for a single trip to the old country. We shall see that it was the aeroplane, and in particular the advent of the jet engine, that has resulted in a world where it is commonplace to cross the Atlantic or Pacific several times a year and executives routinely make weekly transcontinental trips.

Some recent examples of very long range flights resulting from propulsion developments include the following:

Year	Destination	Distance (nm)	Time	Engine
1989	London-Sydney	9720	20 hrs. 9 min.	RB211-524G
1993	Auckland-Paris	10392	21 hrs 46 min	CFM56-5C
1996	Seattle-Kuala Lumpur	10823	21 hrs 24 min.	Trent 800

The above, of course, is the engine man's point of view and it should be noted that the engines were connected to 747-400, A340 and 777 respectively. Each, in turn, represented the longest flight by a civil airliner; the Seattle-Kuala Lumpur flight flew eastbound over Europe, the distance across the Pacific would have been much lower. It should be emphasised that these were demonstration flights with minimal payloads, but it is useful to recognise that 10,000 nm is basically half way around the world and there is no merit in a longer range!

1950-1960 - The Transition from Pistons to Turbines

At the beginning of the decade the dominant long haul aeroplane was the Lockheed Constellation, powered by Wright R3350 18 cylinder radial engines, with a take-off power of 2200 BHP and a weight of 2780 lb [1]. A very successful post war design, the Convair 240, carried 40 passengers over a 500 mile range using two Pratt and Whitney R2800 14 cylinder radial engines. It should be noted that US piston engines were designated in terms of their swept volume in cubic inches; 3350 cubic inches is equal to 204.4 litres. These engines required 100/135 octane fuel, specially blended for aircraft applications. The US airline industry used solely air-cooled radial engines, being distrustful of the complications of liquid cooled in-line engines; the Rolls-Royce Merlin liquid cooled engine was used in the Canadian version of the DC-4, known as the North Star in Canada and the Argonaut in Britain. There is no question that the air-cooled radial was more successful.

The piston engine reached its peak in the Lockheed Super Constellation, Boeing Stratocruiser and Douglas DC-7C. Wright developed the R3350 TC18 for the DC-7C and L-1649 Super Constellation, with exhaust driven turbines which were connected to the crankshaft through quill shafts and fluid couplings to increase the power supplied by the pistons; this was known as the turbo compound (TC) engine and achieved a specific fuel consumption of 0.38 lb/BHPhr, the ultimate for the piston engine. The Stratocruiser used the Pratt and Whitney R4360, a 28 cylinder turbo supercharged engine using 4 rows of 7 cylinders. Key data for these engines is given below.

Figure 1: Lockheed Constellation

Engine	BHP (T/O)	BHP (cruise)	Weight (lb)
Wright R3350 TC18	3400	1700	3645
Pratt & Whitney R4360	3500	1750	3584

According to Borger [1] both of these very powerful piston engines had major reliability problems; unscheduled removal rate of the R4360 frequently exceeded 2 per 1000 hours and the inflight shutdown rate was "intolerable" (too high to guess a number?). After numerous modifications, engine operation was considered to be barely tolerable. The R3350 was plagued by service problems and Borger concluded that the problems were soluble; the engineering spirit was willing but the financial backing was almost non existent. It is perhaps not a great surprise that Wright was the first of the big names to disappear from the engine business.

The DC-7C and the L-1649 were the only piston engined aircraft with a true westbound transatlantic non stop range. During the piston era airports such as Gander and Shannon were necessary because of the limited ranges of piston aircraft, but these have not been required for many years.

The limitations of the piston engine focused attention on the prospects of the turbine, in the form of both turboprops and turbojets. The jet engine was already playing a dominant role in military aircraft and the Viscount (turboprop) had its first flight in July 1948 while the Comet 1 had its first flight in July 1949. In the 1950s there was a major controversy over the relative merits of the turboprop versus the turbojet for long haul transport. The British were the leaders in the application of turbines; this was largely because of US dominance in the civil transport field based on civil development of piston engined military transport designs. The Viscount was aimed at the short-medium range markets. For long haul, the main proponents were the Britannia (first flight August 1952) and the Comet. The first transatlantic crossing by a jet was made by a Canberra, from Ireland to Gander (2072 miles) in 1951. The Americans, however, still had faith in the piston engine and the DC-7 did not make its first flight until May 1953; it is worth noting that the Comet 1 had already been in service for a year, and was withdrawn from service after the DC-7 first flight. Key dates for first flights are given in Table 1.

Table 1
FIRST FLIGHTS

Viscount	R-R Dart	July 1948
Comet	DH Ghost	July 1949
Britannia	Bristol Proteus	August 1952
DC-7	Wright R3350	May 1953
707 (KC-135)	P&W JT3	July 1954
747	P&W JT9D	Feb 1969
Concorde	RR Olympus 593	March 1969
767	P&W JT9D	Sept. 1981

It was clear, however, that the writing was on the wall for the piston engine. Boeing flew a prototype of the KC-135 tanker in July 1954, and one year later were authorised to produce a civil version which became the 707; this was the aeroplane that really launched the jet age. On October 13th 1955 Pan American placed orders for 20 707s and 25 DC-8s, the DC-8 being the Douglas entry into the turbine era. The first flight of the DC-7C did not occur until two months after this landmark order. Lockheed had a different view and announced the development of the Electra in 1955, a four turboprop short-medium range airliner.

In the twilight of the piston era the DC-7C and L-1649 were operating on the Atlantic in 1957, with the Super Constellation providing the first Los Angeles-London flights. The Britannia appeared on the Atlantic in 1957, having met with serious development problems on the Proteus turboprops, particularly flame outs in tropical icing conditions. If the Britannia had entered service on time it would have had a considerable time to demonstrate its superiority over the piston aircraft, but it was less than a year after it started on the London-New York route that the pure jets appeared on the scene.


Figure 2: Vickers Vanguard

The Viscount, however, was extremely successful. The Rolls-Royce Dart was a single shaft turboprop using a two-stage centrifugal compressor (scaled up from the Merlin supercharger) and the Dart remained in production until 1987, with over 7500 engines built; the Dart was widely used, other key aircraft being the F-27 and the Gulfstream 1. Air Canada were one of the biggest users of Viscounts and operated them from 1955 until 1974. The Electra had an unfortunate entry into service with a critical nacelle/wing flutter problem which resulted in several fatal accidents; the Electra was a commercial failure which led to Lockheed's disappearance from the civil market until the emergence of the 1011 (TriStar) in 1972. It should be noted, however, that the Electra resulted in the military P-3 Orion which was extremely successful and is expected to remain in service until at least 2020. The Allison 501D turboprop powering the Electra has been very widely used (military designation T-56) in both the P-3 and C-130 Hercules with over 14,000 engines built.

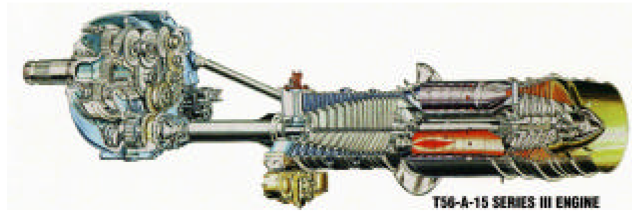

Figure 3: Allison T56

The Vanguard was an aircraft designed to be a very economic "airbus" type aircraft, and was powered by 4 Rolls-Royce Tyne turboprops of 5500 BHP, with a speed of about 425 mph. This was an even greater failure than the Electra, and although only 43 aircraft were sold (to BEA and Air Canada) the design was sound and it had an excellent safety record.

Airlines generally were not enamoured of the large turboprops, which did not have the passenger appeal of the turbojets and also required additional maintenance for propellers and gearboxes. The turboprop did offer significant advantages in fuel burn, but in an era of low fuel costs this was not sufficient to overcome the lack of passenger appeal. In the late 1970s NASA promoted "propfans" which were basically turboprops with swept propellers allowing operation at flight Mach numbers comparable to turbofan aircraft but at lower fuel burn. The airlines showed no interest and the propfan faded away.

The turboprop has been remarkably successful in smaller sizes, and the Pratt and Whitney Canada PT-6 is still in production 45 years after the start of its design. The impact of the turboprop on the regional market will be discussed in a later section.

Table 2 from reference [2], provides some key data on the bigger turboprop aircraft.

Table 2

Aircraft	Max TOW (lb)	Power Plant (ehp)	Max cruise (mph/alt)	Range (miles)	Passengers
Britannia	185,000	4 Proteus x 4450	357/30000	5300	139
Electra	116,000	4 Allison x 4050	405/22000	2770	74-98
TU-114	396,800	4 NK 12 x 12,000	497/32800	6200	120-220
Vanguard	146,500	4 Tyne x 5500	425/20000	3100	139

1960-1970 - The Turbojet Era

The early jet engines, developed for fighter applications, were designed for maximum thrust at minimum weight; fuel economy was unimportant, reliability was deplorable and noise was not even considered. When the future application of turbojets to civil propulsion was considered a blue ribbon panel of experts concluded.

> "In its present state, and even considering the improvements possible when adopting the higher temperatures proposed for the immediate future, the gas turbine could hardly be considered a feasible application to airplanes mainly because of the difficulty in complying with the stringent weight requirements imposed by aeronautics.
>
> The present internal-combustion-engine equipment used in airplanes weighs about 1.1 pounds per horsepower, and to approach such a figure with a gas turbine seems beyond the realm of possibility with existing materials. The minimum weight for gas turbines even when taking advantage of higher temperatures appears to be approximately 13 to 15 pounds per horsepower."

It is interesting to note that Theodore von Karman was a member of this committee.

The basic theory of the gas turbine [3] shows that thermal efficiency is primarily determined by pressure ratio while specific output (i.e. power per unit airflow) is strongly dependent on turbine inlet temperature (TIT). Early engines, such as the de Havilland Ghost used in the Comet, had centrifugal compressors with a pressure ratio of about 4 and a turbine inlet temperature of 1100 K. The need for high pressure ratio required much aerodynamic research and the development of the axial flow compressor, while increasing TIT required continued research and development in materials, heat transfer and manufacturing methods resulting in the widespread use of cooled blades in civil engines. As a result, advanced engines today have pressure ratios in excess of 40 and TIT of 1600-1700K.

Much of the basic research in compressor aerodynamics was carried out in government laboratories on both sides of the Atlantic (NGTE in Britain and NACA in the US). These programs led to a better understanding of compressibility and boundary layer effects, allowing higher Mach numbers and stage loading. This allowed compressors to achieve significantly higher pressure ratios while reducing the number of stages required, with important benefits to both engine weight and manufacturing costs. NGTE and NACA provided the basis of compressor design, but in later years these developments were pursued by the major engine manufacturers and much of the work became of a proprietary nature and not openly published.

The development of Rolls-Royce axial flow compressors, showing the increase in pressure ratio and decrease in the number of stages required is summarised in Table 3 from [2]; similar data would apply to compressors designed by GE and P&W.

Table 3

Engine	Date	Pressure Ratio	Stages
Avon	1958	10	17
Spey	1963	21	17
RB-211	1972	29	14
Trent	1995	41	15

The increase in TIT over time is shown in Figure 4, where it can be see that the gains have come primarily from increasingly complex air cooling systems which, in turn, depended on major developments in manufacturing technology. Figure 5 shows the evolution of blade cooling at Rolls-Royce.

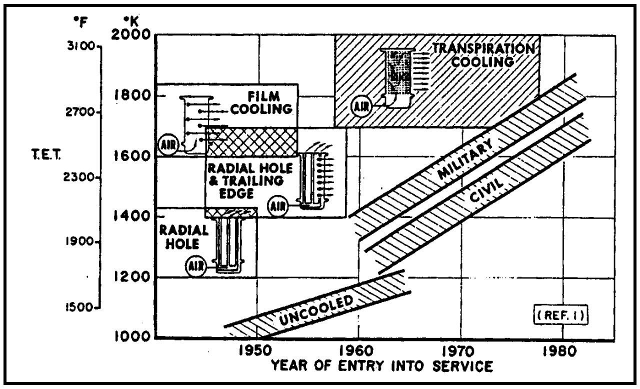

Figure 4: Increase in TIT Over Time

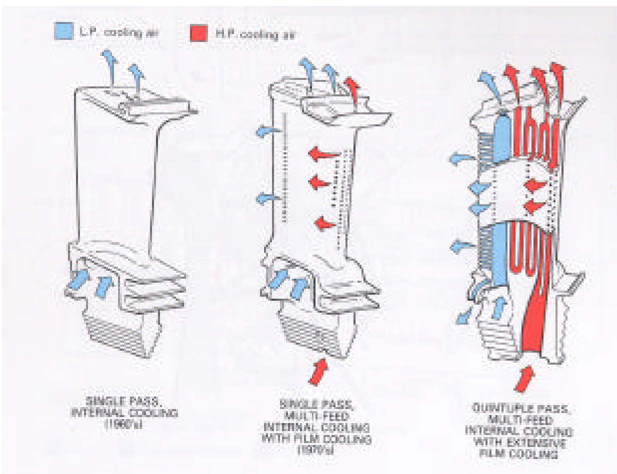

Figure 5: Evolution of Blade Cooling

The structural problems of the Comet 1 have been widely publicised, but it should be noted that the Comet 1 entered service in 1952 where it clearly demonstrated the passenger appeal of high speed and low vibration; the Comet was in direct competition with aircraft such as the North Star/Argonaut and Constellation. Despite the initial failure of the Comet, it initiated the jet age leading directly to the end of the piston era and, in not much more than a decade, the elimination of the ocean liner as a means of passenger transport.

The jet age began in earnest with Pan Am's historical purchase in 1955 of both the 707 and DC-8. Both of these aircraft used podded installations, building on the military success of the B-47, the first large swept wing jet aircraft. British designs had used engines buried in the wing root, both for military aircraft (Valiant, Victor and Vulcan) and civil aircraft (Comet). The concept of buried engines placed a major restriction on engine diameter, as the engine had to pass through the main spar of the wing. The podded configuration, however, gave the engine designer much greater freedom in choice of diameter and this proved critical to the development of the bypass engine, or turbofan as it came to be known.

The 707-120 and DC-8 entered service with the Pratt and Whitney JT3 and JT4, civil versions of the widely used J57 and J75 military turbojets. The Comet 4 was an enlarged version of the Comet 1, with more efficient Rolls-Royce Avon turbojets. The 707-120 was initially used on transcontinental flights in the US and was not a true transatlantic aircraft. Neither was the Comet 4, but it was used by BOAC to inaugurate scheduled transatlantic flights on October 4, 1958. Once commercial jet service began it was clear that airport noise was going to be a major concern. Fluted silencers were used in the exhaust to promote rapid mixing and reduce jet noise, but these led to significant performance problems. Early transatlantic operations of the 707-120 out of New York required lightweight take-offs with a stop in Boston to refuel and then another stop in Iceland; the turboprop Britannia was actually the fastest way to cross the Atlantic, being capable of non-stop operation. In hindsight, it is not often realised that piston aircraft such as the Super Constellation presented a major noise problem because of their very low rate of climb, and if they had appeared in large numbers there was no technological solution available.

A mathematician, Sir James Lighthill, deduced that aircraft noise was proportional to the eighth power of the jet velocity so it became obvious that the basic solution was the reduction of jet velocity. To maintain a given thrust then required an increase in airflow. Fortunately for the future of air transport, the combination of higher flow and lower jet velocity was exactly what was required to improve propulsive efficiency, and this was achieved by the development of the bypass engine, in which a portion of the compressed air bypassed the combustion system. This approach had actually been patented by Whittle and Rolls-Royce built the first bypass engine, the Conway, which was used in a significant number of 707 and DC-8s.

Pratt and Whitney modified the JT3 by substituting a higher diameter fan/LP compressor to produce the highly successful JT3D, which dominated the civil market for many years. With the podded installation on both 707 and DC-8 it was possible to use a higher bypass ratio than on the Conway, which was originally designed for a buried installation. The JT-3D had a bypass ratio of about 1.4 giving 13-14% improvement in cruise fuel consumption relative to the JT3.

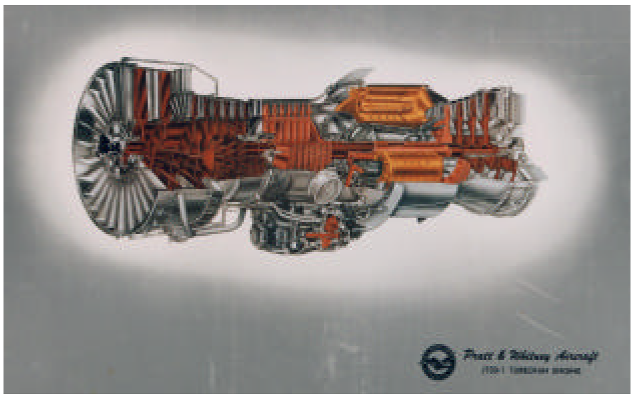

Figure 6: JT3D

By the early 1960s the civil market was dominated by Pratt and Whitney, with Rolls-Royce having a small but significant share; GE had no presence in the civil market. GE, however, were the prime builders of military engines in the US, powering aircraft as diverse as the B47, F86, B58, F4 and F104. The last three were powered by the J79, a very high performance turbojet which pioneered the concept of variable stators, allowing a pressure ratio of 13 be obtained on a single spool, while Pratt and Whitney and Rolls-Royce used two spools. GE broke into the civil market by offering an aft-fan version of the J79, the CJ805, on the Convair 880 and 990; Convair had been shut out of the civil jet market and tried to establish a niche by offering a higher cruise speed than Boeing or Douglas. The aft-fan concept required the use of a combined turbine/fan blade, known as a "blucket" (i.e. combination of blade and bucket, the GE terminology for turbine blades). The blucket was difficult to make and had significant sealing problems between the fan and exhaust streams. The Convair aircraft failed to meet their target speeds, resulting in the biggest financial loss in US history and the disappearance of Convair from the market. This was an unfortunate start for GE, but they returned in force a few years later.

Once the big jets had shown the way, domestic airlines in the US and Europe demanded smaller jets, by far the most successful in the early years being the Boeing 727 and the DC-9. Both used the Pratt and Whitney JT8D, a low bypass ratio turbofan developed from the US navy J52 turbojet. The JT8D achieved total domination in this field and was also used on the 737; the 737 had an uncertain start and the -100 sold only a few, but the improved -200 became a best seller. The Rolls-Royce Spey was a similar design which was used in the Hawker Siddeley Trident, BAC 1-11 and Fokker F-28. The success of both the JT3D and JT8D gave Pratt and Whitney an enviable position of market dominance which lasted for many years.

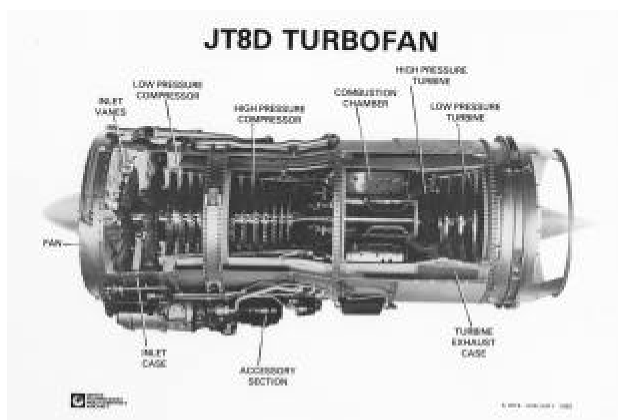

Figure 7: JT8D

The 707 and DC-8 made long range transportation accessible to the masses and new markets opened up for both scheduled and charter traffic. A particularly important development was the start of large scale charter operations to fly immigrants to Australia. The Australian immigrant trade had led to a large number of passenger liners being built in the 1950s, and a typical voyage from Europe took about 6 weeks. If a ship sailed from a port such as Hamburg or Rotterdam, this added a couple of days to the trip as compared to sailing from the UK. Once the capabilities of the 707/DC-8 had been demonstrated, the Australian government found it much more economical to charter an aircraft and fly a full load of immigrants to their destination in a couple of days. Virtually overnight, this killed the immigrant traffic by ship and some excellent ships had service lives as short as 10 years. The same thing happened on the Atlantic and the last of the great liners such as the "France" and "United States" disappeared after only a few years in service. The 727 and DC-9 had a similar impact on transcontinental trains in North America; a 6 hour flight was much more attractive than a 4-5 day train journey!

1970-1980 - Advent of the High Bypass Ratio Turbofan

The emergence of the high bypass ratio turbofan, giving a step change improvement of 20% in cruise sfc combined with a significant reduction in airport noise, was the key technological development in providing mass market air transportation.

Civil engine developments followed military introduction of technology improvements up to this stage; the JT3, JT4, JT8D and Avon all had strong military backgrounds. The first high thrust, high bypass ratio engine also emerged from a military background, based on the USAF requirement for an ultra large long range military transport. Lockheed and Boeing competed for this requirement and both Pratt and Whitney and GE proposed high bypass ratio turbofans to meet the range and take-off requirements. The competition was won by Lockheed and GE, resulting in the C-5A Galaxy powered by TF-39 turbofans. The TF-39 had a bypass ratio of 8 and used a so-called "one and a half stage" fan, in which the inner portion of the fan flow was compressed by two stages and the outer portion by one; this configuration results in a peculiar fan noise quite unsuitable for civil aircraft.

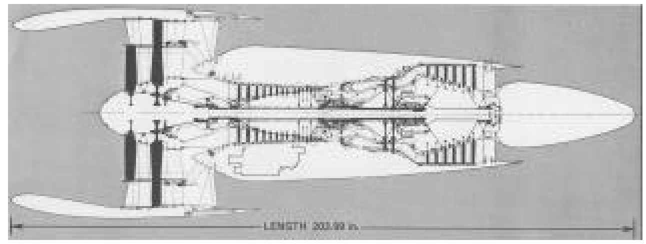

Figure 8: TF39

Boeing then decided to modify their losing contender and offered it to the airlines, using the Pratt and Whitney engine resulting in the 747-JT9D combination. The 747 required a considerably higher flight speed than the C-5A and this necessitated a lower bypass ratio, the JT9D settling on a bypass ratio of about 5. Once again, it was Pan Am that launched a new revolution in air transport with the first orders for the 747, inaugurating scheduled service between New York and London on the 22nd of January 1970; it is perhaps worth noting that this was 6 months after Apollo 11 made the first manned lunar landing.

Lockheed and Douglas did not want to cede the large transport market to Boeing and both countered the 747 with large trijets, the 1011 and DC-10 with the Rolls-Royce RB-211 and General Electric CF6 respectively. These were initially aimed at transcontinental services but were soon upgraded to intercontinental aircraft, both making their first flights in the second half of 1970. The CF6 was based on the military TF39 while the RB211 had no military background and introduced the revolutionary concepts of a 3 spool design with a lightweight composite (Hyfil) fan. The difficulties of bringing this entirely new engine into service in a very short time span led to the widely publicised bankruptcy of Rolls-Royce in 1971. The Hyfil fan, although very light, proved unable to withstand bird strikes and had to be replaced by the backup titanium fan.

Figure 9: Lockheed 1011

The vast improvement in performance relative to the previous generation of engines requires much higher pressure ratios and complex air cooled turbine blades. In hindsight it is not surprising that all the new engines showed poor reliability and much development was required to achieve the current superb levels of reliability which are now taken for granted. All of them had major problems with turbine blade life and the JT9D had performance problems resulting from casing distortion which caused ovalization of the engine, requiring tip clearances to be increased. Borger, however, points out that it took 17 years for the ultimate piston engines to reach overhaul lives of 2000 hours, while the JT4 achieved an overhaul life of 3400 hours after 3 years. Despite their inauspicious entry into service high bypass ratio turbofans have demonstrated lives of 40,000 hours on the wing and are routinely operated using on-condition maintenance.

It is notable that civil and military requirements started to diverge once the airline industry standardized on high bypass turbofans with typical bypass ratios of 5. The basic architecture of the JT9D, CF6 and RB211 have endured for over 30 years while thrust levels have doubled and sfc has been reduced by about 20 per cent. The original JT9D had a fan diameter of 92 inches, and its successor (PW 4000) has variants with fan diameters up to 112 inches. The RB211 was developed to a higher thrust level for the 747 and then to the Trent family with fan diameters up to 110 inches. The CF6 was also uprated to power the 747 and DC10-30 and cemented GE's position as a major player in the civil market.

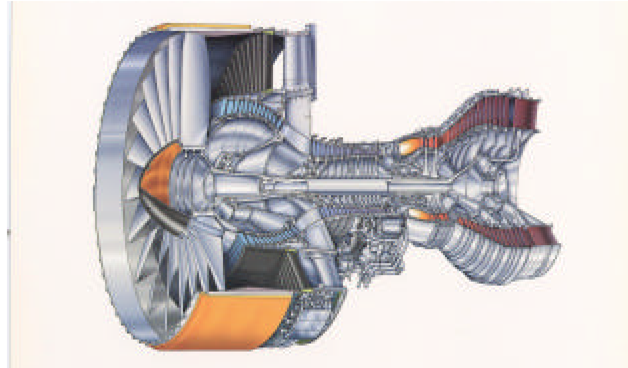

Figure 10: PW4000

The 747, DC-10 and 1011 were all bought in large numbers and became the backbone of the air transport industry with the 707 and DC-8 moving to secondary roles. Little attention was paid to the first flight on October 28, 1972 of a large twin engined aircraft, the A300 built by Airbus; many observers did not believe that it was safe to build a high passenger capacity aircraft with only two engines, at a time when all the big turbofans were demonstrating poor reliability. It transpired, however, that this was the next really major step forward in air transportation.

Another major decision made at the end of 1971 was the approval of the French government for the development of the CFM56 turbofan. This was a joint venture between GE and SNECMA, combining the core of the F101 (used in the B1B) with a low pressure system developed by SNECMA. The original application was for the re-engineering of DC-8s, to provide improved economics and noise reduction. This market was limited and the CFM56 was close to being terminated when CFM were able to persuade Boeing to use it in the 737-300. A further success was its selection for the A320 family (a market shared with the International Aero Engines V2500), followed by Boeing's decision to make the CFM56 sole source for the 737 family. The CFM56 was also selected for the 4 engined A340. Today the CFM56 is the best selling civil engine in the world with over 14000 in service, ending the domination of the JT8D in the domestic market.

The formation of CFM from GE and SNECMA marked the beginning of alliances between the principal engine manufacturers and overseas partners, resulting from the extremely high costs of developing and certifying a new engine. International Aero Engines is a consortium from five nations (hence the V in V2500), Rolls-Royce, Pratt and Whitney, MTU, Fiat and Japan Aero Engines. Current programs for large engines involve numerous risk sharing partners from around the world, often specialising in such areas as gearboxes, electrical systems or thrust reversers.

1980s - The Big Twins

The European Airbus (A300) was designed as a medium range domestic aircraft, providing a wide body with 8 abreast seating. Airbus was originally a French-German partnership but used a British wing, designed and built by BAC, and the American CF6 engine making it a truly international aircraft. Initial sales of the A300 were very slow and confined to Europe; the first export sales were to the Asian market but no sales were made to North America. The breakthrough was the decision by Eastern Airlines to lease a fleet of A300s, greatly increasing the credibility of the aircraft.

Engine reliability had now increased to the point where the DC-10 and 1011 became widely used on transatlantic and transpacific flights, and the heretical notion of long range twins appeared. This again was driven by Airbus, with the A310 which was a shorter fuselage/increased range version of the A300. The American manufacturers had been extremely sceptical about the viability of large twins but both Boeing and Douglas (by now McDonnell Douglas) now started serious studies of large twins. Nothing came of the McDonnell Douglas studies but Boeing came up with the 767, offered with a choice of the JT9D or CF6. The 767-200 was primarily a transcontinental aircraft, but the 767-200 ER and the stretched 767-300 ER were designed for transatlantic and transpacific flights.

Turning back in history, the low reliability of the piston engines led to a requirement that civil aircraft over water flights had to be routed so that the aircraft was never more than 1 hour flying time from a diversion in the event of an engine failure. Transatlantic flights were all based on 4 engined aircraft (Constellation, DC-7, etc.) in the piston era and 3 engined jet aircraft (DC-10, 1011) did not appear until the early 1970s. The concept of extended twin over water operations (ETOPS) required a major rethinking of engine reliability and, indeed, aircraft systems. The authorities were, quite correctly, cautious in their approach and aircraft manufacturers had to demonstrate a large number of flights (for each aircraft/engine combination) to obtain an ETOPS clearance of 90 minutes, and considerable in-service experience before this could be revised to 120 minutes. A major milestone was a 155 minute limit, permitting flights between the US West Coast and Hawaii.

In a remarkably short time transatlantic flights by the 767 and A310 became routine, and many routes started to substitute smaller twins at increased frequency, eating into the market of the 747, DC-10 and 1011. Lockheed, in fact, terminated the 1011 program and made their final exit from the civil market. McDonnell Douglas offered the MD11, an improved version of the DC-10, but the rapid market acceptance of the big twins destroyed the market for trijets. One of the first corporate decisions made by Boeing when they took over McDonnell Douglas was to cancel the MD11, leaving the 767 as a mainstay of long range operations.

With the success of the 767 and A310, both Boeing and Airbus started the design of even larger long range twins. Airbus were first in the field with a combination of the A330 and A340, based on an identical airframe with the choice of either 2 or 4 engines; the A340, using the CFM56, was intended for very long routes where it would not be limited by ETOPS restriction while the A330 was intended for somewhat shorter routes (which were substantially greater than those of the 707/DC8!). The A330 was offered with three different engine types, the PW4000, CF680E and Trent 700. Boeing countered with an even larger aircraft, the 777, which was also offered with PW, R-R and GE engines. The GE-90 was a brand new engine specially developed for the

777, using a bypass ratio of about 8 and a fan diameter of 110 inches. Engine reliability by now had reached a level where the 777 was successfully developed for ETOPS "out of the box" and entered service in 1995 with PW-engines. The latest version of the GE90 is being developed for a take-off thrust of 115,000 lb, more than double the thrust of the original JT9D on the 747.

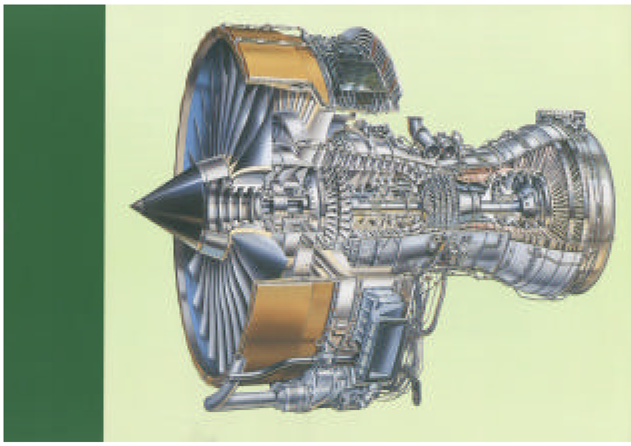

Figure 11: R-R Trent

It is interesting to speculate on future thrust levels. The largest aircraft yet designed is the A380, but being 4 engined its thrust requirement is about 70-75,000 lb per engine; no doubt later versions will follow the normal path of increased maximum gross weight and thrust, but clearly the engine thrust will be less than that required for the twin engined 777. Will there be a bigger twin than the 777? Many studies have shown that thrust is primarily dependent on fan diameter for high bypass turbofans and increasing fan diameter and blade weight causes increasing difficulty in blade containment and bird strike resistance. Increasing fan diameter would also require a decrease in rotational speed and a consequential increase in torque to drive the fan; this would result in increased diameter of the LP shaft, making the design of the HP system more critical. Another problem would be the required increase in undercarriage length and weight to permit adequate ground clearance. Perhaps most significantly, the market would probably be limited to a single twin-engined aircraft so it would be difficult to recoup the massive development cost based on relatively small sales. This suggests an upper limit that is not greatly above the 115,000 lb level currently under development, say 130,000 lb. No doubt the Guggenheim Lecturer of 2052 can look back at this and make disparaging remarks about the short sightedness of the 2002 lecturer!

1990s - Development of the Regional Market

As mentioned earlier, the turboprop versus turbojet controversy of the 1950s ended in the demise of the turboprop for long range aircraft. The turboprop, however, achieved great success at the lower power end of the spectrum. Starting in the late 1950s companies such as Pratt and Whitney Canada (PWC) and AiResearch (later Garrett, now Honeywell) started development of small turboprops in the 500 HP range, both incorporating centrifugal compressors. The PT-6 and Garrett 331 were both very successful, being used initially in business aircraft such as the Beech King Air. Their popularity, reliability and low noise levels led to continuous improvements in power and sfc resulting in the development of commuter aircraft such as the Twin Otter, Beech 1900, Fairchild Metro and Short 330/360. Large numbers of these aircraft entered service providing airline links to small communities, usually feeding into large hubs; many of these small airlines became subsidiaries of the major carriers. The turboprop was superior to the turbofan for short routes because of its much lower fuel burn and at ranges up to 300-350 miles the difference in flight times was negligible.

In the late 1970s PWC started the development of a larger turboprop, the PW 100 [4], aimed specifically at the regional market. This engine made use of the extensive research in centrifugal compressors at PWC, resulting in a twin spool arrangement with centrifugal compressors on both shafts. General Electric also attacked the commuter market, with a turboprop version of the T700 turboshaft, which held a dominant position in the military field. The PW100 family was selected for the Dash 8, Embraer 120, Fokker 50, BAC ATP, ATR 42/72 and Dornier 328 while the GE CT7 was chosen for the Saab 340 and the CN235. It soon became clear that there were too many competitors and today only Bombardier with the Dash 8 and ATR with the ATR 42 and 72 continue in production at very low rates.

It is interesting to note that two high speed turboprops entered the market, the Saab 2000 and the Dash 8-400. The Saab 2000 used the Allison 2100, a heavily derated version of the engine for the Hercules C130J, and had a projected cruise speed of 365 mph; eventually only about 50 aircraft were sold and Saab abandoned the market. The Dash 8-400 used the PW 150, a much more powerful development of the PW100 in the 5000 HP class. At the time of writing only about 70 orders have been obtained and the future looks somewhat bleak.

The decay of the turboprop market is the direct result of the introduction of regional jets. The first of these was the Canadair RJ200, based on a fuselage stretch of the Challenger business jet to give a 50 passenger capacity. Propulsion was by the GE CF34 turbofan, originally developed as a military engine for the Fairchild A10 and Lockheed S3A Viking; the CF 34 has a bypass ratio of about 5, using a similar cycle to the large civil turbofans. Embraer developed the EJ145, using a stretch of the Embraer 120 fuselage with a new wing and Allison 3007 turbofans; this engine was developed using the core of the Allison 2001 turboprop matched to a new fan system. In a very short time it became apparent that the passenger appeal of the turbofans was much higher than the turboprops and large numbers of regional jets entered the market. Larger versions of the Bombardier and Embraer aircraft have extended passenger capacity to 70 and 90 seats, and the regional jet market is growing rapidly while the turboprop market is declining.

The Next Decade

Having reviewed the progress of the last 5 decades, what comes next? The high bypass ratio turbofan has reached a technology level where future gains will be modest, unless some major configuration change is made. Previous studies of ultra high bypass (UHB) engines were driven by the prospect of greatly increased fuel prices, which then stabilised over a long period; in mid 2002 it is impossible to predict future fuel prices, but they are more likely to increase than decrease.

The A380 is the next major program being developed and it will be powered by the Trent 900 or the GPS 7200, built by the Engine Alliance (P&W and GE). Both these engines are conventional turbofans with BPR of about 8. The Sonic Cruiser, under study by Boeing, is intended to cruise at Mach 0.97; this high Mach number would probably require a reduction in bypass ratio for drag reasons, but this would then increase sfc and reduce range. Estimates to date suggest that a 20 per cent increase in fuel burn may result, for a modest increase in speed. The prospect for a successor to Concorde appears to be dim, the conflicting requirements for good supersonic fuel economy and low take-off noise being very difficult to reconcile. The engine development costs would be extremely high, but this would be a single application engine with a restricted market making the economic picture bleak.

It appears very likely that we will continue to see modest developments in the existing families of turbofans, the majority of new aircraft being twins and the issue of reliability making any revolutionary changes unlikely That is precisely the conclusion this author arrived at in 1987 and was certainly true 15 years later.

What would be required to introduce revolutionary changes to the propulsion scene? At the present time business travel provides the major portion of airline income, with the very large leisure (low fare) market producing much less revenue per passenger mile. While it may not happen in the next decade, there is little doubt that teleconferencing will have a major effect on business travel in the future; this, of course, has been promised for many years, just like the paperless office. If, as is likely, we see continually increasing airport congestion, air traffic control limitations, increased security checks and rapidly increasing fuel costs, air travel will become less and less desirable. This is particularly true for business travel, which could largely be replaced by teleconferencing, and the airlines would then become much more dependent on the leisure market, which could only survive if costs were kept low. The switch from business to leisure travel could be the trigger for revolutionary change in engine design.

Conclusions

Over the last 50 years air transportation has changed our way of life, making foreign travel economically available to the masses. This has been a direct result of the development of the gas turbine, culminating in the superbly efficient and reliable turbofans of today. It should be clearly understood it was the impact of jet propulsion which eliminated shipping and railways as prime modes of long distance transportation; without the productivity of jet engines the aircraft would have remained a minor competitor.

In conclusion, we can see that jet propulsion has been one of the most significant technologies of the 20th century.

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