2020 VISION: THE PROSPECTS FOR LARGE CIVIL AIRCRAFT PROPULSION

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Keywords: *civil aircraft, propulsion, aero-engine*

Abstract

This paper will examine the prospects for propulsion systems for large civil transport aircraft over the next 2 decades, to the year 2020. This period is likely to see the market drivers for future propulsion system development change from the more traditional ones of fuel consumption and weight, to also include those that affect the impact of civil aviation on the environment, and the continuing pressure to reduce the cost of ownership of civil engines, namely, product unit cost, maintenance costs and reliability. 50 years of civil aero-engine development are reviewed and trends showing the likely limits to the main engine performance parameters are provided. The paper concludes with consideration of a number of new civil aircraft and engine concepts that may emerge in the next 20 years

1 Introduction

The propulsion systems used on today's civil transport aircraft represent the refinement of the principle of jet propulsion based on the gas turbine, first conceived by Whittle and Von Ohain nearly 70 years ago. In that period, propulsion system concepts have evolved through turbo-props, turbo-jets, low by-pass ratio (BPR) turbofans, to today's high BPR 2-shaft and 3-shaft turbofans. Also, this period has seen remarkable progress in the performance and reliability of these propulsion systems. Aircraft are now three times more fuel-efficient than the early turbo-jet powered aircraft (see Fig.1), and roughly two-thirds of this improvement is due to the giant strides made in reducing engine fuel consumption.

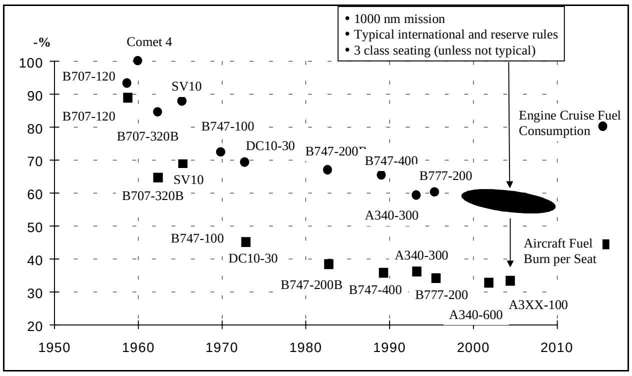

Figure 1. Aircraft fuel burn

Another key engine design criterion over the last 30 years has been noise, driven by the rapid expansion of airport usage at major city hubs and its impact on the local resident population. Here again, the engine industry has responded by producing design that are 75% quieter than the early turbo-jet powered aircraft (see Fig. 2).

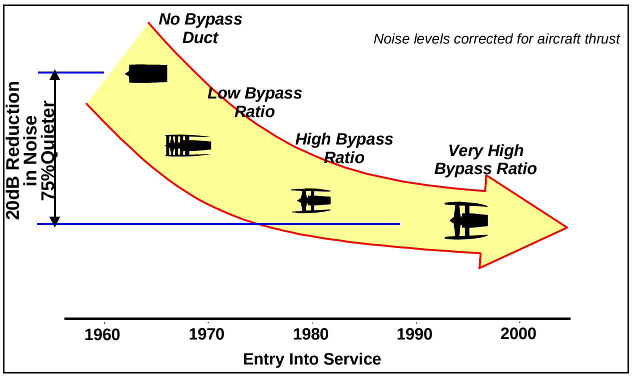

Figure 2. Aircraft Noise

Another key development over the last 30 years has been the emergence of the long-range twin-engine civil transport, exemplified by the B767, B777, A300/310 and A330. This has led to the requirement for improved engine reliability, to allow safe operation of these aircraft types over the world's oceans. Indeed, over the last 25 years, engine reliability as measure by in-flight shut-down rate has improved by more than a factor of ten, largely due to the increased maturity of engine systems, electronic engine controls and increased reliability testing during the development phase (see Fig. 3).

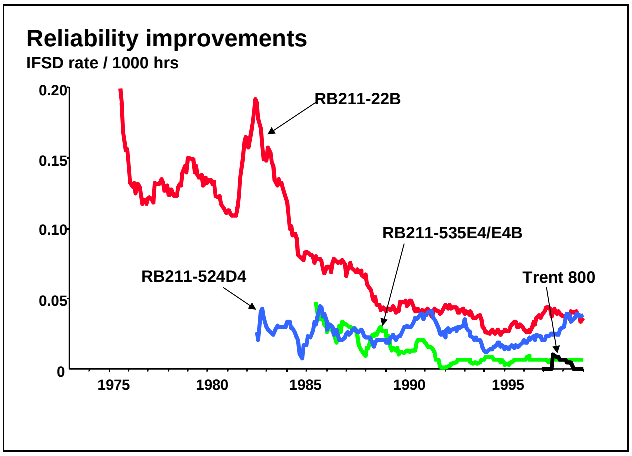

Figure 3. Engine reliability

With these remarkable improvements behind us, as we enter the 21st century it is interesting to look forward and attempt to identify what will drive the civil aircraft industry, and in particular the engine manufacturers, forward in the next 20 years. Whilst there is great uncertainty in making such predictions, it may trigger a debate that does at least allow the industry to try to reach a consensus on what the key long-term engine technologies are that need to developed, and to be ready to respond to the changing market drivers.

2 Future Market Drivers

2.1 Market Growth

The growth of civil aviation has been one of the success stories of the 20th century. Over the last 40 years, growth in traffic (revenue passenger miles) has been between 5 and 6 %, with only one year of reduced traffic (1991), due to the Gulf war. Projections of future traffic by the industry leaders are generally consistent and show growth rates of around 5% in passenger traffic (see [1] for example), and an even higher rate for freight traffic. In engine terms, considering wide-body and narrow-body aircraft, regional jets and business jets, this corresponds to around 83,000 engines over the next 20 years worth over $350bn.

This growth rate is underpinned by forecasts of continued economic growth (especially in Asia), the growth of tourism, and a more global business environment. Air-freight traffic will increase as the manufacture of high value goods becomes more globalised and the public demand both product customisation and prompt delivery. The growth of the internet and e-commerce will accentuate this trend. Barring economic, political or natural disaster, there is good reason to believe that these market drivers will prevail.

However, there will be some constraints that may reduce this forecast rate of growth. High- speed trains and ships will divert traffic away from aviation at the margins, and the internet and e-commerce may reduce high-yield business travel. Airport congestion and an overloaded air traffic control system may also constrain growth, and lead to larger aircraft size.

2.2 Environment and Global Climate

For the past thirty years, the civil aviation industry has become increasingly concerned with the impact of its operation on the environment. This is evident from the emergence of many international and local regulations on aircraft noise and emissions, in and around airports. The stringency of these regulations can be expected to further increase over the next 20 years. Whilst, until now, aircraft have been seen primarily as a problem local to the airport, it is clear from the recently published IPCC report [2], that increasing attention will start to focus on the emissions produced through the cruise phase of flights, not just landing and take-off. This applies to both engine combustion and acoustic emissions. The former, although only making a small overall contribution today, will increasingly impact global climate change, whilst the latter will be a significant factor in the prospects for a new supersonic transport (i.e. airframe-generated sonic boom).

2.3 Cost of Ownership

The past forty years has seen a period where the yields from civil aviation have been falling faster than unit costs. This has led to increased pressure on engine prices and the manufacturers have responded by producing generic families of modular products. This is characterised at Rolls-Royce by the Trent family, where engines based around two fan sizes allow a high degree of commonality between engine types, which, in turn, helps to keep costs low. With falling prices, the engine manufacturers have also addressed maintenance costs and often these are now guaranteed to the operator. In some cases the engines are merely leased and the manufacturer charges so-called Power by the Hour™. There seems no doubt that pressure on costs will continue to drive engine design, perhaps more than any other factor.

For a large, long-range civil transport, engine related factors contribute some 30% to the direct cash operating costs to the airline, (assuming fuel is an engine-related contribution). Fuel costs remain a dominant factor and recent increases in fuel prices illustrate how vulnerable the industry is to unexpected changes. Despite stable fuel prices over the last decade, it remains entirely possible that a sudden increase could occur before 2020, due to the imposition of environmental taxes, socio-economic conflict, political action, or simply demand outstripping supply. Civil aviation today relies heavily on low-cost liquid hydro-carbon fuel.

3 Limits on current engine designs

The engine designer today has to balance a number of requirements, which increasingly conflict with one another. For a long-range aircraft fuel consumption and weight should both be low to achieve range targets, which can today exceed 8000nm. In a crowded sky, an aircraft with good climb performance can achieve operational advantages, although an engine designed for high climb thrust will often have to compromise either cruise fuel consumption or maintenance costs. Stringent noise requirements will lead to engines with very high bypass ratio, which itself can penalize range through high weight and installation drag. Low NOx emissions mean careful control of fuel/air mixing, and lower combustion temperatures, which limit the potential fuel savings from higher cycle pressures and temperatures.

3.1 Fuel consumption

Engine specific consumption (*sfc*) can be related to the cycle efficiency parameters as follows:

$$sfc = V_0 / \eta_{th}\, \eta_{prop}\, F_{HV} \qquad (1)$$

where V_0 is the flight speed, η_{th} is the thermal efficiency, η_{prop} is the propulsive efficiency and F_{HV} is the fuel calorific value. Thus, for a given flight speed and fuel type, *sfc* is reduced by increasing values of thermal and/or propulsive efficiency.

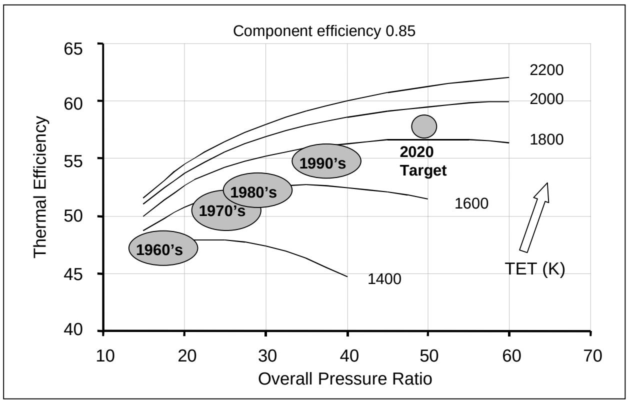

Figure 4. Thermal Efficiency variation with Engine Overall Pressure Ratio (OPR) and Turbine Entry Temperature (TET)

For a by-pass turbo-fan engine, the thermal efficiency is largely determined by the overall pressure ratio (OPR), the turbine entry temperature (TET), and the efficiency level of the individual components in the gas path (i.e. the compressors, turbines and combustor).

Figure 4 shows how thermal efficiency relates to TET and OPR, at a constant component efficiency level. This illustrates an important fundamental point – that efficiency improvements only arise by increasing TET & OPR together. Traditionally, this has been achieved by application of technology, in particular materials with improved temperature capability, improved turbine cooling designs, and smaller, high-speed, high-efficiency cores. If TET & OPR are to increase further, these must all continue to improve, or the fundamental cycle benefits will be eroded by increased losses due to component scale effects and increased cooling flows. This is illustrated in Fig 5, which shows the sfc benefits of increases in TET & OPR both fundamentally, and by taking account of scale and cooling airflow effects at a constant technology level.

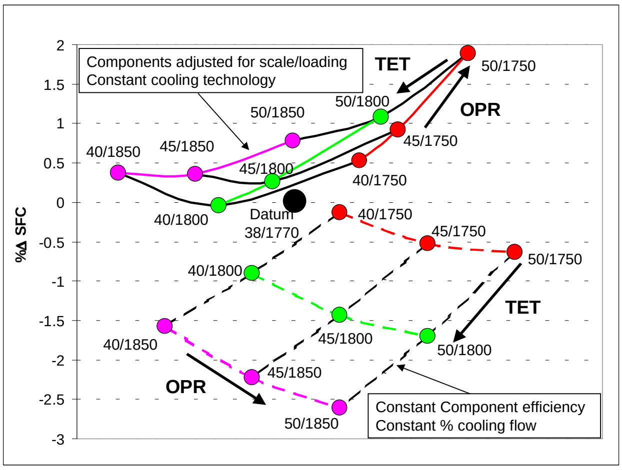

Figure 5. Variation of sfc with OPR & TET

It can be seen that when constant component efficiency levels and percentage cooling flows are assumed, worthwhile gains in sfc can still be achieved from increases in TET & OPR. However, this can only be so if cooling, materials and component performance improve. At a constant technology level, where cooling flows will increase with TET & OPR, and component efficiency will deteriorate as engine cores become smaller and loadings increase, no sfc gains can be achieved from further TET & OPR increases.

It is clear great strides have been made over the last 40 years, but only modest further thermal efficiency gains of about 3% over the next 20 years can be achieved through further TET & OPR increases, and only if materials and cooling technology continue to advance.

Component efficiency levels have a direct effect on fuel consumption, and remarkable strides have been made here over the last 50 years with nearly all turbo-fan components now achieving polytropic efficiency levels in excess of 90%. After some 30 years of research, the emergence of reliable and accurate CFD design codes, that can analyse an entire multi-stage compressor or turbine, has enabled the last degree of freedom (3-dimensional aero-dynamics) to be addressed. The control of secondary flows through the turbo-machinery will deliver a few more increments of component polytropic efficiency, but increasingly these CFD tools are being used to increase component loading and reduce parts count to achieve cost reduction, itself a worthy goal. Overall, there is perhaps an additional ten 1% increments in component polytropic efficiency to be derived over the next 20 years, which are worth around 4% of engine fuel consumption.

Improvements in propulsive efficiency arise largely through increases in bypass ratio (BPR), or, more correctly, reductions in specific thrust, defined as the ratio of net thrust to total engine mass flow. BPR has increased from 1 or 2 in the 1960's to 5 or 6 in the 1970's and 1980's, whilst new engine designs in the 1990's typically have BPR in the range 7 to 9. Whilst these changes in BPR do reflect reductions in specific thrust (and improvements in propulsive efficiency), they are partly due to the increases in TET & OPR outlined above. For example, an engine with a fixed thrust and total mass flow could be re-fitted with a smaller, hotter core, which would increase BPR, but have no effect on specific thrust or propulsive efficiency. Further reductions in specific thrust are still possible and are likely, but will only benefit aircraft fuel burn if ways can be found to reduce the increased weight and drag associated with such engine types.

Fig 6 summarises the progress made in engine sfc reductions made over the last 15 years, and projects forward to 2020. This assumes conventional turbofans will continue to be the preferred engine type and accounts the changes described above.

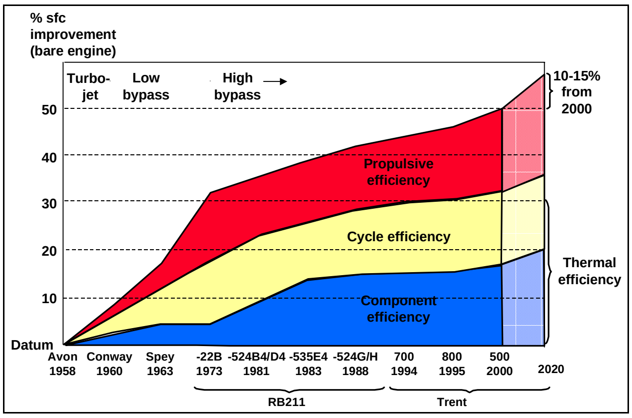

Figure 6. Engine specific fuel consumption

This plot assumes that aircraft will continue to cruise at or near the minimum sfc thrust level of the engine. Increasingly, higher climb thrust is demanded by the aircraft operators, in order to overcome restrictions in the crowded air traffic control system. This in itself can lead to engine designs, which are not well optimised for minimum cruise fuel burn. Increasing traffic forecasts will only accentuate this trend. For the conventional turbo-fan engine, the current improvement rate in sfc of roughly 1% per year is likely to reduce to around 0.5% per year by 2020 as the limits described above are approached. This implies an sfc improvement of about 10-15% in total by 2020 relative to today's best engines.

3.2 Noise and emissions

Acoustic emissions from the engine play an increasingly important part in the design. The key noise sources at take-off and landing from a high BPR turbo-fan are from the large fan, the exhaust jet and the turbo-machinery (principally, the front compressor stages and the rear low-pressure turbine stages). At approach conditions, airframe noise is usually as important as the engine in the overall aircraft noise signature. Fan noise sources can be alleviated by reducing the tip speed, careful shaping of the aerofoil, and increasing the distance from downstream stator vanes. Jet noise sources can be alleviated by reducing jet velocity (via lower specific thrust), optimizing the by-pass to core jet velocity ratio, or introducing devices to modify the free-stream / bypass or bypass / core shear layers. Turbo-machinery noise sources can be alleviated through careful choice of aerofoil numbers, rotor-stator gap increases, and by low aero-dynamic loading and low Mach number designs.

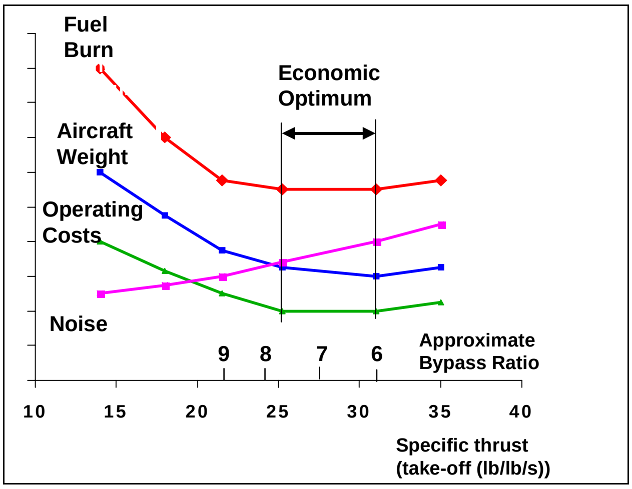

Figure 7. Variation of fuel burn, noise and weight with specific thrust

The nacelle also plays a key role in suppressing acoustic emissions, through incorporation of acoustic liners in the inlet and exhaust system. However, it is the reduction in specific thrust (increase in BPR) that has been the most significant factor in achieving noise reductions over the last 40 years, as illustrated in Fig 2. A low specific thrust engine demands low fan pressure ratio, which allows low tip speed, and delivers lower jet velocities thus addressing two of the key engine noise sources.

Fig 7 shows the trends of noise, weight, fuel burn and operating cost for a series of engine designs at different specific thrust (or BPR) levels. Clearly, there is an optimum specific thrust for fuel burn that represents a balance of stream-tube sfc, drag and weight. However, a stringent noise target would drive the engine design away from this optimum. The challenge is therefore to provide low noise technology that maintains a near-optimum specific thrust design, whilst achieving an acceptably low community noise level. This is the subject of much US and European research activity.

Current combustion emissions regulation centers on the take-off and landing regimes. Limits are imposed on the emissions of nitrogen oxides (NOx), smoke, un-burned hydro-carbons and carbon monoxide. Most modern engines meet these regulations with ease, except for NOx, which is the most difficult. This is because the production of NOx in the combustion chamber is largely a function of the local temperature. Thus the drive to improve fuel efficiency through OPR & TET increases, as outlined in 3.1 above, conflicts with low NOx production. The international ICAO regulations recognize this by allowing a higher NOx level for high OPR engines, but some local regulations (e.g. Switzerland), do not (see Fig 8).

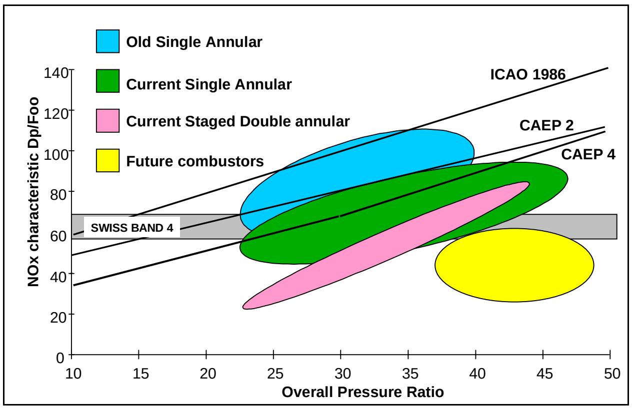

Figure 8. NOx Emissions

This is the problem facing combustion technologists today, and they have responded by producing more complex staged combustors, which reduce NOx production by splitting the combustor into two chambers, each optimised for low and high power operation, respectively. Whilst these have been successful at low values of OPR, the benefits have been much smaller at higher values, where the benefits have been most needed. Combustion research now centres on achieving lower NOx by improving the mixing of fuel and air prior to entry into the combustion chamber, through pre-mixing or pre-vaporisation, which reduces peak combustion temperature.

The IPCC report [2] addresses in-flight emissions, which are currently un-regulated. Although great uncertainties in the atmospheric physics exist, the report highlights carbon dioxide (CO_2) and water (H_2O, as vapour and in contrail and cloud formation) as the key contributors to global warming through high-altitude emissions. NOx itself is shown as broadly neutral, so if regulation is to be imposed on in-flight emissions, it is likely that it will restrict CO_2 and H_2O, which are clearly a direct function of fuel burn. If the growth forecasts outlined in 2.1 above are correct, and the evidence for global warming becomes even more conclusive (see ref [3]) regulation or voluntary commitment from industry seems more likely, and may have a profound influence on the future of the industry.

4 Year 2020 Scenarios

Nearly 100 years ago, in 1901, after the Wright brothers had made another unsuccessful attempt at manned flight, they predicted that it would take another 50 years to achieve it. Two years later, the Wright Flyer took to the air at Kitty Hawk, North Carolina, with Orville Wright aboard. Predicting the future can be a difficult and it has proved difficult for even the well-informed to make predictions just a few years into the future. Civil aviation and its propulsion system requirements are almost certain to take new directions in the next 20 years, so the question is, in which directions, and how should the industry be preparing itself at this time? For any radical change, three elements will be required: the motivation, the capability, and the opportunity to make the change. The motivation for change in civil aviation will be the business drivers discussed earlier, such as environmental pressures, aircraft economics or fuel price rises. As has been shown in previous decades, the acquisition of capability to develop new propulsion system concepts can occur remarkably quickly, once the motivation is apparent. The next two sections discuss various opportunities that are possible within civil aviation in the next 20 years, and the consequences for the airframe and engines. These are separated into two types: the improbable and the probable.

4.1 Improbable

The first prediction to be made is that it is possible that "business as usual" will continue unimpeded for another 20 years, but this is unlikely. "Business as usual" here means that the industry continues to produce existing or new aircraft of the current type, powered by the current families of high BPR turbofans. The pressures on the industry to change are increasing and some new direction is almost certain.

Another prediction that can be made with some certainty, is that Concorde will be approaching the end of its service life by 2020. So what are the prospects for a replacement? It is clear that a new large super-sonic transport (SST) will have to meet at least the same environmental standards as sub-sonic aircraft. In addition, the IPCC report [2] identifies SST's as potentially being five times more damaging to the global atmosphere than sub-sonic aircraft. Future noise regulations will also present a formidable hurdle for a future SST to overcome. The problem of sonic boom from a large SST will probably also limit the use of supersonic speeds to the oceans, severely restricting the benefits of such a vehicle. There is no propulsion system available today that can deliver the thrust-to-weight ratio, fuel consumption, noise signature and emissions performance to meet the requirements of a new generation of SST's. The motivation for pursuing such an engine today is low, so the prospect of a new large SST is consigned to the improbable category here.

So if aircraft are so environmentally damaging, what are the prospects for alternative fuels? Also, what if oil-based fuels become very costly and/or in short supply? Hydrogen (H_2) would appear to offer an alternative to carbon-based fuels, in that it does not produce CO_2 emissions. It will produce NOx and H_2O, and it would need to be clear that these emissions themselves are not equally damaging to the global atmosphere to win the environmental argument. Clearly the use of H_2 fuel would present a very big challenge to aircraft designers. For a given fuel energy, cryogenic liquid H_2 would occupy 4 times the volume of kerosene, but with lower weight, and the conventional aircraft would have to be radically re-designed to accommodate this. The infrastructure at airports would also need to be changed to handle cryogenic fuel, and the fuel itself would have to be produced in a way that was environmentally sound. The propulsion system changes would be relatively minor in comparison, centering on fuel pump, heat exchange and combustion technologies, some of which are readily available from the space industry. All in all, the prospects for hydrogen-powered aircraft are not promising, and it is more likely that oil-based fuel shortage would lead the industry towards synthetic kerosene based on natural gas, as proposed by Allen [4].

4.2 Probable

In the probable category, there are better prospects for the so-called More Electric Engine (MEE) and More Electric Aircraft (MEA) concepts.

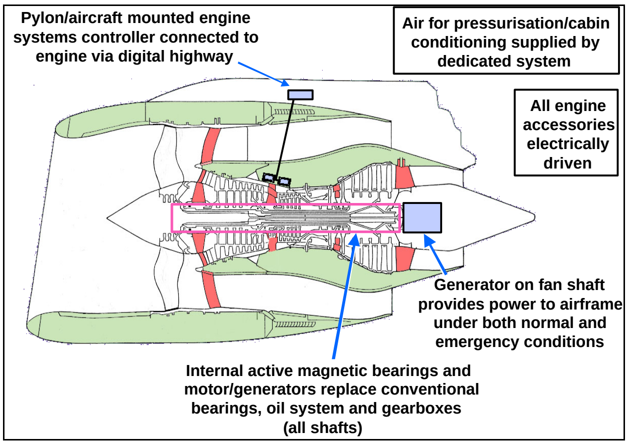

Figure 9. The More Electric Engine

The MEE offers the prospect of making significant reductions in engine maintenance costs and improvements in reliability. By attaching electrical generators to the engine shafts, large quantities of electrical power can be generated. This can be used on the engine itself in a number of ways, to improve altitude re-light capability, or enable improved operability of highly-loaded compressors through shaft-power transfer, for example. Mechanically-driven accessories could be replaced by electrically-driven ones, improving both cost and reliability. As a more radical step, incorporation of active magnetic bearings could make the lubrication system on the engine redundant, significantly reducing maintenance costs.

Combined with the More Electric Aircraft, the MEE could offer further advantages. In principle, electricity generated by the engines could be used to power many of the systems on the aircraft, and could eliminate or reduce the scope of the pneumatic and hydraulic systems. For example, the ram-air turbine (RAT) emergency generator could be eliminated by use of an electrical generator attached to the engine fan shaft, and the pneumatically-driven aircraft air conditioning system could be replaced by an electrically-driven or self-powered alternative. Aircraft control actuation and wing anti-icing could also exploit the large quantities of electrical power available.

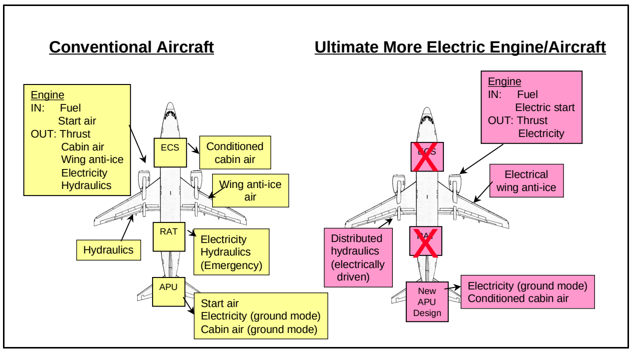

Figure 10 More Electric Aircraft

The MEE and MEA concepts are explored more fully by Provost [5].

To meet growing concerns on the effects of aviation on global warming, what solution can the industry offer? Some incremental improvements to the current generation of turbo-fans are possible, as outlined above, but they are limited. What is required is a radical change to the aircraft concept itself. A flying wing, broad delta-wing (see Denning et al [6]) or Blended Wing-Body (BWB) offer a potentially attractive solution.

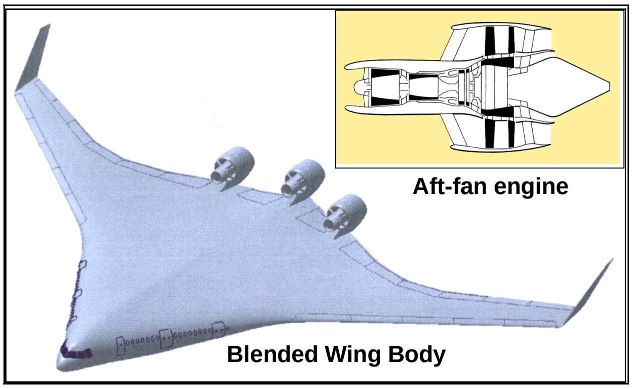

Figure 11 Blended Wing Body with ducted aft-fan engine

Besides the large potential benefits in aircraft weight and lift/drag ratio, there is better scope to integrate novel propulsion systems. By locating the power-plants above the wing and to the rear of the aircraft, ground clearance constraints on fan diameter (and hence BPR) are removed and the potential for engine noise shielding from the aircraft are considerable. A re-consideration of the ducted and un-ducted prop-fan concepts developed in the 1980’s is definitely worth pursuing, as they have proven demonstrated fuel burn advantages. Borradaile [7] and Peacock [8] give a good summary of such work carried out at Rolls-Royce. To achieve the best overall environmental performance, the BWB aircraft may have to be designed to fly slower ($<M=0.8$) to allow un-ducted rotors to be used, and perhaps lower to minimise contrail generation, but such a vehicle would seem to be very attractive. Besides the civil transport application, the vehicle potentially provides a good basis for a military transport, tanker or freighter, and this may well

be the initial opportunity for such a vehicle to be developed.

The super-sonic business jet (SSBJ) certainly is a more probable concept by 2020 than the new large SST discussed above. A vehicle design to travel at M=1.8 (double the speed of today's business jets), provides a more realistic means of continuing to make fast business travel available at the end of Concorde's life. Such a vehicle would need to have low sonic boom characteristics to allow supersonic overland flight to maximize its market potential, and would need to meet the same environmental regulations as sub-sonic aircraft. Although the fleet of such aircraft would not be large by 2020, a successful business case can probably be made for an 8-10 passenger SSBJ, with a propulsion system derived from a current turbo-fan engine, to keep development costs low.

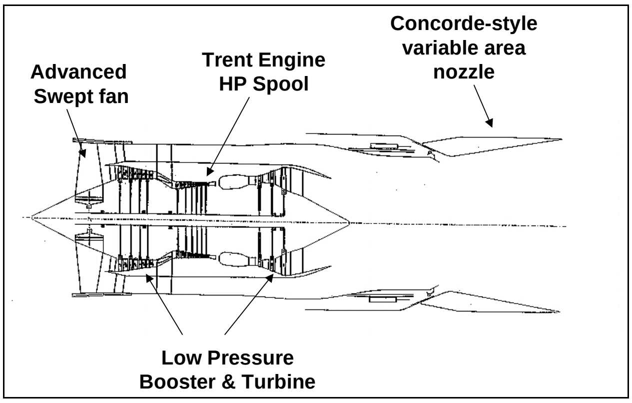

Figure 12. Engine for Supersonic Business Jet

In fact the high-pressure spool of the Rolls-Royce Trent engine 3-shaft architecture provides a good basis for an SSBJ propulsion system, and the incremental technology to make such an engine successful in this application is not large, see Figure 12.

5 Conclusions

This paper has reviewed the prospects for civil aviation over the next 20 years with particular focus on the requirements and limitations of the propulsion systems to be used. The aero-engine industry has made significant strides over the last 40 years, and there are still prospects for further more modest improvements, as the limits of the turbo-fan concept are approached. The opportunity for more radical changes will come with new airframe vehicles, which will remove many of the constraints on current propulsion system designs. Whatever does happen in the next 20 years, the aerospace industry remains an interesting and innovative place to work, and if only a few of the concepts discussed here come to fruition, there are many exciting challenges ahead.

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7 Acknowledgements

The author would like to thank Rolls-Royce plc for permission to present and publish this paper. Acknowledgement is also made to many colleagues and friends who have helped to develop many of the ideas presented here, in particular, Dr. M J Provost, and Prof G E Kirk.

It should be recognized that the views expressed in this paper are those of the author and do not necessarily represent the policy of Rolls-Royce plc.