Civil aviation and the environmental challenge

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ABSTRACT

In the coming century, the impact of air travel on the environment will become an increasingly powerful influence on aircraft design. Unless the impact per passenger kilometre can be reduced substantially relative to today's levels, environmental factors will increasingly limit the expansion of air travel and the social benefit that it brings. This essay considers the three main impacts, noise, air pollution around airports and influence on climate change. Of the three, impact on climate change is taken to have the greatest long-term importance and is discussed at the greatest length. It is argued that, of the three main contributors to climate change from aircraft – CO_2 emissions, NO_X emissions and the creation of persistent contrails – it is the last two which are the most promising targets. Ways of reducing the impacts of these two are discussed and it is noted that, in each case, the best environmental result is likely to entail some increase in CO_2 emissions. It follows that regulatory or economic measures to reduce impact on climate should be framed so as to do just that. Measures framed purely in terms of CO_2 emissions are likely to be counter-productive. Nevertheless, the design of aircraft to reduce fuel burn and hence CO_2 emission remains a key long-term objective; the essay considers the potential offered by new technology and new design concepts in this arena.

NOMENCLATURE

b	wing span
C_{DO}	drag coefficient at zero lift
D	drag
g	gravitational acceleration
H	calorific value of fuel (energy per unit mass)
k	vortex drag factor (unity for elliptically loaded wing)
L	lift
$(L/D)_m$	maximum lift/drag ratio
M	Mach number
p	static pressure
q	dynamic pressure ($= 0{\cdot}7p\mathrm{M}^2$)
$(q)_m$	dynamic pressure at flight condition for maximum L/D
R	range
S_{DO}	drag area ($= D/q$) at zero lift
Th_S	specific thrust (= net thrust per unit mass of engine air flow)
V	flight velocity
W	aircraft weight
W_E	aircraft empty weight
W_{MF}	weight of mission fuel
W_P	weight of payload
X	aircraft range parameter ($= H\eta L/D$)
η	overall propulsive efficiency ($= \eta_E\eta_P$)
η_C	combined efficiency of fan and its drive turbine
η_E	engine thermal efficiency
η_P	propulsive efficiency of jet (Froude efficiency)
λ	$q/(q)_m$

ACRONYMS

ACARE	Advisory Council for Aeronautics Research in Europe
BWB	blended wing-body
CAEP	Committee on Aviation Environmental Protection
DOC	direct operating cost
HLFC	hybrid laminar flow control
ICAO	International Civil Aviation Organization
ICR	inter-cooled recuperative engine cycle
IPCC	Intergovernmental Panel on Climate Change

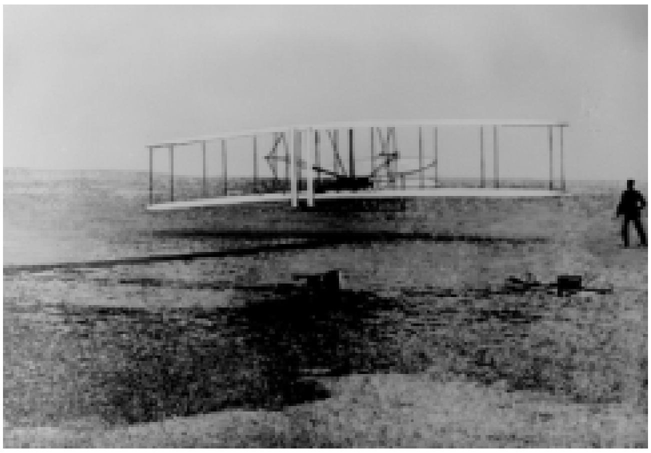

Figure 1. Wright Flyer, Kitty hawk, 17 December 1903.

Figure 2. Boeing B-47 Stratojet, first flight 17 December 1947.

NASA	National Aeronautics and Space Administration
NO_x	mixture of oxides of nitrogen, NO and NO_2, emitted by gas turbines
OAG	trademark of international provider of information on airline services and timetables
OPR	overall pressure ratio
TET	turbine entry temperature
TsAGI	Central Aerohydrodynamic Institute, Moscow
UDF	unducted fan

1.0 INTRODUCTION

At this time 100 years ago, in June 1903, the Wright Brothers were in Dayton, Ohio, preparing for the fourth of their annual trips to Kitty Hawk and for their first attempt at powered flight. In the fields around the villages of Colnbrook, Poyle and Horton, west of London, the loudest sounds were the call of birds and the hum of bees, augmented at intervals by the striking of church clocks and, very occasionally, the sound of a motor car. In London itself, travel was predominantly by horse-drawn trams and among the environmental concerns were fears that the city would be overwhelmed by horse manure and that there would be insufficient iron-making capacity to keep up with the demand for horseshoes(1).

In the 100 years since then the world has changed. Within 20 years the horse-drawn trams in London had been replaced by motor buses. Today, traffic congestion and the effect on air quality of motor exhausts are major environmental concerns, not only for Londoners but for the inhabitants of all large cities. Colnbrook and its neighbouring villages remained relatively quiet places until 1946, when operations began from the new London airport at Heathrow and they found themselves under the flight path. Today they are noisy places.

The evolution of the aeroplane has been an important factor in world change, both as a decisive force in warfare and, with the growth of air travel over the past 50 years, as a contributor to economic development and to better mutual understanding between the peoples of the world. Today, air transport is a main element in the world's largest industry, tourism and travel, which accounts for some 10% of world GDP. It is also growing faster than world GDP and is expected to continue to do so, with traffic projected to double over the next ten to 15 years and quadruple by 2050(2).

With this growth has come increasing environmental impact, both local and global. At present, the most significant impact is noise around airports which generates strong local opposition to airport expansion and to the construction of new airports. Potentially more important in the longer term is the impact on climate change. Although the effect of aviation on climate is relatively small at present, and imperfectly understood, it is forecast to increase and is already seen by environmental advisers as something which must be curtailed. If we do not reduce these impacts the future growth of air travel is likely to be inhibited.

In the UK, the Air Travel – Greener by Design initiative is the response of the civil aviation community to this environmental challenge. Its participants are the main stakeholders in air travel – the aircraft and engine manufacturers, airline and airport operators and the appropriate Government departments – and its primary objective is to assess and promote options for mitigating the environmental impact of aviation. More widely within Europe, the aeronautical research community has established the Advisory Council for Aeronautical Research in Europe (ACARE) and has set out a Strategic Research Agenda(3) which gives high priority to, and sets ambitious goals for, reducing environmental impact.

The first 100 years of aviation have seen the Wright Flyer transformed on the one hand into a formidable weapon and on the other into a safe and affordable method of travel. Over the next 100 years, the nature of the challenge to aeronautical scientists and engineers in the field of civil aviation is likely to change. Up to the present day, the challenge has been to design aircraft to fly further, faster, higher and at less cost. In the 21st century we may expect the emphasis to shift towards increasing safety and, above all, reducing the environmental impact arising from the ever-increasing demand for air travel. The Technology Sub-Group of Air Travel – Greener by Design considered this latter issue in some detail and, in looking ahead, this essay will draw heavily on the Sub-Group(4) report. The reports of the other two Sub-Groups, on Operations and Market-Based Options, are included in the overall Air Travel – Greener by Design report(5), published in February 2002, and are also relevant here.

Just over 100 years ago, on 4 December 1902, the President of the Royal Aeronautical Society, Major B.F.S.Baden-Powell, in his Presidential address to the Society(6), said:

> "*In America, Mr Wilbur Wright and his brother have been making wonderful progress with gliding machines and Professor Langley has been hard at work constructing a large machine ... what we see then, looming in the future, ... is the introduction of a new invention forming an invaluable and all-powerful weapon of war, an important aid to science and to the practical knowledge of our globe, and a speedy, economical and pleasant mode of getting from place to place, such as will completely revolutionise our present method of travel.*"

He was right. There is little hope of matching such an extraordinary prophecy in this essay but an attempt will be made, nevertheless, to set out the reasons why civil aviation might be expected successfully to meet the environmental challenge of the new century.

Figure 3. Airbus A380, first flight due 2005.

2.0 THE FIRST 100 YEARS

Figure 1 is perhaps the most famous photograph in aviation history, taken at Kill Devil Hills, North Carolina, at 10.35am on 17 December 1903. It shows Orville Wright taking off in the Flyer on the first of the four successful flights on that historic day. Wilbur is standing to the right.

Progress after those first flights was relatively slow, with the first US contract for a Wright aeroplane not being placed until 1908, the same year as the first powered flight in the UK by Cody in an aircraft of his own design at Farnborough. However, with the approach of World War 1 the pace began to quicken and by 1918 the aeroplane had changed from an object of curiosity into a potent military asset, thousands of which saw action in the war. In the post-war years commercial air travel began, using derivatives of wartime bomber aircraft, and technology continued to advance. Less than 30 years after the Wright brothers' first flights, in September 1931, a Supermarine S6B – an all-metal monoplane – set a new world speed record in excess of 400mph. World War 2 and the Cold War which followed brought a new burst of technological progress and on 17 December, 1947 the Boeing B-47 Stratojet shown in Fig. 2 made its maiden flight, 44 years to the day after the first powered flights at Kill Devil Hills.

The advances of World War 2 brought the all-metal monoplane to full fruition. The jet engine made it possible to fly economically at high altitude and the swept wing, developed but not fully exploited during the war, enabled aircraft to cruise at high subsonic speeds. The cruising speed of the developed version of the Stratojet, the B-47E-II, which entered service just 50 years ago and 50 years after the Wright brothers' first powered flight, was Mach 0·84 at 38,500ft.

Some 55 years after the first flight of the Stratojet, the aircraft in Fig. 3, the Airbus A380, is in development but is not scheduled to fly until 2005. It has a cruise Mach number and cruise altitude very similar to the Stratojet and is of the same basic configuration, a variant of the classical aircraft as characterised by Kuchemann[7], and first set out by Cayley in 1809, having a fuselage to carry the payload, a wing to provide lift, an empennage to provide stability and control and engines to provide thrust. The separation of these functions, which was central to Cayley's concept, has remained a feature of all subsonic transport aircraft.

Since the Stratojet, podded jet engines slung beneath swept wings have also become standard features of long- and medium-range civil transport aircraft. For Boeing airliners, from the 707 to the 777, and for the Airbus family, culminating in the A380, this has become the dominant design.

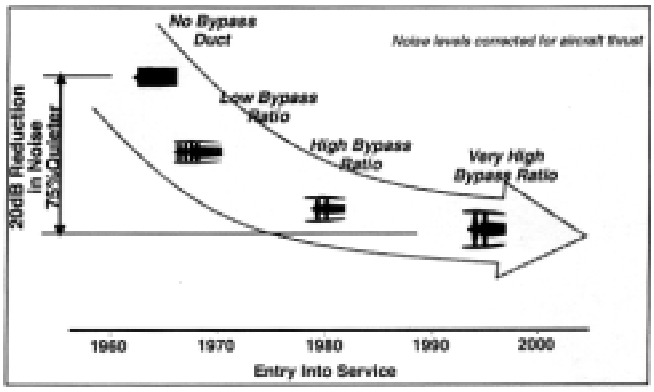

Figure 4. Aircraft noise, 1960 - 2000.

Murman and his colleagues[8], in a thought-provoking paper discussing the evolution of the aircraft industry, say:

> *"Examination of literature on industrial innovation indicates that aeronautical products have evolved to a 'dominant design' and entered the 'specific phase' of their product life cycle. Innovation in this phase centres on: incremental product improvement, especially for productivity and quality; process technology; technological innovations that offer superior substitutes."*

With the classical swept-winged configuration now so long established and highly developed, the analysis of Murman *et al* indicates that a powerful new incentive will be needed to induce any switch to a significantly different configuration. The environment may conceivably provide such an incentive but, for reasons set out by Murman *et al*, the forces of conservatism are strong in the 'specific phase'.

2.1 Aircraft noise

Over the first half of the twentieth century, aircraft noise was more often a cause of interest or excitement than of annoyance. Aircraft movements were relatively infrequent and the noise of propeller driven aircraft was not sufficient to arouse much public hostility. However, with the advent of turbojet powered civil aircraft and the steady growth of air travel which followed, noise around airports generated an increasing volume of complaint from local residents and in 1969, little more than a decade after the entry into service of the Comet 4 and the Boeing 707, the United States introduced its first aircraft noise regulations, FAR Part 36.

Two years later, in 1971, the International Civil Aviation Organization (ICAO) followed suit by adopting similar standards in ICAO Annex 16, Chapters 1 and 2. Chapter 1 covered the earliest jet aircraft, many powered by pure turbojets, while Chapter 2 covered the second generation of aircraft, powered by the quieter low bypass ratio turbofans. In 1977 ICAO adopted Chapter 3, setting more demanding standards which could be met only by aircraft with medium or high bypass ratio engines. In 1990, further regulations were adopted requiring all Chapter 2 aircraft to be withdrawn from service by 2002. Some of the Chapter 2 aircraft have been re-engined or fitted with 'hush kits' to enable them to be re-certificated under Chapter 3, so that today the entire world fleet satisfies the Chapter 3 requirements. In 2001, ICAO took a further step in adopting Chapter 4, which imposes tighter noise limits on all new aircraft types certificated from 1 January 2006. Chapter 4 will be met only by aircraft with high bypass ratio engines.

The evolution of ICAO noise regulation has tracked the reduction of aircraft noise since the jet airliner first came into service. Fig. 4, taken from a review by Birch[9] of future engines for civil aircraft, shows how, over a period of 30 years from the mid 1960s to the 1990s, aircraft noise at a given power level fell by 20dB. It is generally held that a reduction of 10dB is perceived by the listener as a halving of the noise, 20dB thus being subjectively a fourfold

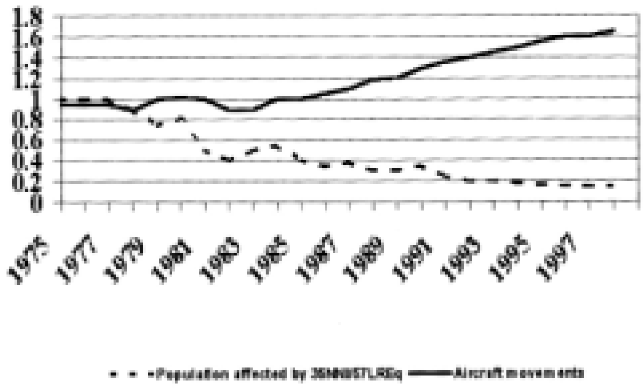

Figure 5. Heathrow population affected by noise.

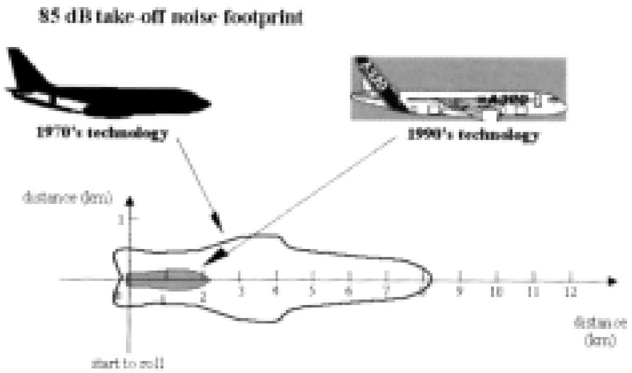

Figure 6. Noise comparison between old and new technologies, Airbus Industrie.

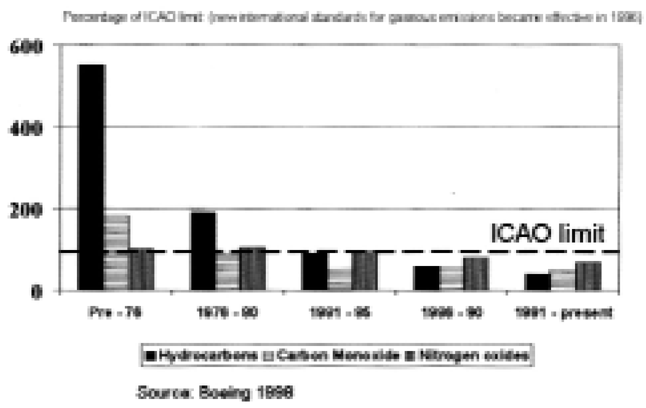

Figure 7. Aircraft engine emissions, percentage of ICAO CAEP/2 limit, Boeing 1998.

reduction. In physical terms, 20dB is a reduction in sound energy by a factor of 100 – an immense change.

Measured objectively, noise nuisance around airports was at its highest in the mid-1970s, when most of the fleet were Chapter 1 and Chapter 2 aircraft. Since then, the growth in traffic has been more than offset by the progressive replacement of these older aircraft by newer types powered by engines of higher bypass ratio. As a result, we see in Fig. 5 that, while the number of flights from Heathrow has increased by 60% since 1974, the number of people affected by noise has reduced to one fifth of what it was. The change is strikingly illustrated in Fig. 6 which compares the 85dB take-off noise footprints of typical passenger jet aircraft of the 1970s and 1990s.

The main reason for the reduction in noise has been the progressive increase in engine bypass ratio, driven by the demand from the airlines for better fuel economy. The progression from the pure turbojets of 1958 to the high bypass ratio turbofans of the 1990s has been a steady evolution at a pace largely dictated by what at the time has been technically achievable without unacceptable risk. The great leap forward was the advent of the high bypass ratio engine, the first of which entered service on the Boeing 747 in 1970. Since then, bypass ratio has continued to increase, fuel economy to improve and noise to fall. With each step forward, however, the gains have become increasingly hard to achieve.

ICAO regulation, which is done by international consensus, has followed rather than led the noise reduction achieved over the past 30 years. The members of ICAO are representatives of the governments and industries of the states that are signatories to the Chicago Convention, the legal framework that has governed international aviation since 1944. ICAO regulations are binding on the member states. In considering any proposed new regulation, ICAO members take account not only of environmental concerns but also of the commercial interests of their domestic airlines and manufacturing industries. Thus, for example, regulation to phase out older types of aircraft tends to be opposed by countries in which there are still a significant number of the older types in the fleet, the operators of which are looking for many more years of service to achieve a return on their investment.

That said, the first ICAO regulations were followed by a burgeoning of research into aircraft noise in the 1970s and the introduction of measures such as acoustic liners in intake ducts to reduce fan tones and mixer exhaust nozzles to reduce jet noise. These measures entailed weight and performance penalties and the work to develop and validate them added to aircraft first costs. Since the 1970s, therefore, noise reduction has imposed some economic penalty on all new civil aircraft.

A further influence on aircraft operators and, through them, on the manufacturers, has been the introduction of local regulations at particular airports. A notable example is the night-time curfew at Washington National, now Ronald Reagan Airport, introduced in the 1980s. The ability of the Boeing 757 powered by Rolls-Royce RB211-535 engines to meet the Washington night-time curfew levels was considered a great technical achievement at the time. Since then, local restrictions have become more widespread and today it tends to be these restrictions, at airports that are important destinations, that drive the noise requirements for new aircraft. Looking to the future, we may expect this to remain the case.

2.2 Local air quality

As they took off, the first generation of jet airliners left a highly visible trail behind them, a mixture mainly of soot and unburned hydrocarbons but containing also carbon monoxide and a mixture of nitric oxide (NO) and nitrogen dioxide (NO_2) collectively termed NO_x.

Although the effect of these emissions on air quality in the vicinity of airports became a matter of public concern rather later than noise, work to develop more efficient combustion chambers had been in progress from the beginning of the jet age. Fig. 7 shows how emissions of the three main noxious components of engine exhausts have reduced over the past quarter of a century relative to the ICAO standard that became effective in 1996. The most striking reduction is in unburned hydrocarbons, the result of research to improve combustion efficiency in order to reduce operating costs, but the advances in combustor design have also reduced soot dramatically. The ICAO standard for soot came into effect in 1983, followed in 1986 by the first standard for the three other main pollutants. Since then, the standards for soot, unburned hydrocarbons and carbon monoxide have remained unchanged while the standard for NO_x has been tightened.

The international emission standards are formulated by the ICAO Committee on Aviation Environmental Protection (CAEP). For NO_x the standard allows the emission index, expressed as the weighted average NO_x emission over four phases of the landing and take off cycle divided by the engine take-off thrust, to increase with engine pressure ratio. Fig. 8 shows this variation with pressure ratio for the original standard, CAEP/1, which came into effect in 1986, CAEP/2, a 20% reduction on CAEP/1 which has been effective for new engine types since 1996 and is the 100% line in Fig. 7, and CAEP/4 which reduces the CAEP/2 level by a further 16·25% for an engine with a pressure ratio of 30 but increases more steeply at higher pressure ratios. CAEP/4 is due to come into effect in 2004.

Figure 8 also shows the NO_x characteristics of a range of engines currently in service and two lower lines, representing reductions of 50% and 70% of the CAEP/2 standard, which have been proposed by NASA as near term and longer term goals for combustion research. The engine pressure ratio for the first target is 45:1. Although, for emissions as for noise, ICAO has adopted more stringent standards only when they have been shown to be economically achievable, CAEP does provide a focus for forward thinking and a stimulus for continued efforts to reduce emissions, as witness the formulation of NASA targets in terms of improvements relative to the CAEP/2 limit.

On the other hand, as with noise, local regulations are appearing which override the CAEP rules. Zurich airport, for example, has introduced a levy on aircraft that have NO_x emissions above a specific threshold, irrespective of engine pressure ratio. We shall come back to the relationship between NO_x emission and engine pressure ratio later.

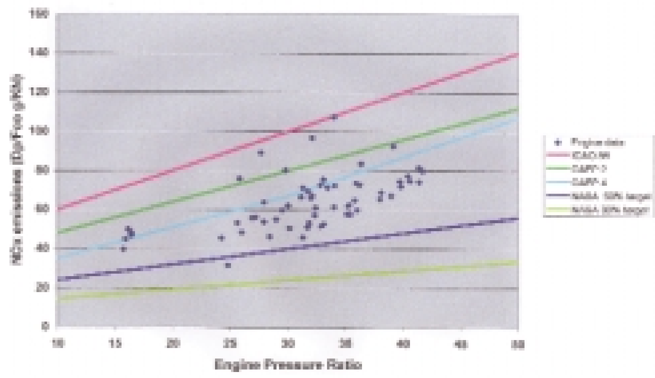

Figure 8. Engine NO_X characteristics values of D_p/F_{oo} for the ICAO LTO cycle, and changes in regulatory limits.

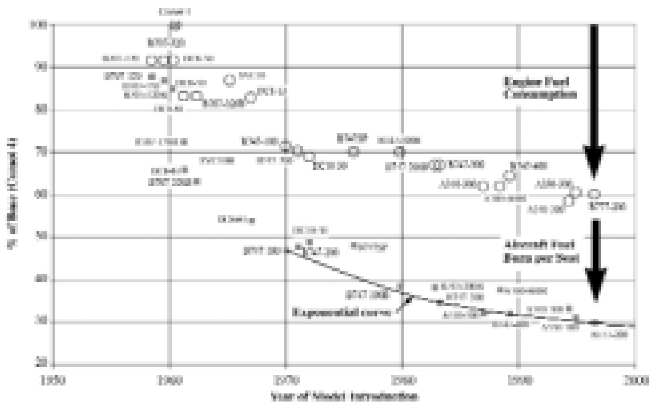

Figure 9. Trend in transport aircraft fuel efficiency.

2.3 Climate change

Concern about the impact of aviation on climate change is a relatively new phenomenon, lagging more than a decade behind concern about emissions in the vicinity of airports and two decades behind concern about noise. There is as yet no ICAO regulation in this field, although the subject is being considered by CAEP.

An important international milestone was the joint action in 1988, by the World Meteorological Organisation and the United Nations Environmental Programme, to establish the Intergovernmental Panel on Climate Change (IPCC), with the remit to: "(*i*) assess available information on the science, the impacts, the economics of, and the options for mitigating and/or adapting to, climate change and (*ii*) provide, on request, scientific/technical/socio-economic advice to the United Nations Framework Convention on Climate Change."

Since then the IPCC has produced a series of Assessment Reports, Special Reports, Technical Reports, methodologies and other products that have become standard works of reference, widely used by policy makers, scientists and other experts. In 1996, following a request from ICAO, the IPCC decided to produce a Special Report assessing the consequences of greenhouse gas emissions from aircraft engines. The resulting report, 'Aviation and the Global Atmosphere', was published in 1999(2) and is the most substantial work of reference currently available on this subject.

Although the Kyoto Protocol of 1997, which committed signatories to cutting greenhouse gas emissions by 12·5% of 1990 levels by 2012, explicitly excluded international aviation, the contribution of aviation to climate change has become increasingly prominent in the public eye. The Greener by Design initiative of March 2000 is partially a reflection of this growing concern.

More recently, on 29 November 2002, the Royal Commission on Environmental Pollution published a Special Report(10) entitled 'The Environmental Effects of Civil Aircraft in Flight' which took a far from sanguine view of the future. It expressed concern about the contribution of aircraft emissions to climate change, held that the projections of traffic growth and technological advance in the IPCC Report were likely to prove optimistic, in underestimating the first and overestimating the second, and included in its recommendations: the imposition of climate protection charges for aircraft taking off and landing within the EU; the restriction of airport development; the encouragement of a shift to rail transport for short-haul journeys and freight. In a similar vein, the Sustainable Development Commission, in a paper(11) which was issued on the same day addressing all environmental aspects of air transport, said:

> *"Above all, carbon dioxide and other greenhouse gas emissions from aircraft are becoming a more and more significant component of the greenhouse gases that are causing climate change. The contribution of air traffic to this crucial global problem can no longer be disregarded, but needs to be addressed as a central issue in considering the future of air traffic and of airports policy."*

Although the general subject of policy measures to reduce the environmental impact of air travel is beyond the scope of this

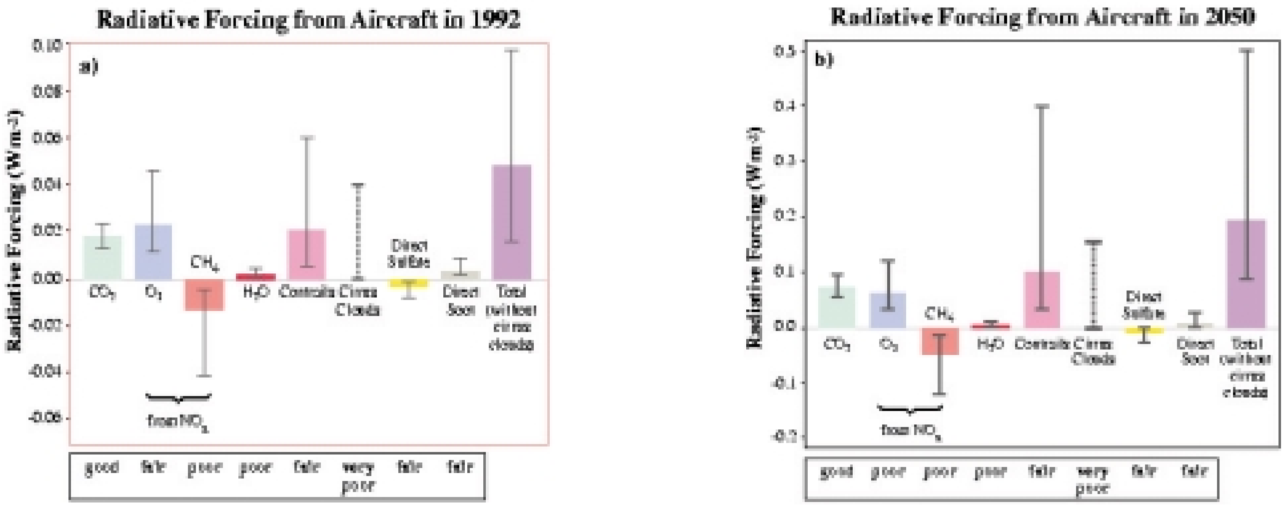

Figure 10. IPCC assessment of radiative forcing from aircraft.

essay, there are some aspects of policy which need to be aired. In particular, impact on climate tends in policy discussion to be linked to carbon dioxide emission, which is proportional to fuel burn. One of the measures proposed by environmental groups is a tax on aviation fuel, partly with the idea of promoting better fuel economy, and in the ACARE Strategic Research Agenda[3] one of the environmental goals is to reduce carbon dioxide emissions from new aircraft by 50% per passenger kilometre by 2020.

In fact, civil aviation has been very successful in reducing fuel burn, more successful over the past 40 years than any other form of transport. Fig. 9 shows how fuel burn per seat mile has fallen since the beginning of scheduled jet flights across the Atlantic. Today's new aircraft are 70% more fuel efficient than the Comet 4 of 1960, with 40% of the improvement attributed to greater engine efficiency and 30% to the airframe through more advanced aerodynamics and reduced weight. As an example of today's aircraft, the fuel burn per passenger kilometre of an Airbus A330 on a charter flight from Gatwick to Orlando, Florida, with a typical load factor, is 100 passenger mpg in motoring terms[12], comparable to a family car with three people on board.

An exponential curve is shown in Fig. 9, fitted through the most efficient aircraft of the last 30 years. Although it is only a curve fit, with no underlying theoretical basis, it does broadly reflect the trend of the data over quite a long time span. Its extrapolation forward to 2050 gives a further reduction of 9% relative to a 1997 baseline, a long way short of the 20-year goal of 50% reduction set by ACARE.

For climate change, however, fuel burn is not the whole story. Fig. 10, taken from the IPCC Report[2], shows the estimated contribution of the main components of aircraft emissions to radiative forcing in 1992, together with a projection forward to 2050. Radiative forcing is a measure of the importance of a potential climate change mechanism. It expresses the perturbation or change to the energy balance of the Earth-atmosphere system in watts per square metre.

Points to note about Fig. 10 are: (a) the factor of five increase in the scale of the chart between 1992 and 2050; (b) the quality of the estimated effects of all components except carbon dioxide is rated fair, poor or very poor, as indicated also by the whiskers denoting 67% confidence limits; (c) the fact that carbon dioxide is estimated to account for only about one third of the total contribution.

This last point is recognised, for example, in the recommendation by the Royal Commission on Environmental Protection[10] that:

> "*Any inclusion of aviation emissions in an emissions trading scheme will also have to take into account the fact that the total radiative forcing of aviation is about three times that of the carbon dioxide emitted. Just as non-carbon dioxide gases are accounted in terms of their global warming potential compared to carbon dioxide, so aviation emissions will need to be accounted to reflect their true contribution to climate change. This requires that the aviation industry should acquire three carbon emission permits for each unit of carbon that it actually emits.*"

The drawback of a simple approach of this kind is that incentives which focus on carbon dioxide emissions *per se* simply add to the already strong commercial pressure to reduce fuel burn. Because of the complex nature of radiative forcing by aircraft emissions, this may drive aircraft and engine design in a direction which increases radiative forcing. As is suggested later, the greatest reduction in radiative forcing may require compromises in which some increase in fuel burn is accepted.

2.4 100 years recap

It is some 45 years since the inauguration of scheduled jet airliner flights across the Atlantic and more than 55 since the first flight of an aircraft with the configuration that is now the dominant one for jet transport aircraft. Over that period there has been steady improvement in aircraft aerodynamics, structures, materials and engines, the high bypass ratio engine and supercritical wing design being the two greatest evolutionary steps.

Traffic, measured as payload times range, has increased by a factor of rather more than 20 since 1960. Public concern about noise and air pollution in the neighbourhood of airports and impact on climate change has also increased and is now a potential constraint on the future development of air travel.

The aircraft of today consume 70% less fuel, are 20dB quieter and emit substantially fewer pollutants than the first generation of jet airliners. ICAO regulations for noise and emissions have been progressively tightened to follow these advances, while always staying within the bounds of what has been shown to be economically achievable. Consideration of climate change by ICAO is still in its infancy.

Two facts above all should shape our thinking about the future. After 55 years, the dominant configuration is highly evolved and offers limited scope for further improvement. And two thirds of the contribution of aircraft emissions to climate change are estimated to come from emissions other than carbon dioxide.

3.0 ENVIRONMENTAL OUTLOOK IN THE 21st CENTURY

There is a song in the Rogers and Hammerstein musical Oklahoma! which proclaims, 'Everything's up to date in Kansas City. They've gone about as far as they can go.' This has led some to term the classic swept winged turbofan powered aircraft 'the Kansas City aeroplane' and the phrase does, indeed, capture the essence of the dominant configuration as described by Murman *et al*[8].

There are good reasons for this configuration to have emerged as the dominant one. It follows the principles of Cayley's classic aeroplane in separating the functions of providing volume, lift, stability and propulsion. It has optimised its exploitation of the swept wing to achieve efficient flight at high speed. It is built from materials that provide an admirable balance between weight, strength, durability and cost. It is powered by an engine which is close to the limit of achievable efficiency of a turbofan operating on the simple Joule cycle. It is now a very efficient machine.

Moreover, it serves an industry which is by nature, and for good reason, conservative and risk averse. Both the airline and aircraft industries operate in a highly regulated, highly competitive environment where margins are small, investment costs are high, many years are required to achieve a satisfactory return on investment and, above all, passenger safety is paramount. The travelling public and the airlines have become accustomed to the swept-winged airliner with windows in the cabin. The airports are equipped with gates designed to suit an aeroplane which carries its passengers in a long, relatively thin fuselage. After half a century of living happily with the dominant configuration, the public, the airlines and the manufacturers are unlikely to embrace a radically different alternative without a fairly powerful incentive.

The fact that the Kansas City aeroplane has gone almost as far as it can go, particularly in terms of improved economic and environmental performance, is recognised in the ACARE Strategic Research Agenda[3]. Under the heading 'ACARE Key Findings', addressing the 'Top Level Objectives', we find:

> '*The objectives are* ***not*** *achievable* ***without important breakthroughs, both in technology and in concepts of operation***'

(the emphasis here comes from ACARE) and similarly, in the section 'Meeting the Challenges', we find:

> 'The Environmental Challenge has clearly identified the limits of current technology, which, while it has more to offer and more that will be achieved over the next decade or so, must be succeeded by completely fresh approaches that require an early start.'

That echoes exactly the conclusions reached by the Greener by Design Technology Sub-Group[4].

The following sections discuss the potential for technological advance to offset the impact on the environment of continued growth in air travel. However, alongside technological advance, changes in operating procedures can also reduce the impact of both noise and emissions. The all-round opportunities here are discussed by the Operations Sub-Group in the Greener by Design report[5] and the opportunities to minimise fuel use and reduce emissions are discussed in an ICAO Circular[13] approved in 2001 at CAEP/5. The Sub-Group recommendations are wide–ranging, covering all aspects of operations on the ground as well as in the air, including travel to and from the airport.

Some of these offer worthwhile short-term gains, such as the use of a continuous descent approach (CDA) to reduce both fuel burn and noise beneath the approach path. Many leading airlines are promoting the use of this, and other fuel saving measures, within their guidelines on best practice. The most significant fuel savings, however, are expected to come from improvements in CNS/ATM systems, defined by ICAO[13] as 'Communications, navigation and surveillance systems employing digital technologies, including satellite systems together with various levels of automation, applied in support of a seamless global Air Traffic Management system.' We are many years away from the full realisation of this goal but ICAO claims in the Circular to have identified savings of about 5% to be expected by 2015 in the Continental US and Europe as a result of specific, planned, changes to the CNS/ATM systems. In the longer term, somewhat greater savings are projected. Operational procedures will not be discussed further in this essay.

Of the three environmental impacts of aviation, noise, local air quality and climate change, the Technology Sub-Group considered climate change to be the most important in the long term and devoted most of its attention to this subject. In the recent discussion paper issued jointly by the Department for Transport and the Treasury[14], estimates were given of the external costs of UK civil aviation of these three impacts for the year 2000, as follows:

Noise	£25m
Local air quality (LAQ)	£119m – £236m
Climate change	£1,400m

The origins of these figures are set out in Ref. 14 It is interesting that, although the external cost of air pollution around airports is estimated to be some five to ten times the cost of noise, complaints from the public about noise vastly exceed those about air quality. The key point about the figures is that, while they may be open to challenge on several fronts, they lead to the conclusion in Ref 14 that:

> '*Aviation's principal externality, which can be translated into monetary terms, arises from the effect of greenhouse gases and the impact they have on climate change.*'

This was also the view of the Technology Sub-Group and is the underlying theme in this essay.

3.1 Noise

While ICAO decided in 2001 to introduce the more stringent Chapter 4 standard, to be satisfied by all new aircraft types certificated from 1 January 2006, the pace is now being set by still tougher local requirements. At the London Airports (Heathrow, Gatwick and Stansted), movements at night, from 11pm to 7am, are controlled by a system of noise and number quotas imposed by the Department for Transport[15].

Figure 11 illustrates the system of Quota Count (QC) noise bands, spaced at 3dB intervals and doubling in QC value between bands, that apply to aircraft at departure. A similar scale applies to arrivals. The Department for Transport specifies the annual noise quota for each airport, defined as the total QC points (total movements times average QC per movement). The customers for the Airbus A380 required its certificated noise levels to fall within QC/2 for departure and QC/1 for arrival. Relative to ICAO Chapter 3, this increase in stringency is approximately twice that required by the change in 2006 to Chapter 4.

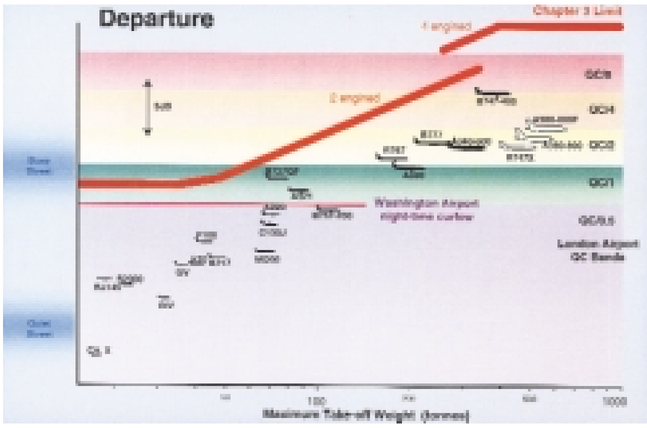

Figure 11. Noise Quota Count (QC) values for night time departures from Heathrow.

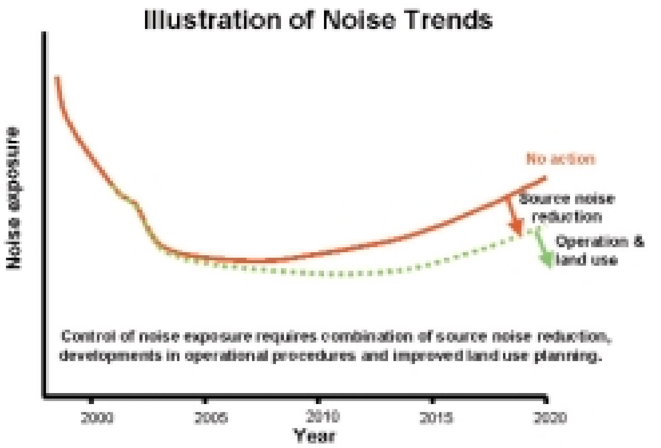

Figure 12. Illustration of noise trends, based on Rolls-Royce data.

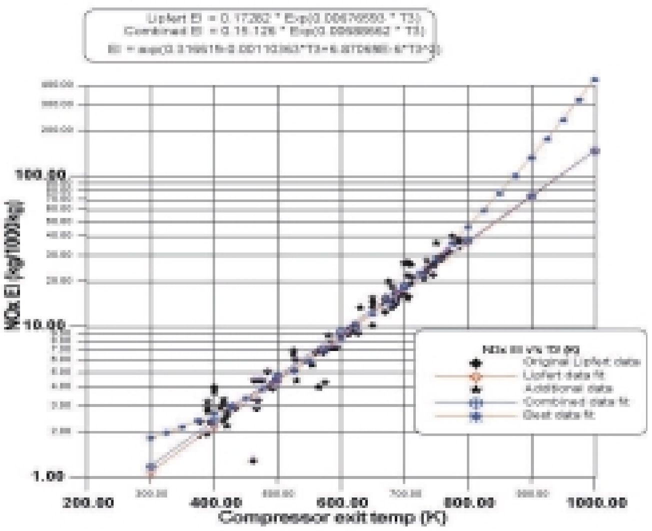

Figure 13. Correlation on NO emission index against compressor exit temperature, Karlsruhe University.

Looking to the future, we may expect the downward trend in noise exposure around airports, as shown in Fig. 5, to continue for a time, while the effect of retiring the older and noisier aircraft continues to outstrip the effect of growing traffic. However, as illustrated in Fig. 12, taken from Ref. 4, exposure is predicted to reach a minimum in about five years' time if there is no reduction in aircraft noise output below today's standards. There are, however, further noise reduction technologies in the pipeline and these are expected to move the time of minimum exposure to about a decade from now. Beyond that, further reductions in exposure can certainly be expected from improved operational procedures and, possibly, from better regulation of land use.

A mid-term goal of reducing aircraft source noise by a further 10dB has been declared by NASA[16] and is also included in the ACARE Strategic Research Agenda. Research on both sides of the Atlantic suggests that this will be achievable. It will amount to a reduction in acoustic energy of 99·9% relative to the aircraft of the 1970s. NASA has declared a further goal of 20dB below today's standards in 25 years' time. This would be a reduction in energy of 99·99% relative to the aircraft of the 1970s. It is unlikely to be achievable without a radical change in aircraft configuration to enable the engine noise sources to be shielded from the ground and perhaps, because of the noise generated by the airframe itself, not even then.

3.2 Local air quality

The focus of efforts to improve local air quality around airports is on reducing NO_x emissions. Current ICAO CAEP/2 and CAEP/4 regulations allow NO_x emissions to increase as engine pressure ratio rises. This reflects the fact that, for a given standard of combustor technology, increasing pressure ratio in order to increase engine thermal efficiency results in increased NO_x emissions. Fig. 13 shows an empirical relationship between NO_x emission index and compressor outlet (combustor inlet) temperature derived by the University of Karlsruhe[18]. This is for combustors of current design and curves upwards, even on a logarithmic scale, in contrast to the straight lines adopted by CAEP.

There are significant research programmes on both sides of the Atlantic aimed at reducing NO_x emissions. Fig. 14, taken from Ref. 2, shows three 'staged' combustors, representing the fourth generation of combustor design. The concept of the two separate combustion zones is that the pilot stage should provide good operational performance at low power while the main stage gives low NO_x at full power. The dual annular combustor shown in example (a) is the only type currently in service but is effective in reducing NO_x only in smaller engines.

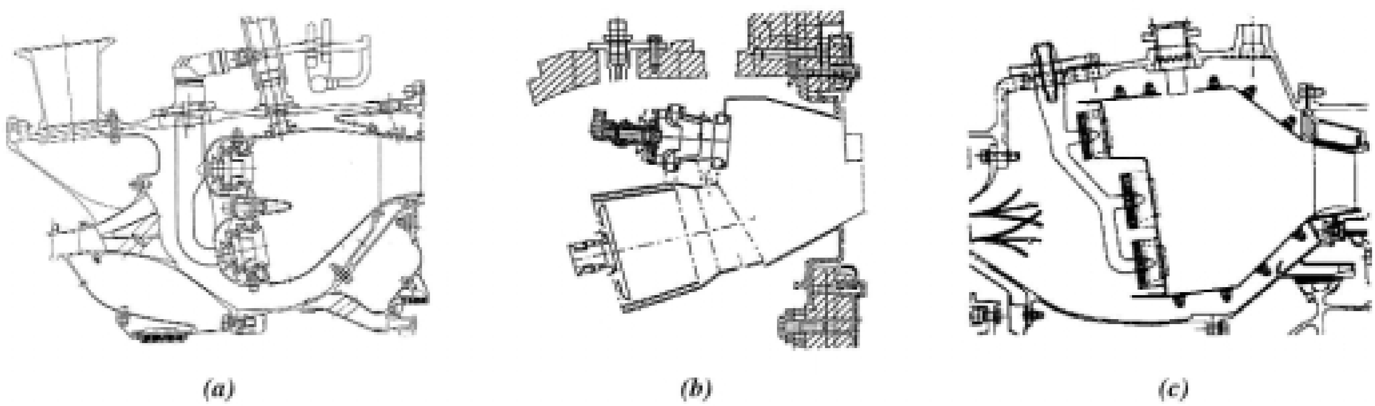

Figure 14. Staged combustors: (a) General Electric; (b) Snecma; (c) Pratt & Whitney.

So far, this technology has shown average NO_x emissions approximately 12% below the best of the third generation combustors at engine pressure ratios in the range 20 to 30. At pressure ratios above 35, however, demonstrated NO_x levels from fourth generation combustors are in the same range as the best of the third generation designs. In research aimed at a second generation supersonic transport, more advanced concepts, 'lean pre-mixing pre-vaporising' and 'rich burn quick quench', have been shown in rig tests to give very low levels of NO_x at the relatively low pressure conditions obtaining in the combustor of a supersonic transport.

There are difficulties in applying such concepts in the high pressure, high temperature environment of a modern high bypass ratio engine. Nevertheless, some of the features are incorporated, for example, in the combustor shown in Fig. 14(b) which is being studied under the EC Targeted Research Action EEFAE (Efficient and Environmentally Friendly Aero Engines). The ANTLE (Affordable Near Term Low Emissions Engine) Programme, led by Rolls Royce, is part of the same Targeted Research Action.

The primary objective of this research has been to achieve a substantial reduction in NO_x in the vicinity of the airport while at the same time pursuing ever higher engine pressure ratios and turbine entry temperatures in order to reduce fuel burn. It is suggested in Ref. 4, however, that this may not be the best way forward. In the context of climate change, it is argued that it would be better to strike a balance between NO_x and CO_2 emission which gives priority to reducing NO_x at the expense, possibly, of increasing CO_2.

3.3 Climate Change

Figure 10 shows the IPCC assessment in 1999 of the main contributions to climate change from aviation. The large uncertainty in the estimate of most of the contributions has already been noted and work since 1999 has changed the best estimates of some of the contributions. For example, it is now thought the reduction of methane by NO_x from aircraft is towards the lower limit of the error bar in Fig. 10 while the impact of ozone may be higher than shown[18]. Also, the combined effect of contrails and contrail-induced cirrus has now been strikingly illustrated by Travis *et al*[19] in an analysis of the average diurnal temperature range across the United States for the period September 11-14 2001, when no civil aircraft were flying. This was 1·1°C higher than the average for the same three days over the 30 years from 1971 to 2000. Moreover, its departure from the 30-year norm was 1·8°C higher than the average for the two adjacent three day periods in 2001.

The uncertainties in the published data remain large. Nevertheless, it is fairly safe to say that atmospheric scientists in Europe broadly accept that contrails and cirrus, together with the ozone generated by NO_x, are major contributors to the total impact of aviation on climate change. In the absence of a new generally accepted breakdown of that impact, and for the purposes of this essay, Fig. 10 can be taken as a working estimate of aviation's impact on climate. However, if nothing else, the present uncertainties in individual components point up the urgent need for a better understanding of atmospheric phenomena. The following sections will consider what might be done to reduce the impact of the three main contributors in Ref. 2, contrails and contrail-derived cirrus cloud, NO_x and CO_2. Before that, however, it is worth noting the lifetimes of the main greenhouse gases, shown in Table 1 taken from Rogers *et al*[18].

In the sections which follow, it will be suggested that there is greater potential for reducing the impact of ozone and contrails than of CO_2. However, because CO_2 has such a long life in the atmosphere, it is vital in the long term to achieve a substantial reduction in CO_2 emissions also.

3.3.1 Reducing contrails and aviation-induced cirrus cloud

For every tonne of kerosene burned, 1·23 tonnes of water vapour are emitted in the engine exhaust plume. At altitude in the upper troposphere and lower stratosphere, under conditions of low ambient temperature and high relative humidity, the exhaust stream is cooled by mixing with the ambient air and the water vapour condenses to form a visible trail. Minute particles in the exhaust stream, mostly soot and aerosol particles produced during combustion, provide the nuclei for condensation. The trail may evaporate again within a short time or it may persist as an identifiable contrail for an hour or more. As time passes, a persistent contrail is distorted and dispersed by wind shear to form cirrus cloud which is similar in character to naturally occurring cirrus.

Table 1
Lifetimes of greenhouse gases and aircraft emissions

Carbon Dioxide	50 – 100 years
Methane	8 – 10 years
Water	days (sea level)
	weeks (tropopause)
Ozone	week (sea level)
	months (tropopause)
NO_x	days (sea level)
	weeks (tropopause)

The processes and the underlying physics are well set out by Lee *et al*[20], where it is noted that there may be a second type of aviation-induced cirrus. This is postulated to form, without necessarily a contrail precursor, when a body of humid air seeded with particles from aircraft exhausts cools and becomes ice-saturated. There is circumstantial evidence that this mechanism does create additional cirrus but neither the processes nor the extent to which they add to naturally occurring cirrus are well understood.

As regards contrails themselves, the conditions under which they can form are reasonably well understood, as are the conditions under which they quickly evaporate again. For contrails to persist and to degenerate into cirrus the air within the contrail, when the engine exhaust is extensively mixed with the ambient air, must be saturated or supersaturated with respect to ice. However, because the engine exhaust adds heat as well as water vapour to the air mass, the critical conditions of temperature and humidity for a contrail to persist depend on the propulsive efficiency of the engine. As engines have become more efficient, mean exhaust temperatures have fallen and the temperature-humidity boundary for the creation of a long-lived contrail has moved upwards, so that contrails are found in warmer air today than in the 1970s.

Lee *et al* observe that there is no current or envisaged technology that will inhibit the formation and persistence of contrails. If a kerosene-fuelled aircraft flies through an ice-saturated air mass, contrails will form and persist. That said, ice saturation tends to occur in defined volumes of cold, relatively humid air which have been characterised[21] as 'moist lenses'. These have a maximum vertical extent of a few kilometres and a maximum horizontal extent of about 1,000km, the precise extent for a particular air mass depending on engine propulsive efficiency. As Lee *et al* note, an individual lens could, in principle, be avoided by flying over it, under it or around it.

There are several reasons why it would be premature to recommend this as an operational procedure: the basic scientific understanding is not yet sufficiently robust; neither air traffic management nor meteorological forecasting are currently well placed to support such a procedure; the possible impact of changes in flight altitude on ozone is not well understood; evasive action would increase fuel burn, CO_2 emission and airline costs.

Nevertheless, if we allow for some significant contribution from cirrus, Fig. 10 suggests that a strategy of contrail avoidance would be a powerful way of reducing the impact of air travel on climate. In, say, 20 years' time, improvements in air traffic management and meteorological information might well make such a strategy practicable. Regulation, perhaps backed up by on-board monitoring, could require compliance. The costs to airlines would probably be small in

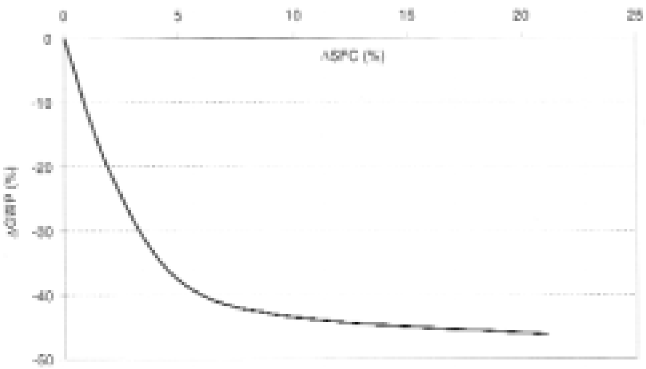

Figure 15. Trade off between reduced Global Warming Potential and increased SFC relative to minimum SFC design (Whellens and Singh).

comparison to some of the environmental charges on fuel that have been suggested recently.

For the aircraft designer, the longer term challenge would be to minimise the economic penalty of a strategy of contrail avoidance. This could mean designing wings to perform efficiently over a wider range of altitude, possibly using some form of variable wing geometry to maintain good performance over a wide range of lift coefficient. Also, if flying lower to avoid contrails were to result in more time spent flying through turbulence, we might envisage the introduction of active control technology coupled with forward-looking turbulence sensing in order to reduce structural loads and improve passenger comfort. These are not impossible challenges. Within 20 years, possibly less, the key technology to adapt economically to contrail avoidance could be available for incorporation into new designs and possibly also into later versions of existing designs. Fig. 10 suggests that this would be a cost effective, and possibly the single most powerful, way of reducing the impact of aviation on climate, even though it would increase CO_2 emissions.

3.3.2 Reducing the impact of NO_x

As noted in 3.2 earlier, there are substantial research programmes in Europe and the United States aimed at reducing NO_x emissions. The goals of these programmes tend to be related to the ICAO Landing and Take-Off (LTO) cycle, being expressed as percentage reductions relative to the CAEP/2 standard. Nevertheless, any major reduction in emissions in the LTO cycle can be expected to produce a worthwhile reduction of NO_x at cruise. The research referred to in section 3.2 is described more fully in Refs 2 and 4. If the contribution of NO_x to climate change is as Fig. 10 indicates, then the large reduction in emissions promised by the more ambitious of these research programmes will reduce impact on climate significantly.

The conflict between reducing CO_2 and reducing NO_x was noted in 3.2 and considered at greater length in the Technology Sub-Group report[4], where it was suggested that the pressure ratios of current large engines may be higher than optimal from the standpoint of impact on climate. Although the high pressure ratios of these engines give lower fuel burn and hence lower CO_2 per unit thrust than their smaller, lower pressure-ratio counterparts, the effect on climate of their higher NO_x emissions more than outweighs the effect of lower CO_2. From the perspective of climate change, the current drive to achieve still higher pressure ratios in the name of greater fuel efficiency appears open to question.

The IPCC report[2] quoted a conclusion of the International Coordinating Council of Aerospace Industries Association in a paper[22] submitted to CAEP/3:

> '*There is no single relationship between NO_x and CO_2 that holds for all engine types. However, for the best current aircraft engine and combustor design technologies, there is a direct link between the emissions of NO_x and CO_2. As the temperatures and pressures in the combustor are increased to obtain better fuel efficiency, emissions of NO_x increase, unless there is also a change in combustor.*'

The IPCC report went on to discuss two scenarios for the year 2050, one in which engine design was aimed at both improved fuel efficiency and NO_x reduction, the other in which there was much greater emphasis in designing to reduce NO_x. The forecast reduction on CO_2 emissions by 2050 was 40-50% for the first scenario, 30-40% for the second. The forecast reductions in NO_x were 10-30% and 50-70%. Forecasts 50 years ahead have to be treated with caution but it is worth noting that the mean values of these forecasts suggest a four-to-one trade-off between percentage increases in NO_x and reductions in CO_2.

One of the recommendations of the Technology Sub-Group was that a study should be made of aircraft and engine design concepts aimed specifically at minimising impact on climate change rather than fuel burn. As part of a broader study of methods for propulsion system optimisation, Whellens and Singh[23] took up this suggestion. Within an overall multi-disciplinary optimisation based on a genetic algorithm, the authors embedded a design model for a large high bypass ratio turbofan engine which was optimised under a range of design constraints against alternatively economic or environmental objective functions. The design model, though it involved fairly simple modelling of components, was essentially complete insofar as it included sizing and performance calculations for all the key components including the combustor, together with a prediction of the NO_x emission index based on the geometry, pressure, temperatures and residence time within the combustor.

The impact of emissions at cruise altitude was estimated using the model of Klug *et al*[24], which was also used in Ref. 4 to explore the effect of cruise altitude on climate change. This model uses the now out of favour metric of global warming potential (GWP) rather than the preferred metric of radiative forcing. A further shortcoming is that it includes only the effects of CO_2, NO_x-generated ozone and water. Reservations about the use of GWP are discussed in Refs 2,4 and 18. Deficiencies in the model will affect the numerical results obtained by Whellens and Singh but are not likely to affect the trends shown by their study.

They took as their baseline an engine optimised for specific fuel consumption (SFC) at cruise. This optimal design had an overall pressure ratio of 43·8 and a turbine entry temperature of 1,555K. An equivalent engine optimised to minimise its impact on climate had an overall pressure ratio of 11·5 and a turbine entry temperature of 1,300K. Its estimated impact on climate was 46% lower than the baseline engine but its SFC was 21% higher. This was seen as an unduly large penalty but it was found, by considering a range of intermediate designs optimised to minimise climate impact for a fixed SFC penalty, that a substantial reduction in environmental impact could be obtained for a relatively modest increase in SFC. The results, shown in Fig. 15, suggest a reduction in impact on climate of between 30% and 40% for a 5% increase in SFC.

The authors included in their study an illustrative case of an engine with a hypothetical ultra-low NO_x combustor. They assumed pre-mixed pre-vaporised combustion and adapted the formula for NO_x generation in their engine model to represent this. With this different combustion technology, the engine giving minimum impact on climate had an overall pressure ratio of 39·5 and a turbine entry temperature of 1,469K. It achieved a reduction in climate impact of 64% relative to the baseline engine for an increase in SFC of 1·2%.

The study formed part of a wider investigation of multi-disciplinary optimisation and its conclusions with respect to climate change must be qualified. First, the model of Klug *et al* makes use of Global Warming Potential as a metric, against the opinion of current atmospheric scientists. Second, it covers only the contributions to climate change of CO_2, NO_x-generated ozone and water and it is only the change in the total effect of these three components that is noted above and plotted in Fig. 15. The effects on contrails and methane are not included. Third, the modelling of the combustion processes, particularly in the case of the pre-mixed pre-vaporised combustion, is illustrative rather than exact. Fourth, the understanding of the atmosphere, particularly the effect of NO_x on ozone and methane, and the consequent impact on climate, is not sufficient to allow firm quantitative conclusions to be drawn.

Nevertheless, the study provides two strong pointers. First, there is the potential of a significant reduction in impact on climate, at the cost of a modest increase in fuel burn, by reducing engine pressure ratio in order to reduce NO_x generation. Secondly, the development of ultra-low NO_x combustion technology should provide a substantial environmental improvement, with an engined optimised to minimise impact on climate only slightly less fuel efficient than one optimised to minimise SFC.

The study was done for a single cruise altitude of 35,000ft. In the report of the Technology Sub-Group, the model of Klug *et al* was used to explore the effect of varying cruise altitude on climate change. It was suggested in the report that the impact on climate might be considerably reduced by reducing cruise altitude, primarily due to the reduced effect of NO_x on ozone at lower altitude according to the model. There has, however, been no further evidence to support the model and at the time of writing it is possible only to say that the effect of NO_x on climate change probably does vary significantly with the altitude at which it is released. Atmospheric science does not yet allow the effect to be expressed quantitatively with any confidence but, if there is indeed a significant variation with altitude, then there are implications for future aircraft design. It is too soon to say whether these implications will be in harmony or conflict with the implications of contrail avoidance discussed in the previous section.

3.3.3 Reducing CO_2 emissions

For kerosene-fuelled aircraft, Reducing CO_2 emissions requires reducing fuel burn, pure and simple. The appropriate cost-benefit metric is fuel burn per passenger-kilometre. Within the constraints on noise and emissions imposed by ICAO, one of the primary economic goals of manufacturers and airlines, particularly for medium- and long-haul operations, is to reduce fuel burn per passenger-kilometre or, in engineering terms, fuel burn per unit payload-range.

In Annex A of the report of the Technology Sub-Group[4], a form of the Breguet range equation was derived which can be cast as an expression for fuel burn per unit payload-range. The equation assumes continuous cruise climb so as to maintain the aircraft at its optimum cruise condition and includes an allowance for the fuel burned during taxiing, climb to cruise altitude and enroute manoeuvring. If we write W_{MF} for the mission fuel burned between engine start up and shut down, W_P for the payload and R for the range, then from Annex A of Ref. 4 we can derive, for an aircraft with a mean cruise altitude of 35,000 ft,

$$W_{MF}/RW_P = (1 + W_E/W_P)(1{\cdot}022\exp(R/X) - 1)/R \qquad \ldots (1)$$

in which X is a range performance parameter given by,

$$X = H\eta L/D \qquad \ldots (2)$$

where H is the calorific value of the fuel, η is the overall propulsion efficiency of the engine and L/D is the lift-to-drag ratio of the aircraft at cruise. It is usual to express H in Joules/kg but, since this has the dimension length, H can also be expressed in km, as was done in Ref. 4 and will be done here. Since η and L/D are dimensionless, X is expressed in km. For a kerosene-fuelled, medium- or long-range swept-winged aircraft with currently achievable values of η and L/D, X is approximately 30,000km.

It is apparent from Equation (1) that, if an aircraft design specification is fixed in terms of payload and range, fuel burn per unit payload range can be reduced only by reducing the ratio of empty weight to payload and by increasing X. For a kerosene-fuelled aircraft, H is fixed, leaving η and L/D as the only two variables in X. Design range itself has an important influence on fuel burn but, once it is fixed, the only options for reducing fuel burn are to reduce empty weight and increase propulsion efficiency and lift-to-drag ratio. Although there are some interactions between these three variables, it is convenient to discuss them in turn.

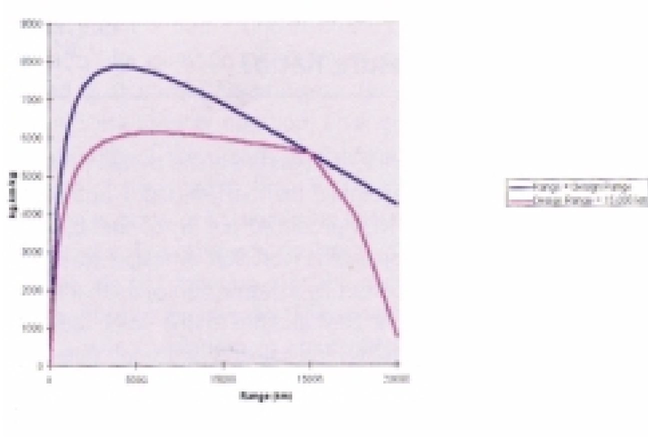

Figure 16. Payload-fuel efficiency versus range and design range for swept-winged, kerosene-fuelled aircraft.

3.3.3.1 Effect on fuel burn of design range

The variation of fuel burn per unit payload-range for a given standard of technology was analysed in Ref. 4. The reciprocal of this quantity, payload-fuel efficiency, expressed in km, is plotted against design range for a kerosene-fuelled, swept-winged aircraft of current technology standards as the outer curve in Fig. 16. Fuel efficiency is a maximum at a design range around 4,000km and remains reasonably high for design ranges between 2,000km and 7,500km. The inner curve shows the variation of payload-fuel efficiency with range for an aircraft with a design range of 15,000km. It has a maximum at a range of 6,000km but this is some 20% lower than that of an aircraft with a design range of 6,000km.

Further analysis in Ref. 4 indicated that an aircraft designed to carry a given payload over a range of 15,000km in a single stage would have an empty weight and a total mission fuel burn 40% greater than an aircraft designed to carry the same payload over a range of 5,000km which did the journey in three stages. The corresponding values of W_E/W_P in Equation (1) were 3·0 for the long-range aircraft and 2·1 for its medium-range counterpart. With such large differences in capital and fuel costs, which typically account for 60% or more of direct operating costs, the three-stage option appears likely to be the best value for money. It was therefore proposed in Ref. 4 that a full system study should be made of the feasibility of undertaking long distance in travel in stages not exceeding 7,500km. Since the publication of Ref. 4 it has been suggested more than once, not altogether flippantly, that in-flight refuelling might be a preferable alternative to the passenger carrier landing and taking off again. Now there's a thought!

3.3.3.2 Reducing empty weight

There is undoubtedly scope for greater use of lighter structural materials within both the airframe and engine, though cost and safety considerations have slowed their uptake. The subject was reviewed by

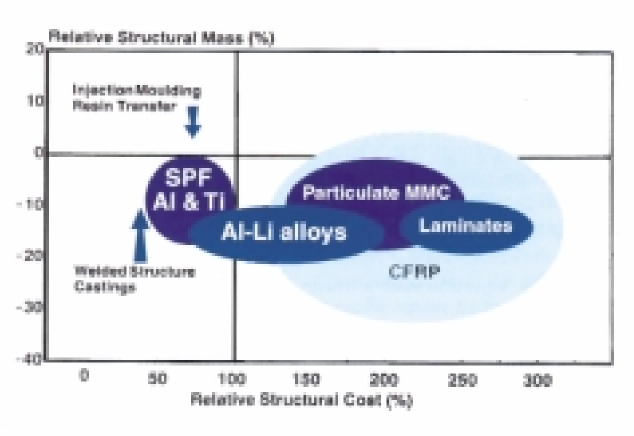

Figure 17. Relative mass savings and costs of advanced materials (Peel, 1996).

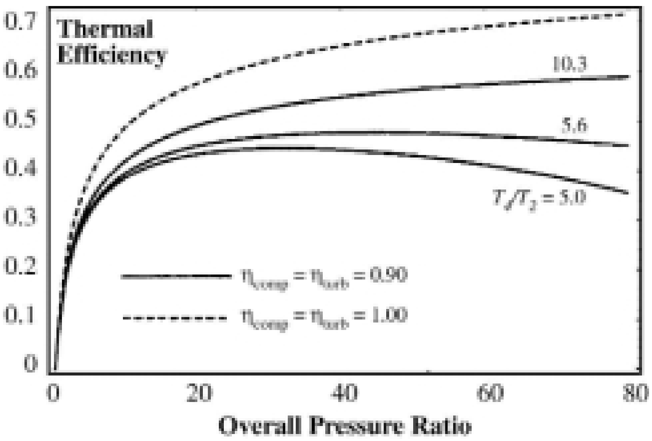

Figure 18. Gas turbine thermal efficiency (from IPCC report).

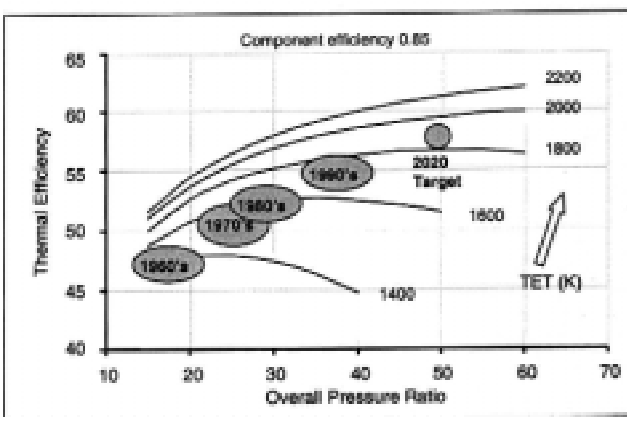

Figure 19. Gas turbine thermal efficiency (from Birch).

Peel[25] and Fig. 17, taken from that review, illustrates the potential weight savings and costs of some of the alternatives to the traditional materials†.

Peel cites two alternative forecasts, made in the early 1980s, of the proportion by weight of structural composites to be expected in subsonic transport aircraft of the 1985-95 epoch. These envisaged an increase from 3% in the contemporary Boeing 767 to 25% ('conservative') or 65% ('optimistic'). In the event, the so-called conservative estimate proved to be highly optimistic. For the Airbus A330 and Boeing 777, both aircraft of the 1990s, structural composites account for some 15% of structural weight. This leaves scope for further weight reduction but Peel sets out the reasons why, historically, the replacement of conventional materials by lightweight alternatives has been slower than forecast and may continue to be slow in the future.

Structural weight can also be reduced by more efficient structural design. The Kansas City aeroplane has been evolving for more than half a century, however, and there can be little scope for significant gains through structural design alone, without the introduction of new manufacturing technology. On the other hand, a change of configuration, such as the adoption of a flying wing or blended wing-body layout, could lead to quite appreciable reductions in empty weight.

The aircraft specification and general design features also affect weight. As was noted in 3.3.3.1, design range can have a powerful influence on empty weight. The difference in empty weight between long-range and medium-range aircraft designed for the same payload is substantially greater than the reduction in weight of the long-range aircraft that can be expected from advances in structures and materials over the next, say, 20 years.

Design cruise Mach number affects weight to a lesser extent, but it also affects propulsive efficiency. Reducing it enables wing sweep to be reduced or thickness increased, resulting in a wing optimised for lower cruise Mach number being lighter, but at the cost of reduced propulsive efficiency. Similarly, increasing wing span in order to increase lift-to-drag ratio increases weight, particularly if wing area is held constant and aspect ratio increased. These interactions are complex and can only be addressed in detailed design studies. In Ref 4 it was conjectured that developments over a 50-year period would reduce empty weight by 15% relative to current designs. Although there was also some feeling within the Technology Sub-Group that this might be optimistic, reducing empty weight without compromising safety will remain a significant environmental objective.

3.3.3.3 Increasing overall propulsion efficiency of conventional turbofan engines

The overall propulsion efficiency η appearing in Equation (2) can be written as the product

$$\eta = \eta_E \eta_P \qquad \ldots (3)$$

where η_E is the thermal efficiency of the gas turbine and η_P is the propulsive (Froude) efficiency of the jet. The Froude efficiency has to be less than 100% because the engine develops thrust by ejecting the engine flow at a velocity higher than that of the aircraft. Consequently some of the work put into the flow by the engine is dissipated – i.e. wasted – in mixing downstream of the exhaust. If the specific thrust of the engine (the net thrust of the engine divided by the total air mass flow through the engine in kg/kg/s) is Th_S and the aircraft is flying at velocity V, the propulsive efficiency of a turbofan engine is closely approximated by

$$\eta_P = \eta_C/(1 + gTh_S/(2V)) , \qquad \ldots (4)$$

where g is the gravitational acceleration and η_C is the efficiency of conversion of power in the engine exhaust into power in the fan

†See also the papers by A. Beukers et al. and H.Flower and C.Soutis in this issue of *The Aeronautical Journal.*

stream – i.e. the product of the efficiency of the fan and of the turbine driving it. This equation shows that propulsive efficiency increases as flight speed increases and specific thrust decreases. For an aircraft cruising at Mach 0·85 near the tropopause, with engines having a specific thrust of 12kg/kg/s in cruise, typical of today's standard, the ideal propulsive efficiency in equation (8) is 81%. Typically, the conversion efficiency η_C lies between 80 and 85%, giving a propulsive efficiency between 65% and 70% and an overall propulsion efficiency η around 37% on an advanced engine today.

Unless a more complex engine cycle than the classical Joule or Brayton cycle is adopted, the scope for further increases in η through technological advance is strictly limited. Fig. 18, taken from Ref. 2, shows how, for this cycle, thermal efficiency η_E varies with engine overall pressure ratio for a range of ratios of turbine inlet temperature to engine inlet temperature. The solid lines are for compressor and turbine efficiencies of 90%, the uppermost one being for a temperature corresponding to stoichiometric combustion – ie, to a fuel/air ratio sufficient to consume all the oxygen in the air. The broken line above represents stoichiometric combustion in a machine with 100% efficient turbomachinery. This is a limit imposed by the laws of physics, but an unreachable one.

Figure 19, taken from the review by Birch[9], is in the same form as Fig. 18 but shows the evolution of actually achieved thermal efficiency from the 1960s to today, with a target shown for 2020 some 2% to 3% above the best of today's engines. To achieve that target will require an increase in both overall pressure ratio (OPR) and turbine entry temperature (TET).

As is shown however in Fig. 20, taken from Ref. 9, merely increasing OPR and TET without improvements in other aspects of engine technology will not necessarily reduce fuel burn. The upper, rather distorted carpet in the figure shows the effect of increasing TET at constant OPR, and vice versa, on the assumption that the higher pressure ratio will lead to a reduced engine core size and higher performance losses through scale effects while the higher turbine temperatures will require higher cooling flows. Both effects reduce cycle efficiency with the result that all the points on the carpet give higher specific fuel consumption (SFC) than the datum. The lower carpet shows the reduction in SFC that would be achieved if cooling flows and component efficiencies could both be held constant at the higher duties, but this would require significant technological advance.

The assessment in Ref. 9 is that efficiency gains of about 3% can be achieved over the next 20 years through further TET and OPR increases, but only if materials and cooling technology continue to advance. In addition, improvements in turbomachinery aerodynamics might lead to increases in component efficiency worth about 4% of engine fuel consumption over the next 20 years. However, while this possibility is noted in Ref. 9, it is also recognised that the benefit of further aerodynamic advances might well be taken in increased component loadings, hence reduced parts count, weight and cost of ownership, rather than in increased thermal efficiency.

For the turbofan engine based on the Joule cycle, the scope for increasing propulsive efficiency η_P is even more limited. Increases in the energy conversion efficiency η_C of the fan and its drive turbine may provide a further few percent but both components are already highly developed and highly efficient. Of the other terms on the right hand side of Equation (4), Th_S and V, flight velocity V is limited by the onset of transonic drag rise over the wing, when drag begins to rise more rapidly than propulsive efficiency, and reducing specific thrust is in principle the only way of increasing propulsive efficiency.

However, as Fig. 21, taken from Ref. 9, indicates, today's high bypass ratio engines are at an economic optimum for current technology. Although it is evident from Equation (4) that further reduction in specific thrust would increase propulsive efficiency, any gain relative to today's standards would be offset, in the overall assessment of aircraft performance, by the increase in nacelle drag and engine weight consequent upon the increase in fan diameter.

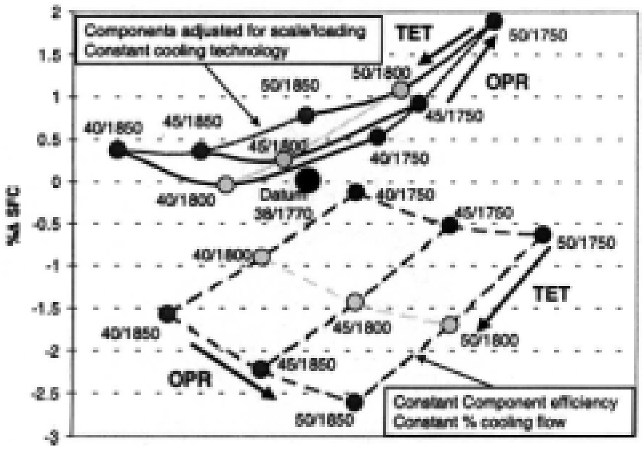

Figure 20. Variation of SFC with OPR and TET.

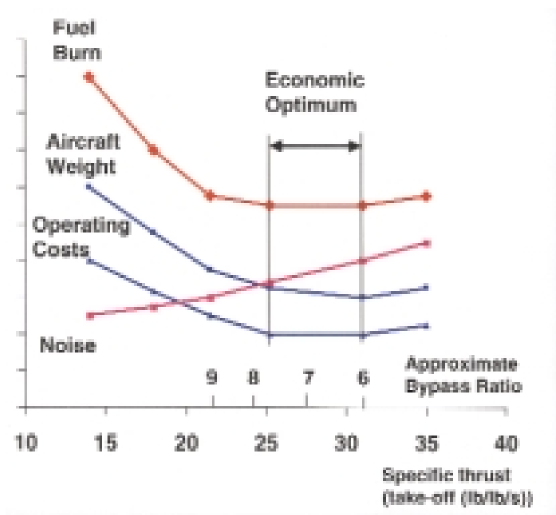

Figure 21. Variation of fuel burn, weight, operating costs and noise with specific thrust.

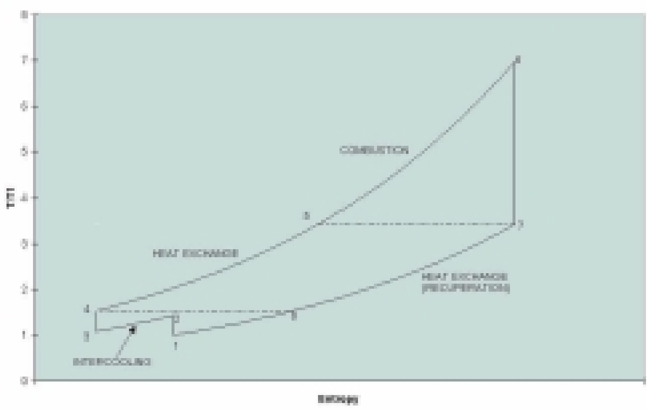

Figure 22. Temperature-entropy diagram for ICR cycle.

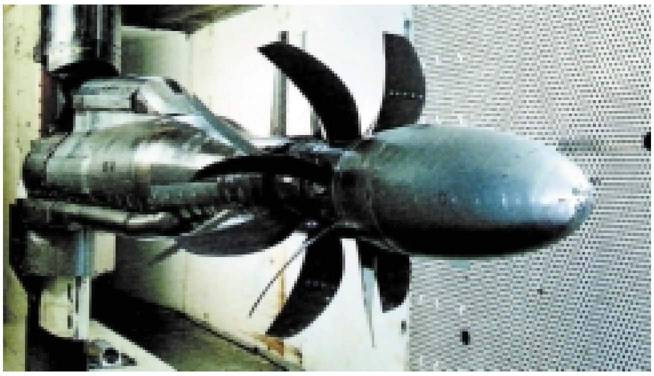

Figure 23. Large scale UDF model in the ARA transonic wind tunnel.

From Fig. 21 it is seen that, with today's technology, the net effect of any further, significant reduction in specific thrust would be to reduce noise but to increase operating costs, aircraft weight and fuel burn. It is no secret that the customers for the Airbus A380 have accepted a fuel burn penalty of 1-2% as a consequence of specific thrust being reduced sufficiently to meet particular Heathrow night-time QC levels (Fig. 11).

Further technological advances which reduce nacelle drag or weight – for example, laminar flow control applied to the nacelle or greater use of lightweight materials in nacelle construction – might lead to the economic optimum being at a lower specific thrust than today, but the overall improvement in fuel efficiency can be only a few percent at best.

3.3.3.4 Alternatives to the Joule cycle and the turbofan

A change from the simple Joule thermodynamic cycle to a more complex alternative is one option for increasing thermal efficiency which merits serious investigation. A recent study[26] of an engine employing a more complex cycle concluded that the adoption of an inter-cooled recuperative (ICR) cycle could lead to an engine with significantly higher thermal efficiency and substantially lower NO_x emissions than an equivalent engine based on the Joule cycle. Although considerably heavier than the baseline engine, the ICR engine would be similar in frontal area and general layout to the baseline engine and could therefore be installed in an under-wing position on a low-winged, wide-bodied aircraft.

An ideal thermodynamic cycle for an inter-cooled-recuperative turbofan engine is shown in Fig. 22. The compression is done in two steps, 1-2 and 3-4 on the diagram. Between these two, the compressor flow is cooled (2-3), thereby reducing the shaft power required for the second step of compression. The cooling of the core flow between 2-3 is achieved by heat exchange with the fan stream. The exit flow from the compressor outlet 4 is then heated (4-5) by heat exchange with the turbine exhaust flow (7-8). To achieve this, the compressor outlet flow is ducted to the rear of the engine, to a heat exchanger downstream of the turbine, and then ducted forward again to enter the combustion chamber at 5. The addition of fuel (5-6) raises the temperature to the turbine entry level.

For an ideal cycle, with 100% efficient compressor and turbine, perfect heat exchange and no pressure losses in the heat exchanger, an overall pressure ratio of 12 and temperature ratio of seven would give a thermal efficiency of 81%, compared with 64% for an ideal Joule cycle at a pressure ratio of 35. If component efficiencies are 90% rather than 100%, but heat exchange is still perfect and no pressure losses occur in the heat exchangers, the thermal efficiencies of the two cycles would fall to 78% and 54% respectively.

In the real world, however, much of this advantage of the ICR cycle is eroded. Heat exchangers sufficiently compact to be incorporated into a turbofan engine will, inevitably, achieve significantly less than full equalisation of temperatures between the turbine exhaust and compressor outlet streams (and also the fan and intermediate compressor streams) and will cause pressure losses in the fan, compressor and turbine exhaust streams. In addition, the heat exchangers will increase engine weight substantially.

The study reported in Ref. 26 was concerned with the practicalities of suitably compact heat exchangers. It concluded that it was feasible, using well established heat exchanger technology, to produce an ICR engine comparable to a current high by-pass ratio engine but with reductions of approximately 10% in SFC and 35% in NO_x emission, with the two engines having equal technology standards in all other respects. The estimated weight of the ICR engine was between 70% and 75% greater than the conventional counterpart adopted as a baseline for the study, the CF6-80C2B1F.

The feature of the ICR engine which led to the substantial reduction in NO_x was the low overall pressure ratio chosen for this cycle, 12 as compared with 35 for the baseline engine. The authors point out that, because of this low pressure ratio, there is potential for further improvement in emissions by incorporation of ultra low NO_x combustor technology. For example, the lean pre-mixed pre-vaporised (LPP) combustion system, which offers very substantial reductions in NO_x emissions on SST engines but which is at risk of 'flashback' or upstream burning at the high pressure ratios of modern engines, may be a realistic option for the ICR engine.

There are many practical obstacles to the introduction of this technology, not least of which is the achievement of efficient, low pressure-loss heat exchange at an acceptable weight penalty. The paper study of Ref. 26 suggests that the technology exists to do this, but it has yet to be demonstrated in an aero-engine. The CLEAN programme, which is part of the EEFAE programme now in progress under the EC Fifth Framework Programme, is aimed at a demonstration, at the component level, of the potential of the technology. Even then, there are questions of safety, reliability, maintenance, cost of ownership, structural implications for the airframe, to be resolved before the ICR engine can be considered a candidate powerplant for future aircraft. A substantial programme of research and technology demonstration will be needed to reach this point.

As regards Froude efficiency, the one available way of bypassing the impasse revealed in Fig. 21 is to discard the fan cowl and the weight and drag penalties it entails and revert to an advanced propeller. Although it too, ultimately, runs into limits set by the laws of physics, the so-called the prop-fan or unducted fan (UDF) engine does offer the prospect of a significant increase in propulsive efficiency relative to the turbofan engine.

Over the past 20 years there have been appreciable advances in propeller design methods, notably in the evolution of blades with swept tips designed to reduce compressibility effects and achieve high efficiency at higher flight speeds. Single-rotation propellers of this form will be used, for example, on the Airbus A400. However, the Mach number range of this aircraft is 0·68 to 0·72, well below the cruise speed of today's long-range civil aircraft, and the single-rotation propeller is not suitable for appreciably higher cruise speeds. On the other hand, a pair of contra-rotating propellers in tandem[†] can operate with high efficiency at cruise speeds up to Mach 0·8 and this configuration has been considered a credible alternative to the turbofan for some applications.

Figure 23 shows a large scale UDF research model that was tested aerodynamically and acoustically in the transonic wind tunnel of the Aircraft Research Association. Interest in the concept was at its highest in the mid to late 1980s and culminated in successful flight demonstration programmes, notably of the General Electric UDF mounted in a rear-engine installation on the MD-80 aircraft. The reduction in fuel consumption achievable by this form of propulsion was not, however, considered sufficient to offset the concomitant weight, first-cost, maintenance, noise and safety (blade-containment) penalties. As a result, the concept was not supported either by the manufacturing or the operating industries. Moreover, it was applicable only to rear-engined and high-wing layouts and was considered primarily as a

[†]The terms prop-fan and unducted fan have both been used for this form of propulsion. In this essay, unducted fan and its abbreviation UDF, which is a General Electric trade mark, are adopted.

candidate for short and medium haul aircraft. This last point is noteworthy, since it is in a long-haul application that the benefits in fuel saving, and the associated saving in aircraft structure weight and cost, offer the greatest commercial benefit.

If the UDF is considered at some future date for large aircraft, we can expect the noise regulations then in force to drive the fan design towards large diameters and low specific thrusts. This will benefit fuel burn, but will mean that such fans will be candidates only for configurations significantly different from today's, having the engine thrust line sufficiently high to give the propellers adequate ground clearance. Designs with high wings, rear or over-wing engines are possible candidates, as is the blended wing-body, but it would require a major change in the commercial and regulatory environment to make such a development likely, particularly for longer-range aircraft.

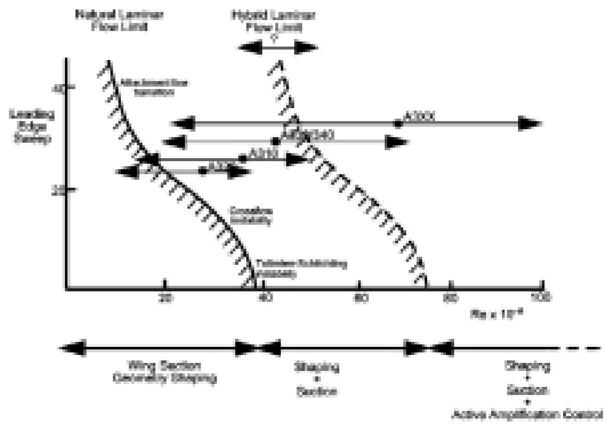

Figure 24. Limits of laminar flow control technologies.

3.3.3.5 Increasing aircraft lift-to-drag ratio

Basic relationships. For the third component of X in Equation (1), lift to drag ratio, it is a classic result that L/D is a maximum when the profile and vortex drag components are equal. There is a more detailed discussion in Section 4.2.2.3 of Ref. 4 and here we need only consider the key results. With suffix m denoting conditions at which L/D is a maximum, we have

$$(L/D)_m = b\sqrt{(\pi/(4kS_{DO}))} \qquad \ldots (5)$$

at a flight condition given by

$$(q)_m = 0{\cdot}7(p\mathrm{M}^2)_m = W\sqrt{(k/(\pi b^2 S_{DO}))} \qquad \ldots (6)$$

where p is pressure at the flight altitude, M is Mach number, W is aircraft weight, b is span, S_{DO} is drag area at zero lift, k is the vortex drag factor and π is π. Since k is slightly above unity and approximately constant for modern swept winged aircraft, maximum L/D is proportional to the ratio of two lengths, the span and the square root of the zero-lift drag area, and the dynamic pressure at the flight condition for maximum L/D is proportional to a loading based on the product of these two lengths.

If the aircraft operates at a dynamic pressure q greater than $(q)m$ and we write

$$q = \lambda(q)_m\,, \qquad \ldots (7)$$

L/D is then given by

$$L/D = 2(L/D)_m/(\lambda + 1/\lambda) \quad , \qquad \ldots (8)$$

which varies relatively slowly for values of λ around unity. For example, for a value of λ of 1·25, corresponding to flight at the design Mach number at an altitude approximately 5,000ft below the altitude for maximum L/D, the value of L/D given by Equation (8) is 2·5% below the maximum.

In fact, in the overall optimisation of the aircraft design, taking account of factors such as the influence of cruise altitude on engine weight and hence on payload, it is usual to design for a cruise L/D slightly lower than the maximum. For today's long-range aircraft, maximum L/D is typically slightly less than 20. In the aircraft design studies reported in detail in the Technology Sub-Group report[4], the design point was taken to be at a lift coefficient corresponding to a lift-to-drag ratio 2·0% below $(L/D)_m$ and a value of λ of 1·22. All the modelling in Ref. 4 was then predicated on aircraft adopting the most fuel efficient cruise condition, which is continuous cruise-climb at a constant value of λ, with Mach number held constant and altitude increasing so as to reduce ambient pressure in line with reducing weight as fuel is burned.

Vortex-drag factor and wing span. As Equation (5) shows, there are three variables which determine maximum lift-to-drag ratio, vortex-drag factor k, span b and drag area at zero lift S_{DO}. For a modern swept-winged aircraft, k is typically around 1·20 and there is little that can be done to reduce it (disregarding the addition of winglets, which complicates the analysis underlying the classic model and is analogous to increasing span).

Increasing span directly, with S_{DO} constant, produces a proportional increase in L/D. In practice, increasing span will usually increase S_{DO}, so that the increase in L/D will be less than proportional to the increase in span. Span is not, however, something that can be easily increased, being constrained by structural and weight considerations and, after more than 50 years of evolution of the Kansas City aeroplane, being close to optimum on today's aircraft. Furthermore, for large aircraft such as the Airbus A380, the requirement to stay within the 80m box allowed by today's airports is a new constraint which effectively defines maximum span. Folding wing tips, using the technology developed for naval, carrier-based aircraft, offer a route to spans greater than 80m and may in due course become a feature of large aircraft, but they add weight and complexity and raise interesting certification questions.

Reducing drag: swept-winged aircraft with laminar flow. The third variable in Equation (5), S_{DO}, is the basic profile drag of the aircraft, ie the sum of the skin friction drag and pressure drag of the aircraft at zero lift. For the Kansas City aeroplane, with turbulent boundary layers over almost its entire surface, there is little more that can be done to reduce profile drag. There may be scope for some further aerodynamic refinement of the powerplant installation and of the wing-body junction and underbelly fairing but here too, after 50 years of progressive improvement, scope is limited. The use of riblets to reduce turbulent drag has shown a modest benefit and there has been research into schemes such as passive shock control which may or may not reduce drag but these have not shown sufficient promise to justify their complexity. Some other possibilities are noted in Ref. 4 but none show real promise.

There are, however, alternatives to the swept-winged aircraft with fully turbulent boundary layers which can reduce S_{DO} significantly. The first of these is the application of laminar-flow control to the swept-winged aircraft. For smaller aircraft, this can be done by shaping the aerofoil so as to maintain gently accelerating flow over the forward 50% or so of both upper and lower wing surfaces, thereby maintaining laminar boundary layers over the first half of the wing and reducing the pressure drag arising from rapid growth of the turbulent boundary layer in the decelerating flow over the rear of the wing. This entirely passive form of control, termed natural laminar flow (NLF), has been demonstrated both in the wind tunnel and flight. It is most suited to smaller aircraft with relatively low wing sweep, and therefore relatively low cruise Mach numbers.

For larger swept-winged aircraft, hybrid laminar-flow control (HLFC) is a candidate. This employs aerofoil shaping in combination with boundary-layer suction over forward parts of the wing to

Figure 25. Wind tunnel model of a blended wing-body configuration.

achieve the same effect that NLF produces on smaller wings. It has been demonstrated in flight on a glove fitted to the wing of a Boeing 757 and on the fin of an Airbus A320. The possible limits of sweep and wing Reynolds number over which NLF and HLFC might be applied are shown in Fig. 24 and discussed more fully by Wong and Maina[27]. The design studies in Ref 4 drew on a joint project study by Airbus and Cranfield University[28] to model the application of HLFC to the wings, empennage and nacelles of a large transport aircraft. With this comprehensive application of HLFC, the modelling gave a reduction of 28% in C_{DO} and an increase of 18% in *L/D*. Relative to the datum of a swept wing aircraft designed for its most fuel efficient range, 4,000km, the aircraft with HLFC burned 14% less fuel per unit payload-range at its most fuel efficient design range of 4,750km. The Airbus/Cranfield study gave a fuel burn reduction of 19% over a sector of 5,500km for an aircraft with a design range of 14,500km.

A drawback of HLFC is that the distributed boundary-layer suction carries with it weight, suction-power, surface-manufacturing cost and maintenance penalties. However, the suction in the leading-edge region, required to suppress the flow instability due to sweep, also suppresses disturbances caused by surface roughness. Susceptibility to leading-edge contamination by insects should be less of a problem than on natural laminar-flow surfaces, but maintaining the perforated suction surfaces in good working order might be a challenge to maintenance teams.

For certification purposes, there will be a requirement to carry fuel reserves sufficient to complete the mission safely in the event of a failure of the suction system. Wing design philosophy has a part to play in selecting a design which remains aerodynamically efficient in this event. The rules governing the commercial operation of a hybrid laminar-flow control aircraft are not yet defined but it is possible that they will require a fuel load which erodes an appreciable fraction of the potential reduction in fuel burn achieved by laminar flow. The certification of HLFC aircraft is discussed in Ref 29.

One of the important conclusions of the Airbus/Cranfield study[28] was that the reductions in fuel burn and direct operating costs (DOC) are appreciably greater for an aircraft optimised to exploit HLFC than for an aircraft with HLFC applied as a retrofit. Relative to a datum long-range aircraft with fully turbulent boundary layers, operating over its optimal range of 3,000nm, the aircraft re-optimised for full HLFC gave a reduction in DOC of 6·6% while the datum aircraft retrofitted with HLFC gave a reduction of only 2·6%.

Reducing drag: the blended wing-body. Over the past decade, there has been a growth in interest in the blended wing-body (BWB) as an alternative to the dominant design for large, long-range aircraft. The concept (Fig. 25) has evolved from earlier flying-wing and delta-wing aircraft as a combination of a moderately swept outer wing, similar to that on the dominant design, with a central wing-cum-fuselage capable of housing a large number of passengers, typically in two decks with 24 or 26 abreast seating at the widest part of the cabin.

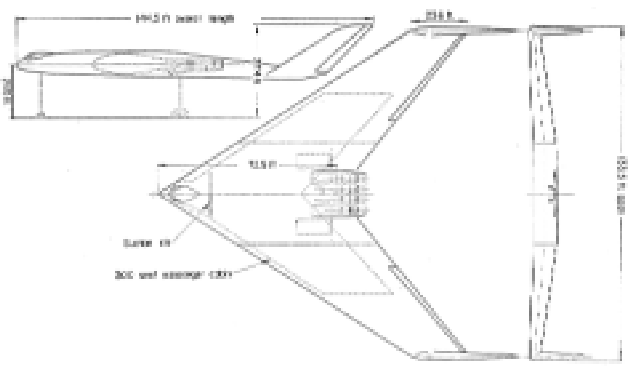

Figure 26. Handley Page projected 300-seat laminar flow airliner.

In the UK, the most substantial investigation of this type of configuration has been the design study at Cranfield University, involving some 76,000 engineer hours of MSc student time over a three-year period[30]. The principal aerodynamic advantage offered by the BWB is greater aerodynamic efficiency arising from the elimination of the fuselage and tail surfaces. For a typical BWB configuration, the ratio of total surface area (and hence S_{DO}) to the square of the wing span is roughly 75% of that of the A340. From Equation (5) we would expect maximum *L/D* to be 15% higher as a result. This is, in fact, what is reported to be the result of a study by TsAGI[30] of this type of configuration. The other significant result reported by TsAGI is a reduction of 14% in take-off weight relative to a conventional aircraft designed for the same payload, range and cruise Mach number (0·85). The BWB configuration included in the Technology Sub-Group studies derived its aerodynamic and structural constants from the TsAGI work. Relative to the datum swept-wing aircraft, the BWB at its most fuel efficient design range, 4,750km, showed a reduction of 17% in fuel burn per unit payload-range.

Reducing drag: the laminar flying wing. The case has been argued by Denning *et al*[32] for a re-appraisal of the concept of a large flying wing with all-over suction to maintain a laminar boundary layer over virtually the entire surface of the aircraft. This is not a new concept. In Ref 33, which reviews the large volume of research into laminar flow up to 1961, there is an account of a projected 300 seat laminar flow flying wing (Fig. 26). This aircraft, designed to cruise at Mach 0·8, was predicted to have direct operating costs a third less than those of an equivalent conventional aircraft.

In the 40 years since the aircraft in Fig. 26 was proposed there has been some progress in understanding the engineering challenges presented by such a design and a more realistic assessment of its potential is now possible. There can be little doubt that, within a time span of under 50 years, such an aircraft could be built and put into service. Whether it would be attractive to the operators in terms of first cost, maintenance cost, reliability or susceptibility to environmental hazards is another question but, if these can be made acceptable, a significant reduction in operating costs and environmental impact should be in prospect.

The Technology Sub-Group formulated a notional flying wing design with full laminar flow achieved by all-over suction through a perforated skin. The derivation of its aerodynamic and structural parameters is explained in Ref. 4. The basis of these parameters is the US data on flight tests on an F-94 aircraft fitted with a full-chord suction glove on the wing upper surface, reported in Ref. 33, together with figures for suction system weight derived from the Handley Page engineering studies also reported in Ref. 33.

As set out in Ref. 4, the values adopted for drag, suction-power requirements, system-weight and structural-weight constants were

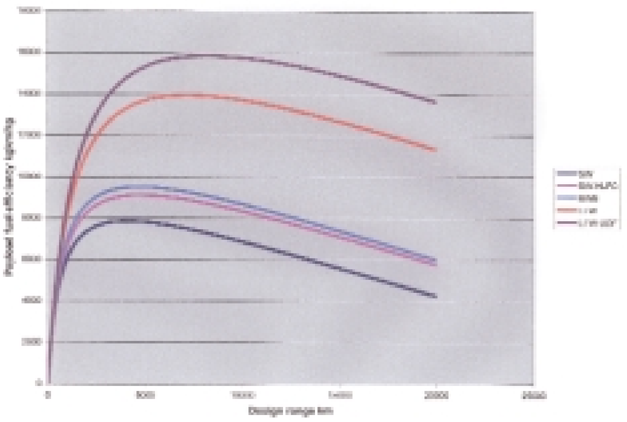

Figure 27. Payload fuel efficiency versus design range for kerosene-fuelled aircraft.

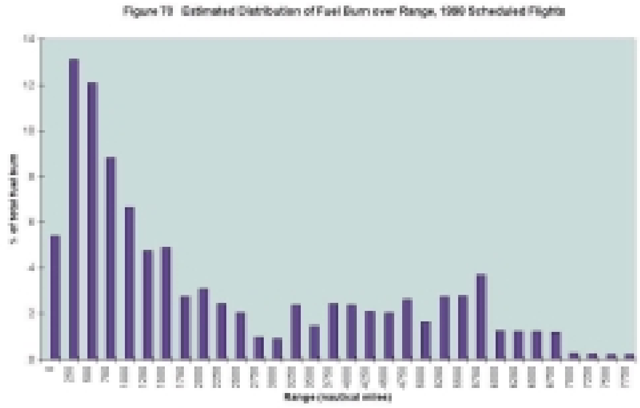

Figure 28. Estimated distribution of fuel burn over range, 1998 scheduled jet flights.

believed to be conservative and significant potential weight savings on structure and engines were ignored. Even so, the projected fuel burn per unit payload-range for this aircraft, at its optimum design range of 7,250km, was 44% lower than that of the datum swept-winged aircraft designed for 4,000km.

Flying wings with unducted fan propulsion. In the design studies in Ref. 4, versions of the BWB and laminar flying wing were also modelled with UDF propulsion, resulting in further fuel burn reductions. The most fuel-efficient configuration modelled was the laminar flying wing with UDF propulsion which, at its optimum design range of 8,250km, gave a projected fuel burn per unit payload-range 50% lower than the datum 4,000km swept-winged aircraft.

In Fig. 27 the payload-fuel efficiencies of the swept-winged aircraft, the HLFC swept-winged aircraft, the BWB, the laminar flying wing and the laminar flying wing with UDF propulsion are plotted against design range. As noted already, relative to the baseline swept-winged aircraft the respective reductions in fuel burn per unit payload range are 14%, 17%, 44% and 50% for each configuration at its optimum design range. For a design range of 15,000km for all configurations, the reductions are 21%, 24%, 56% and 62% respectively.

The blended wing-body with laminar flow. A configuration not included amongst those studied in Ref. 4 is an aircraft of blended wing-body layout which employs HLFC on its relatively narrow outer wings and full laminar-flow control by suction over its body. Comparable versions of this and the laminar flying wing derived in Ref. 4 are likely to have similar values of *L/D*, the blended wing-body having a higher drag area S_{DO} at zero lift but also a greater span. This suggests a way forward in which, in the first instance, the blended wing-body might be introduced as an aircraft with turbulent boundary layers all over. In parallel with this, swept-winged aircraft designed to exploit HLFC might be entering service. A second generation BWB with laminar-flow control, hybrid on the wing and all-over on the fuselage, might then follow. A target for this of half the fuel burn per unit payload-range of a contemporary swept-winged aircraft might not be unreasonable.

3.3.3.6 Sector length, total fuel burn and impact on climate

In the discussion of the potential for reducing fuel burn by advanced technology, the focus tends to be on large, medium- and long-range aircraft. The prominence given to the blended wing-body configuration as the possible shape of things to come is one example of this focus and, indeed, the modelling of alternative aircraft configurations done by the Technology Sub-Group[4] was all for travel over ranges from 5,000km to 15,000km (2,700 to 8,100 nautical miles).

However, Fig. 28, showing an estimate from Ref. 4 of the distribution of world fuel burn against length of sector (in nm) for scheduled jet transport flights[†], suggests that less than 30% of fuel is burned on sectors of 5,000km or more. More than half the estimated consumption for civil aviation is over sectors of less than 2800km (1,500nm). These are indicative estimates rather than definitive statistics but they help to focus thought.

One thought that comes to mind is that, in general, the longer the sector, the higher the cruise altitude. The risk of forming persistent contrails is dependent on altitude and it is suggested in 3.3.2 that the impact of NO_x may also vary significantly with altitude. Consequently, the extent to which the impact of CO_2 emissions are augmented by the effects contrails and NO_x may vary with cruise altitude and hence with sector length. As our understanding of atmospheric behaviour increases, we could possibly come to the conclusion that, by virtue of their higher cruise altitude and the greater proportion of the flight spent at cruise altitude, long-range aircraft make a greater contribution to climate change per tonne of CO_2 emitted than do short-range aircraft.

A second thought which comes to mind is that, by and large, short-range aircraft have simpler, less costly and less fuel-efficient engines than their long-range brethren. If CO_2 is the metric against which environmental performance is judged and, it has been suggested, should be taxed, the logical consequence is a move towards more fuel-efficient engines, with higher overall pressure ratios and turbine-entry temperatures. This would increase NO_x emission per tonne of fuel burned by short-range aircraft and would quite probably increase impact on climate change. The present uncertainty about the effect of NO_x on ozone creation, methane destruction and the variation of these effects with altitude makes it difficult to assert this with confidence. Similarly, we cannot confidently assert that short-range aircraft have less impact on climate than long-range aircraft by virtue of their lower NO_x emissions per tonne of fuel burned. Nevertheless, this also seems likely to be the case.

Putting the two above thoughts together, we might expect a histogram similar to Fig. 28, but for percentage contribution to climate change rather than percentage fuel burn, to be more heavily biased towards long-range aircraft. Also, for short-range aircraft, the economic penalty of avoiding the risk of forming contrails by reducing cruise altitude in 'contrail weather' may not be very severe

[†] The raw data for this figure are a breakdown of scheduled seats per week against sector distance, taken from the OAG schedules, September 1998. The number of seats scheduled within each increment of range has been multiplied by the mean range and a nominal weight per passenger and divided by the payload fuel efficiency given by the outer curve in Figure 16 to arrive at a nominal fuel burn.

and it may be practicable, in the medium term, to move to a regime in which the impact on climate of short-range aircraft is only a little more than the impact of their CO_2 emissions.

Clearly, we are in urgent need of a better understanding of the effects of aircraft emissions on climate and the dependence of these effects on atmospheric conditions. The effects are known to vary with latitude, longitude, flight altitude and season and the effect of a particular flight may also be influenced by short-term factors such as weather and the altitude of the tropopause. We may be many years from a comprehensive understanding of all these factors but perhaps not so far away from a reasonable working grasp of the key issues. As this grasp strengthens, we should be increasingly able to shape our thoughts about future aircraft and engine design priorities, about future air-traffic management and, not least, about the form of regulatory environment that is most likely to reduce impact on climate rather than simply reduce fuel burn.

That said, reducing fuel burn must remain an important objective for aircraft of all ranges. For the smaller short-range aircraft, flying-wing configurations do not seem practicable and the available routes to reduced fuel burn are reduced weight through greater use of light-weight materials, reduced drag through use of natural or hybrid laminar-flow control and the reversion to propeller or unducted fan propulsion.

Hybrid laminar-flow control is probably the more robust technique for increasing *L/D* but its practicability in airline service has yet to be demonstrated. This could be done by retro-fitting HLFC to one or more existing aircraft types and putting it or them into service alongside their unmodified counterparts. The modifications would be costly and, because HLFC produces less benefit as a retrofit than in a new design, the incentive to airlines and manufacturers to undertake such a demonstration programme is not strong; substantial government support would be needed. Nevertheless, since laminar-flow control by suction is the one route open to significant drag reduction for aircraft of all ranges, ultimately promising large drag reductions for large flying-wings, a demonstration of its practicability in airline service is urgently needed.

As regards range itself, Fig. 27 shows how steeply payload-fuel efficiency falls off for ranges below about 1,200km for swept-winged aircraft. Over ranges shorter than this, the case for shifting passengers from air to rail becomes increasingly strong as range reduces, highlighting the importance of investment in an efficient and rapid surface-transport infrastructure. The figure also prompts the thought that, for medium-and long-range travel, there may be a significant difference in fuel burn per passenger km between a world served by a hub-and-spoke network, with relatively short legs between the hubs and the start and finish points, and one in which the great majority of journeys are made directly between city pairs. A study of this might help clarify forward thinking.

One further point which can be drawn from the flight schedules for 1998 used to derive Fig. 28 is the effect on movements of a change from the present regime for long distance travel to one in which, as suggested in Ref. 4, long journeys are broken down into stages between 2,000km and 7,500km. The estimated increase in total movements is less than 5%, which is approximately one year's growth in total traffic. The estimated reduction in fuel burn is 20-25% on long distance travel or approximately 6% of the total air-travel fuel burn. The Sub-Group suggested that this option, of progressively displacing long-range aircraft by medium-range aircraft over the period from, say 2020 to 2030, should be the subject of a full system study.

4.0 CONCLUSIONS

In the section headed 'Conclusions' in the guidelines for authors printed in the *Journal*, it says: "This section should be very concise and bullet points are recommended for clarity". After a somewhat discursive essay, this seems good advice and will be taken.

- In aviation's second century, reducing its environmental impact will become an increasingly important objective. All three aspects of environmental impact, noise, local air quality and climate change, will continue to need attention. In the long term, impact on climate is the most important of the three.
- There are conflicts between environmental and commercial goals and also between individual environmental goals. These trade-offs need to be evaluated.
- Reducing NO_x and persistent contrails are probably the two most potent means of reducing the impact on climate. In each case, the best environmental result is likely to entail some increase in CO_2 emissions.
- Because CO_2 is such a long-lived greenhouse gas, reducing its emission is a key long-term goal. Drag and weight reduction are the two most potent technologies. Increasing propulsive efficiency by a reversion to open rotor propulsion in order to increase Froude efficiency would also help. Increasing engine thermal efficiency by increasing overall pressure ratio and turbine entry temperature increases NO_x emission and does not seem to be the best way to go.
- To achieve a substantial reduction in CO_2 emission will require radical changes to aircraft design – the adoption of laminar-flow control and departure from the dominant swept-winged configuration as a minimum.
- The impact on climate of aircraft design parameters such as range, cruise Mach number and cruise altitude needs further study.
- Regulatory and economic measures should be framed so as to promote reduction in impact on climate rather then reduction in CO_2 emission. Measures based solely on CO_2 emission will probably do more harm than good.
- The challenge to technology is severe. The timescales for introducing new technology and new design concepts are long. The need for research and demonstration is urgent.
- The interaction between aircraft emissions and the atmosphere, and the consequent impact on climate, is exceedingly complex and imperfectly understood. To evaluate future options for both aircraft and engine design to reduce this impact we need a better understanding of the atmosphere. In environmental aeronautics, there is no higher priority than this.

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