PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Review Lecture: The Technical Aspects of Supersonic Civil Transport Aircraft

George Edwards

Phil. Trans. R. Soc. Lond. A 1974 **275**, 529-565
doi: 10.1098/rsta.1974.0001

REVIEW LECTURE

THE TECHNICAL ASPECTS OF SUPERSONIC CIVIL TRANSPORT AIRCRAFT

By SIR GEORGE EDWARDS, O.M., F.R.S.
British Aircraft Corporation

(*Lecture delivered* 29 *March* 1973 – *MS received* 31 *July* 1973)

[Plates 27 and 28]

CONTENTS

The paper discusses those technical aspects of a supersonic civil transport aircraft which peculiarly distinguish it from conventional subsonic civil aircraft.

The physical, economic and ecological environments in which the supersonic transport must operate are considered and the main stepping stones to the development of the supersonic transport are traced.

It shows that the basic differences between the supersonic transport and subsonic transports can be traced to two causes – the high-temperature environment and the disparity between subsonic and supersonic aerodynamics. The considerations which lead to the choice of speed, configuration and powerplant are considered and some details of their impact on specific areas are discussed.

Finally, Concorde is used to illustrate the development of a practical supersonic transport and the development, from both theory and experiment, of the practical parameters and features for such a vehicle.

Preamble

When the Royal Society paid me the honour of inviting me to give this lecture, the particular supersonic transport work that I have been engaged upon was going through a period of what I imagined was quite unwarranted euphoria. In the past few months there has been a period of equally unwarranted gloom and once or twice it has seemed to me that perhaps I was going to conduct a memorial service rather than give a lecture! However, pendulums have a habit of swinging backwards and forwards fairly fast in the aerospace business and, in any event, I am giving a lecture on the technical aspects of supersonic transport as a whole, as distinct from any particular aeroplane.

At this point I must pay high tribute to the teams that have designed and flown the two supersonic airliners that are currently in being – in Britain, led by Russell & Strang; in France, by Satre & Servanty; and in Russia, by that great veteran designer Andre Tupolev, now sadly no longer with us and replaced by his son Alexei. They have demonstrated their ability to overcome exceptional technical problems and the fruits of their efforts are for the world to see.

Covering the technical aspects of a big and complicated operation of this sort relies on the contributions of many and I am grateful for the help of specialists in each of the principal areas of technical challenge examined in this Review; they are able to cover these aspects in greater depth than it is possible to do here.

In this respect I must point out that this lecture relies heavily on the research and preparatory work of my three colleagues – Hugh Goldsmith, Norman Boorer and Theo Small. At the same time I must add that the resulting paper and interpretation of events are entirely my own responsibility and do not necessarily represent the views of British Aircraft Corporation, Aérospatiale, the British or French Governments, or any other body with which I am associated.

From time to time I have asked myself why I have become so involved with the air transport business at all. My colleague Dr Bill Strang said at the beginning of a recent dissertation to the Royal Institution, 'Down the centuries it has been an article of faith that improved means of transport are a benefit to mankind.' I suppose that I share that view and it is the basic reason that I have spent as much of my life as I have on improving means of transport – including going supersonic.

1. Introduction

1.1. *The influence of speed on transport*

One is not often prepared to be reminded of the things one did fifteen years ago, but despite the quite extraordinary vacillations that characterize the aerospace industry, I am prepared to show again, now, three of the diagrams that I used in my Presidential Address before the Royal Aeronautical Society in February 1958, entitled 'The influence of speed on transport'.

1.2. *The shrinking World*

The theme that I developed in that address was that the progressive increase in the speed of transport – starting with man on foot, then on horse-back, the coming of the stage-coach, the train and ultimately the aeroplane – made a significant contribution to trade between the ever-widening range of places that were joined together (figure 1). The most significant fact to emerge from this was that as soon as two places were joined together by a journey time within 12 hours – man's natural day – trade and population increased dramatically.

Figure 2 – the twelve-hour World – shows how the increasing speed of transport has enabled a day's journey from London to be extended dramatically over the centuries: 1690 to Peterborough, 1890 to Paris, 1940 to cover the Mediterranean, 1960 to mid-Africa; and in 1975 it will embrace the entire World. I must remind you that this last point was my prediction in 1958.

1.3. *Forecasting the advent of the s.s.t.*

At that time I also showed another diagram (figure 3) to demonstrate the way in which aircraft speed has progressed as a logical development, from world speed-record-breaking types to military aircraft of similar performance and the way in which transport aircraft have followed them. I was rash enough then to forecast a Mach 2 airliner coming into service around 1974/75; as both the TU-144 and Concorde are expected to enter service in 1975, this has proved to be right.

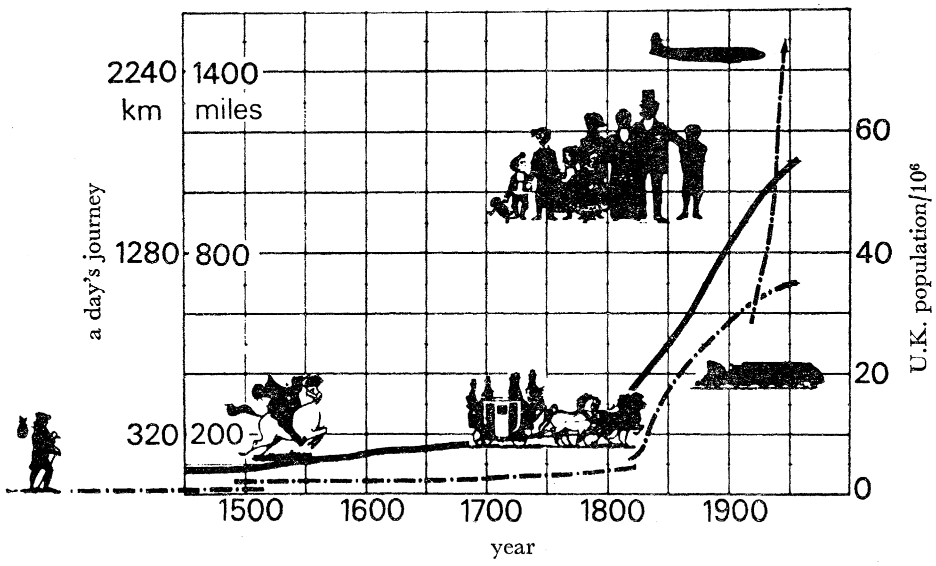


Figure 1. The growth of population – the stimulus to travel.

I also showed that I expected this to be preceded by a Mach 2 bomber. However, this did not happen and I believe that one of the big problems that we have had to contend with on the Concorde – and no doubt the Russians on the TU-144 – has been that a great deal of the technology which was needed for the civil aeroplane had to be developed from scratch and could not be based on a bomber of comparable performance and endurance. The entire jet airliner generation of the United States has derived from the original concept of the Boeing B-47

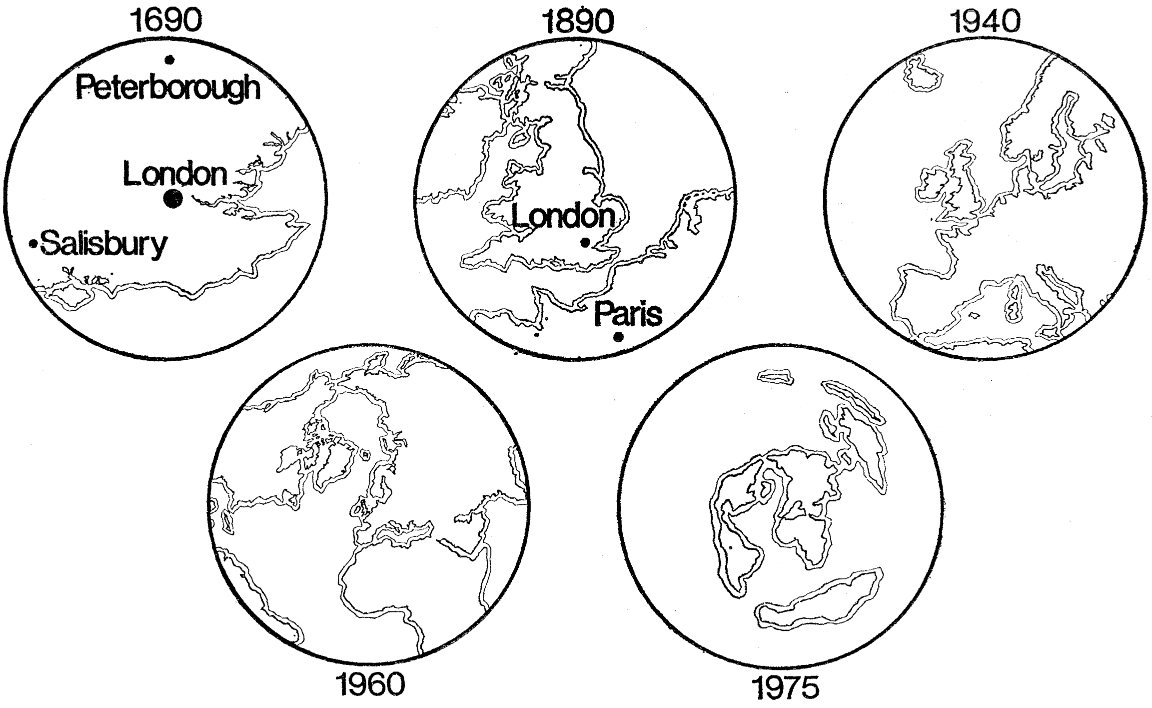


Figure 2. The twelve-hour World.

strategic bomber, which stemmed from the 1944 decision by the U.S.A.F. to initiate development of jet bombers and was first flown in 1947. There has been no comparable basis from which to develop the technology required for supersonic transports.

Indeed, if there is a single engineering reason for the changes that we have had to make during the gestation of Concorde, it is the non-appearance of an operational long-range supersonic bomber to preface it.

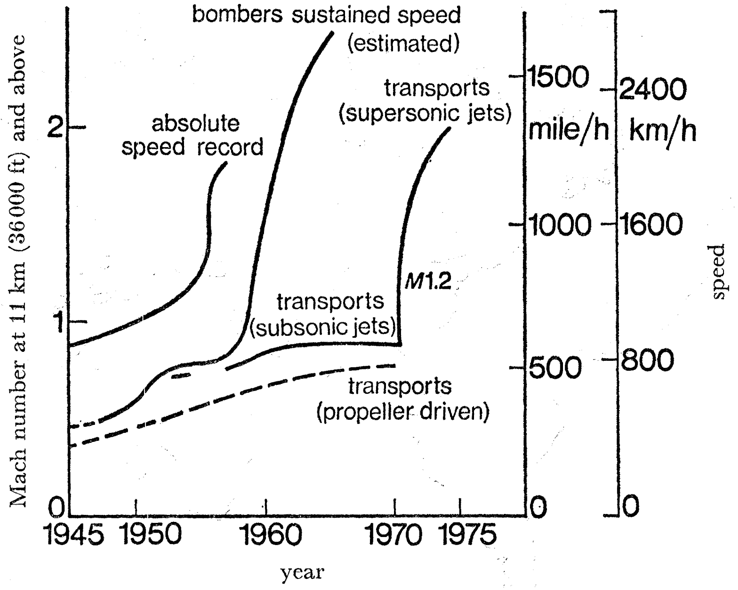


FIGURE 3. Forecast of speed with time.

2. THE IMPACT OF THE SUPERSONIC TRANSPORT

2.1. *Halving the World in size*

Continuing the theme of the shrinking World, figure 4 demonstrates how the size of the World will be halved with the introduction of the s.s.t., from the capability of current subsonic airliners with speeds of Mach 0.8 (965 km/h) plus, to the size of the 12 hour World with the coming of the Mach 2 (2100 km/h) Concorde.

Figure 5 shows the comparative block times yielded by subsonic and supersonic airliners. (Note the relatively small improvement between aircraft with cruising speeds of Mach 2.2 and 2.7, which separate the known technology of aluminium-alloy structural design and the untried and prohibitively expensive steel airliner, about which detailed discussion follows later in this paper.)

This is translated into actual passenger journey times in table 1, which shows that the twice-the-speed-of-sound airliner will reduce the Paris–New York journey time to less than half that of today; the London–Tokyo journey will also be less than half (with a stop at Norilsk, in Northern Russia midway across the Great Circle routing); so, too, will that for the Beirut–New York route.

A notable point about the London–Sydney route (the World's longest) is that Concorde is capable of flying it with only two stops. Operating the route with three stops, the journey time is increased by an hour. My inference from this is that it is much more profitable to increase the range of a Mach 2 aeroplane than to try to save time by increasing the Mach number to 2.7 because, as figure 5 demonstrates, the improvement in block time is small, whereas the cost of the substantially higher technology is demonstrably prohibitive.

In summary, the gains that come from the Mach 2 s.s.t. are substantial, but those small further gains from Mach 2 to 2.7 are very difficult to justify.

Figure 4. The World at supersonic speeds.

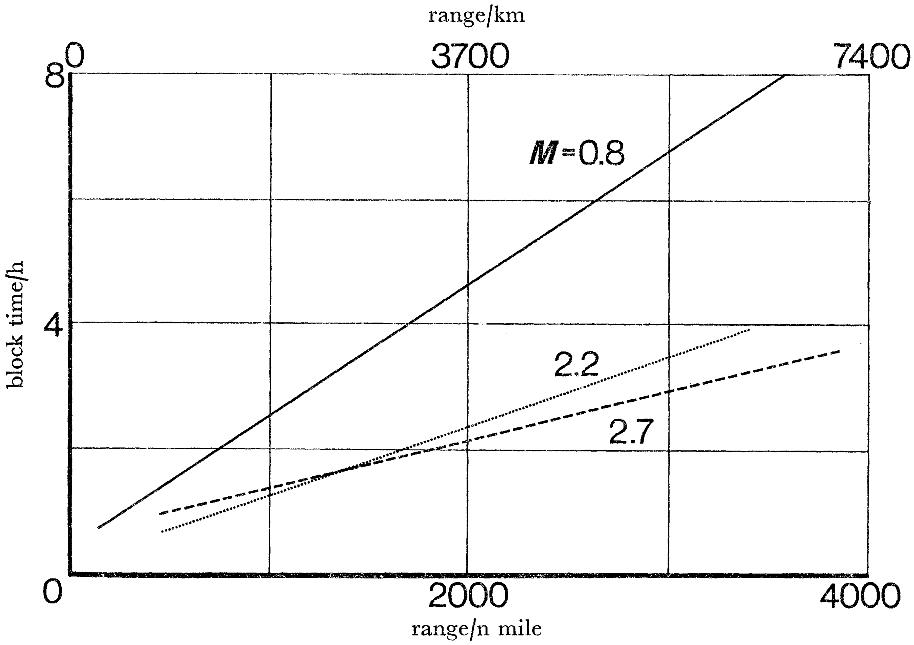


Figure 5. Comparative block times.

Table 1. Time saving

route	Great Circle distance		supersonic journey time	subsonic journey time	time saved
	n mile	km	h min	h min	h min
London–Sydney via Bahrain, Singapore	9561	17750	14 25	25 20	10 55
Paris–New York	3148	5850	3 35	7 30	3 55
Sydney–San Francisco via Nandi, Honolulu	6546	12150	9 10	17 55	8 45
London–Tokyo via Norilsk	5119	9450	6 45	14 40	7 55
Beirut–New York via London	4867	9100	7 15	14 25	7 10

3. The physical environment of supersonic flight

The difficulties of designing a supersonic transport largely result from the characteristics of the environment on the aeroplane, rather than what is more popularly discussed, the other way round.

The physical environment of the s.s.t. is the atmosphere up to an altitude of about 20 km. Three aspects of the characteristics of this atmosphere are of particular significance in the design of the aircraft; first, the large-scale quasi-static parameters of temperature and pressure; second, the small-scale perturbations such as winds, gusts, temperature gradients, etc; and third, the gas dynamics of air as a compressible fluid.

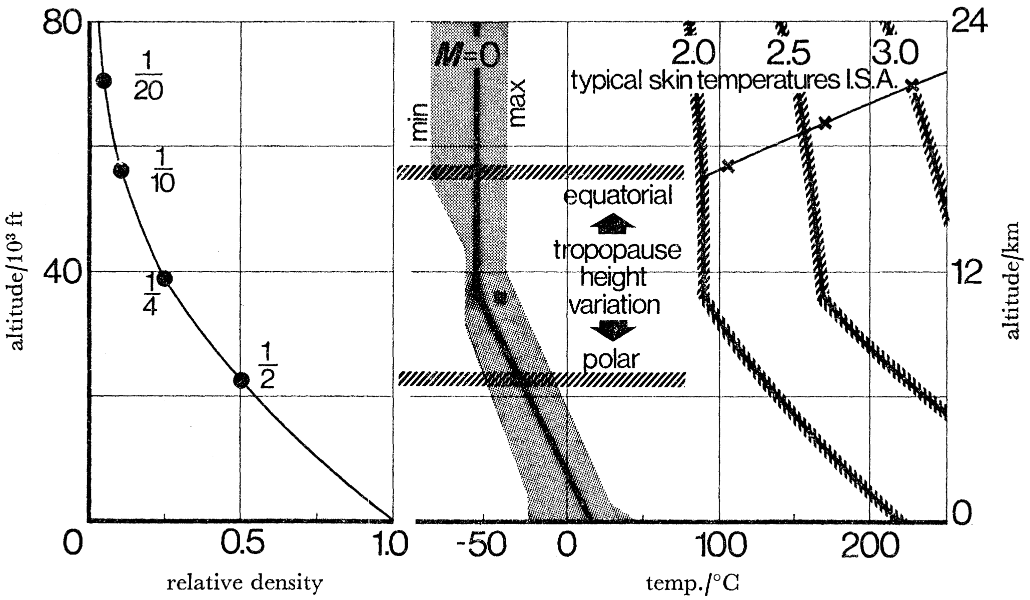


Figure 6. The environment.

3.1. *The International Standard Atmosphere* (*I.S.A.*)

The basis for discussion of this environment is the so-called International Standard Atmosphere (see figure 6). This has an adiabatic temperature lapse rate of 6.5 °C/km up to the tropopause at 11 km and a constant temperature thereafter up to 20 km, where a small rate of increase is believed to begin. The composition of the air is taken to be constant at all altitudes and the pressure and density follow directly from the temperature profile.

3.2. *Relative density and pressurization requirements*

The left-hand side of figure 6 shows the way in which the relative density of air decreases with altitude (symbolized by rho (ρ)) in the dynamic pressure component $\frac{1}{2}\rho V^2$ of the lift and drag coefficients of the aircraft; for constant coefficients, a reduced density allows a higher flight speed V and hence the higher the cruising speed required, the higher the cruising altitude required to achieve it.

Considering first the passenger-cabin pressure differential, this diagram shows that at the cruising height band of a Mach 2 transport, i.e. 16–18 km, the relative density is of the order of one-ninth of the sea-level value, compared with around one-quarter at 12 km, which is the typical cruising height of today's long-range subsonic airliners. In terms of maintaining an acceptable cabin pressure – and this is not as difficult as these values would at first suggest – the working pressure differential for Concorde is 0.752 kg/cm², compared with 0.626 kg/cm² for the Boeing 747 and 0.633 kg/cm² for the B.A.C. VC 10. In other words, while cabin pressurization is obviously more difficult, it is a straightforward extrapolation from what is already well known and proved.

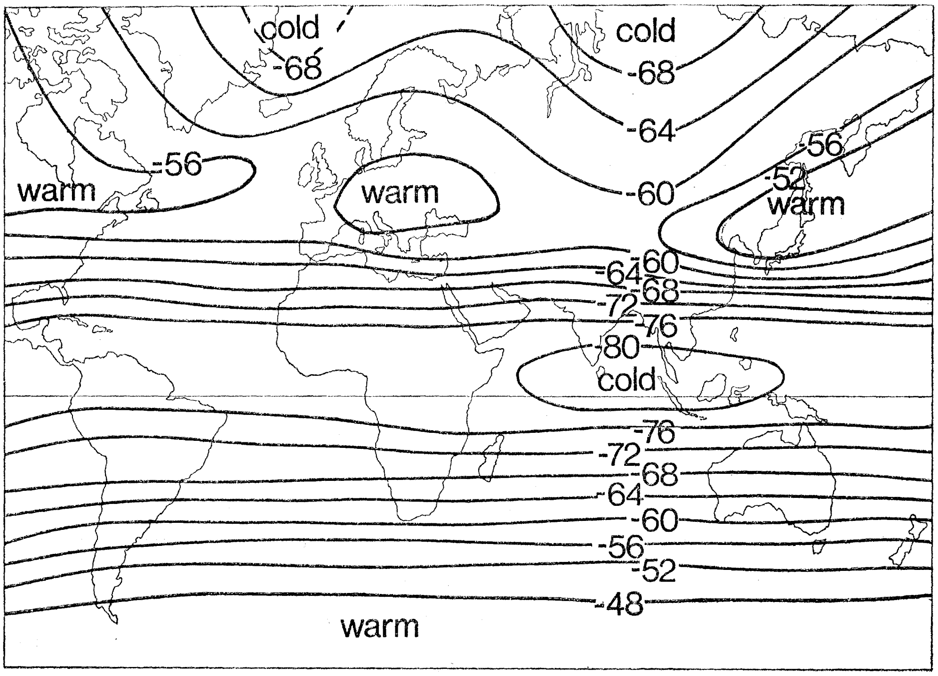


FIGURE 7. Average temperatures (°C) at 16 km (53000 ft); January.

3.3. *Temperature considerations*

The heavy line running through the middle of figure 6 shows the variation of temperature of the International Standard Atmosphere, i.e. at 'standard day' conditions with a sea-level temperature of 15 °C, without any considerations of aircraft speed (i.e. at Mach 0). The shaded area on either side of this line indicates how conditions vary in practice from the 'standard day'. The two horizontal shaded bands also show how the height of the tropopause varies considerably, according to the relative part of the World; at the Equator this is as high as 18.3 km, whereas in the polar regions it is as low as 6.7 km. The significant point in this connexion is that the temperature lapse rate only continues up to the tropopause and then remains constant, so that over the Poles the temperature at the tropopause and in the stratosphere above it is substantially higher than it is over the Equator. This has a particular significance in the flight planning for an s.s.t. and is further discussed later.

This is a highly idealized condition which is rarely realized in practice. Not only does the temperature of the Earth's surface vary widely with both time and geographical location, but so also does the level of the tropopause and the temperature in the lower stratosphere.

Figures 7 and 8 show the average temperatures (isotherms) throughout the World in winter and summer – January and July respectively – at the 16.15 km (100 mb) level. The change in global location of the very low temperature areas most favourable to the s.s.t. are noteworthy.

In equatorial latitudes, temperatures are as low as – 80 °C, whereas over the North Pole they are as high as – 40 °C. As discovered during the Concorde's demonstration tour in the Far East in June 1972, this phenomenon has a dramatic effect on the aircraft's performance. Whereas fuel consumption in temperate latitudes was of the order of 21.3 tonnes/h, it dropped to around 19.3 tonnes/h around the Equator. The practical significance of this is that while range may be critical in one part of the World, this may not necessarily follow in other areas – which is an unexpected bonus, compared to conventional subsonic operation at lower altitudes.

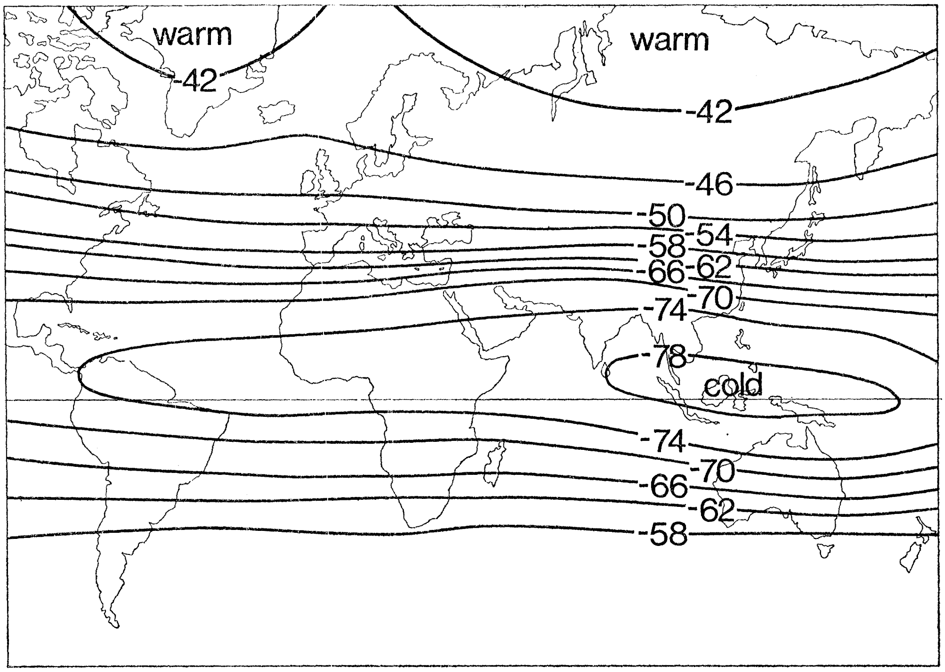


Figure 8. Average temperatures (°C) at 16 km (53000 ft); July.

3.4. *Winds and turbulence*

Aircraft have always had to contend with winds and atmospheric turbulence and the s.s.t. is no exception. However, it is fortunate that the s.s.t. will, in general, cruise above the levels where the highest winds are found. Figure 9 shows typical wind strengths against altitude for five major geographical locations – with the cruising regimes of the s.s.t. (upper) and subsonic transport aircraft (lower) shown superimposed.

Figure 9 shows that cruising at the higher altitudes renders the s.s.t. doubly insensitive to wind effects, since it is already only half as sensitive as a subsonic aircraft to a given wind strength, by reason of its much higher cruising speed.

The effect of atmospheric turbulence on an aircraft is a function of four parameters: the magnitude of the turbulence, the speed of the aircraft, the wing loading and the configuration – in particular the sweepback and aspect ratio of the wing.

A plot of the statistical variation of turbulence with altitude would show that maximum turbulence occurs at low altitudes, where the s.s.t. is in fact operating as a subsonic aircraft.

In general, the combination of these factors, notably aircraft configuration and wing loading, tends to produce a gust response for an s.s.t. broadly similar to that for a subsonic jet transport. When account is taken of the small proportion of flight time spent at low altitude, the overall result is that the s.s.t. experiences a lower degree of loading due to turbulence.

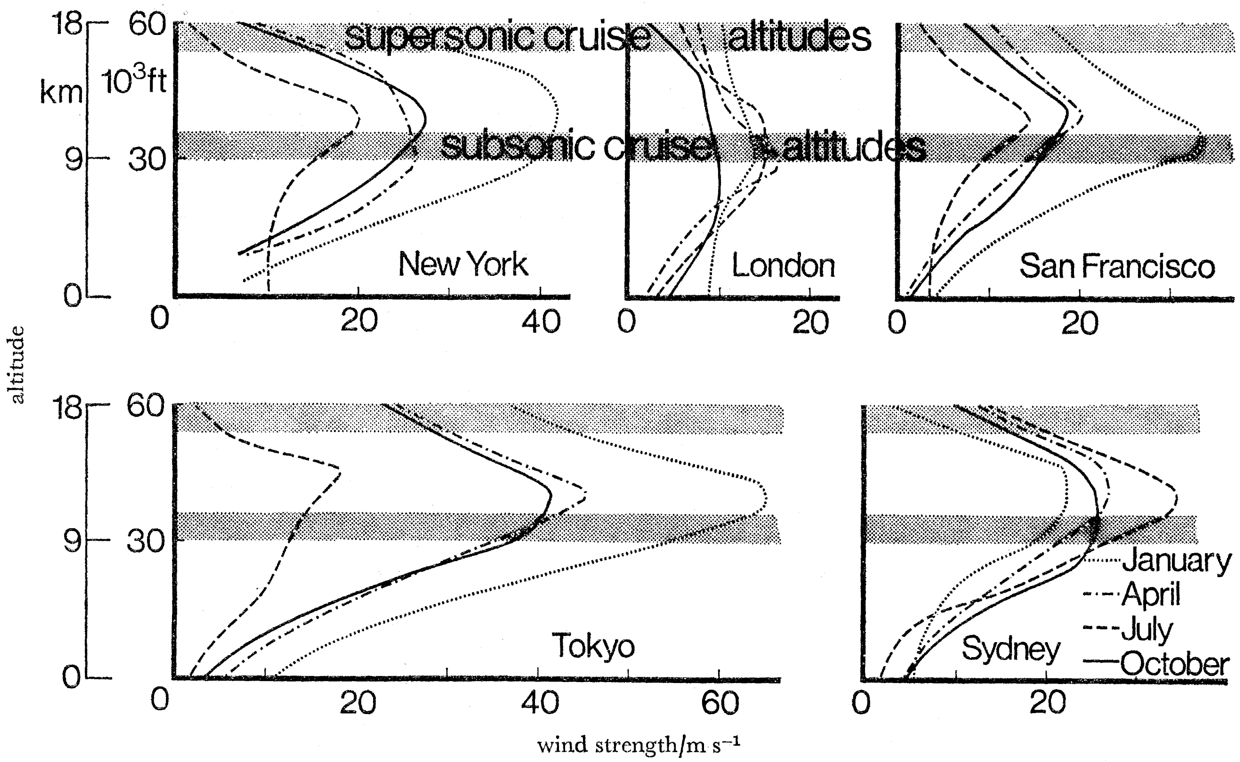


FIGURE 9. Average wind strengths.

3.5. *Wind and temperature gradients*

There are two other atmospheric phenomena of significance in the design of an s.s.t. – wind and temperature gradients.

Wind gradients are associated with jetstreams and can be as high as 10 m s^{-1} km^{-1} horizontally or 170 m s^{-1} km^{-1} vertically. Supersonic aircraft are affected rather more than subsonic types, because their higher speed allows greater departures from equilibrium flight and therefore greater speed excursions.

Temperature gradients are likewise linked to jetstreams, also to mountain waves and frontal phenomena. Since the true speed of an aircraft remains substantially constant during the penetration of such a temperature gradient, both the Mach number and the stagnation temperature will change. The change in Mach number is significant for both subsonic and supersonic aircraft. Whereas the change is larger for the s.s.t., the stagnation temperature is of significance to the s.s.t. alone.

3.6. *The kinetic heating phenomenon*

Finally, there are the physical properties of the air itself to consider. Air is a compressible fluid and as such its dynamics are characterized by a critical speed – that of the propagation of small disturbances. This is not the place for a treatise on the theory of compressible flow; suffice it to say that supersonic aircraft are subjected to significant thermal effects due to kinetic heating. Typical skin temperatures of an s.s.t. in cruise flight are indicated on the right-hand side of figure 6 – the International Standard Atmosphere (I.S.A.). As the speed of an aircraft increases, the lift at constant lift coefficient C_L increases, so that for a given lift (or mass), the aircraft can fly in a less-dense atmosphere, such as at higher altitude. The rising line at the top right-hand side of figure 7 shows typical cruise speed–height–skin temperature relations; typical subsonic cruise Mach 0.9 at 10.7 km and –45 °C; Concorde cruising at Mach 2.2 at 17.4 km and 105 °C; U.S.-s.s.t. proposal at Mach 2.7 at 19.2 km and 170 °C; and the XB-70 at Mach 3.0 at 21.3 km and 230 °C.

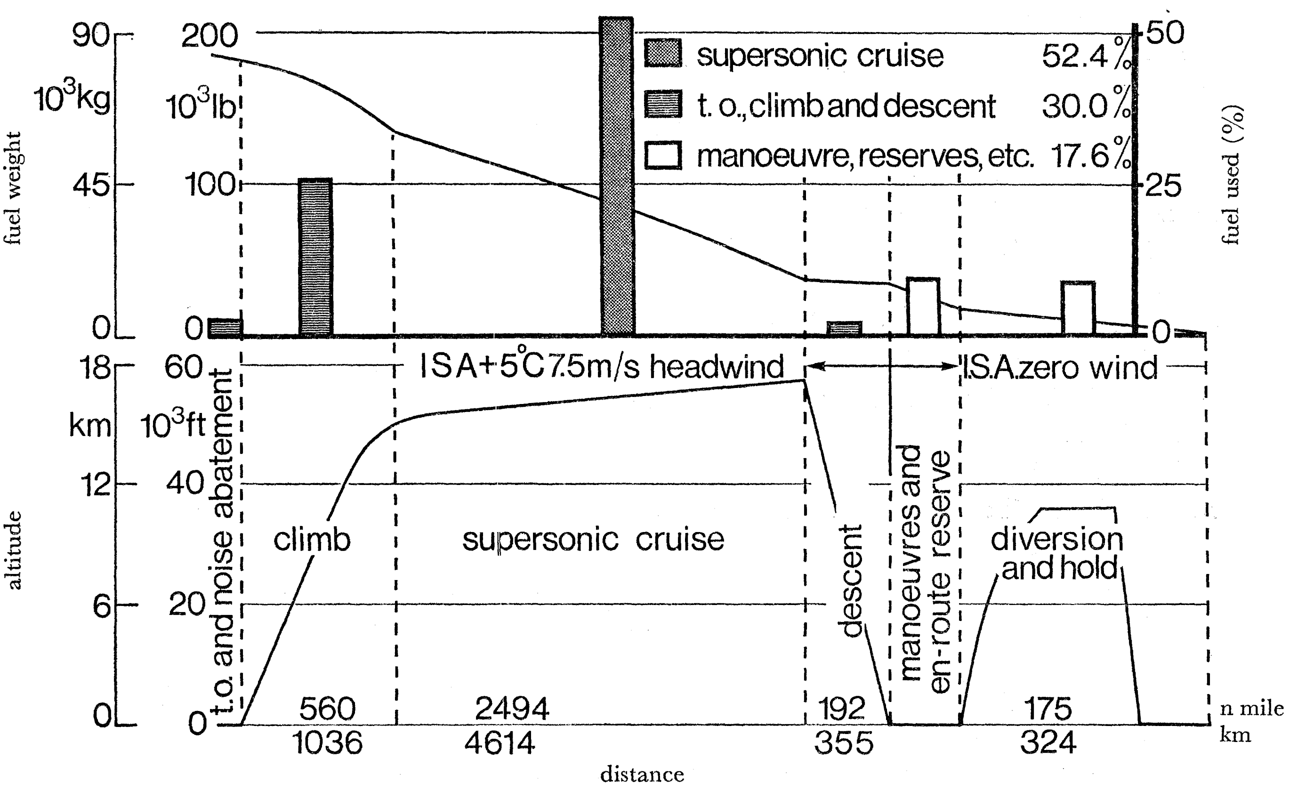


FIGURE 10. Flight plan, Paris–New York.

3.7. *Typical s.s.t. mission: Paris–New York*

Translating these factors into the reality of a typical mission for an s.s.t., figure 10 shows how Mach 2 Concorde performs in the environment on the Paris–New York route (6015 km). From take-off at sea level, the climb and acceleration to cruising height takes place between 8.53

and 9.14 km and supersonic cruise-climb begins at around 15.24 km and continues up to 17.68 km. Descent and deceleration begin about 370 km from destination.

The upper part of figure 11 indicates the way in which the fuel is used and attention is particularly drawn to the fact that the supersonic cruise uses only 52.4 % of the total fuel load carried. The subsonic take-off, climb and descent elements account for 30 % and the remaining 17.6 % is that which has to be carried to cater for *en route* manoeuvre and terminal holding and diversion allowances.

Summarizing, of the total fuel load of about 81720 kg, almost half is used in the subsonic regime and this makes the subsonic performance of the aeroplane very important.

4. Principal design considerations

Having reviewed the principal characteristics of the environment in which the s.s.t. has to operate, the next stage is to discuss the main considerations involved in the design of the aircraft.

4.1. *The range function*

A convenient starting-point for discussion is the classical Breguet range formula which relates the performance of an aircraft's powerplant to that of its configuration and speed and concerns the exchange of energy in the fuel to energy in the vehicle in the achievement of the required specific range:

$$R = V\frac{1}{C}\frac{L}{D}\ln\frac{W_1}{W_2},$$

where R is range, V is speed, C is specific fuel consumption, L/D is the ratio between the aircraft's lift and drag, W_1 is the weight at start of cruise and W_2 the weight at the end of cruise.

This formula is applicable to both the subsonic and supersonic regimes. However, it is only applicable to the cruise segment of the mission and, as already discussed, about half the weight of fuel carried by an s.s.t. is used in the subsonic parts of the mission – take-off and acceleration to cruise speed and altitude, descent, holding and landing; it serves to highlight the interrelation between the key design features of an aircraft – aerodynamic configuration, powerplant size and weights.

Ideally, the best possible design is one which flies as fast as possible, has the highest possible ratio of aircraft lift to drag and an engine with the best cruise efficiency (the lowest s.f.c. for a given thrust).

However, both the L/D ratio and the propulsive efficiency vary with speed and an optimum overall solution must be sought. From the function $\ln(W_1/W_2)$ it is obvious that maximum range is given by the largest ratio of initial to final fuel weight, which in turn implies the need for minimum dry weight, if the aircraft gross weight (including fuel and payload) is not to become prohibitive.

The expression also clearly indicates the extremely sensitive interrelation of speed, configuration and powerplant characteristics on range or payload characteristics and shows that a shortfall in any one of them can only be compensated by diminished range or payload, to allow for a larger ratio of fuel weights W_1 to W_2.

4.2. *Optimum supersonic aerodynamic wing shape and efficiency*

Optimization of aerodynamic cruise efficiency shows that the best lift/drag ratio for a supersonic configuration is little more than half that for a subsonic layout.

Figure 11 shows the approximate upper limit of lift/drag ratios for optimized practical aircraft shapes, plotted against speed (Mach number is plotted on a logarithmic scale) in the subsonic, supersonic and hypersonic speed regimes (the latter being of academic interest only, as far as this lecture is concerned).

The shapes are the classical subsonic wing–fuselage combination, the slender delta of the supersonic airliner, giving way to the waverider at hypersonic speeds.

The principal characteristic of the subsonic design is the high aspect ratio wing which is progressively modified by sweepback as speed increases, in order to minimize drag as the local speed of air over the wing surface approaches sonic velocity. A practical subsonic transport aircraft reaches a peak L/D of around 16 at a Mach number of around 0.8. Thereafter it drops rapidly in the supersonic regime, with a step in the curve as wave drag materializes.

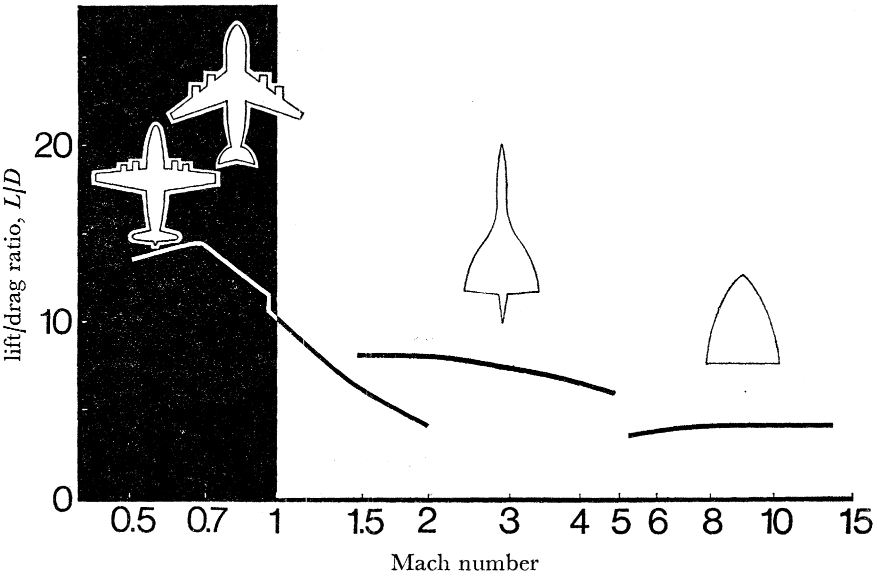


FIGURE 11. Lift/drag ratio against Mach number.

However, most recently a new generation of technology has been devised for highly-swept transonic designs with supercritical wings and waisted, area-ruled bodies, which could become a new class of airliner in their own right.

The slender wing shape dominates early in the supersonic regime and its aerodynamic efficiency varies little over the speed range, up to about Mach 3.0; when optimized for cruise in the Mach 2.0–Mach 3.0 region, it is about half the best subsonic value.

However, as discussed earlier, an s.s.t. spends a substantial part of each mission flying subsonically, so that the ideal supersonic shape requires modification to achieve reasonable performance at subsonic speeds also. In practice it has been found possible to achieve an L/D of about 12 at Mach 0.9 (almost as good as the classic shape at that speed) without significant loss of supersonic efficiency. The adoption of the slender shape, for this purpose and to meet low-speed stability requirements, is discussed later.

4.3. *Propulsive efficiency and choice of engine type*

As a compensation for the generally falling aerodynamic efficiency, the achievable propulsive efficiency increases throughout the speed range of interest. However, this increase in efficiency is achieved at the expense of having to progress through various classes of engines towards those which have lower compression ratio and higher specific thrust.

Figure 14 shows the propulsive efficiency of various classes of engine on the same speed base as figure 11. The efficiency of the high bypass ratio fan-jet engine, which has good subsonic fuel consumption and low noise characteristics, declines just before reaching the speed of sound. At this point the straight turbo-jet engine takes over. However, to achieve the efficiencies shown by the turbo-jet line requires a decreasing compression ratio as the forward speed is increased, so that the envelope covers a number of curves of this characteristic for different compression ratios. At about four times the speed of sound the ram compression which is achieved within the air intake system is by itself sufficient, without need for rotating machinery.

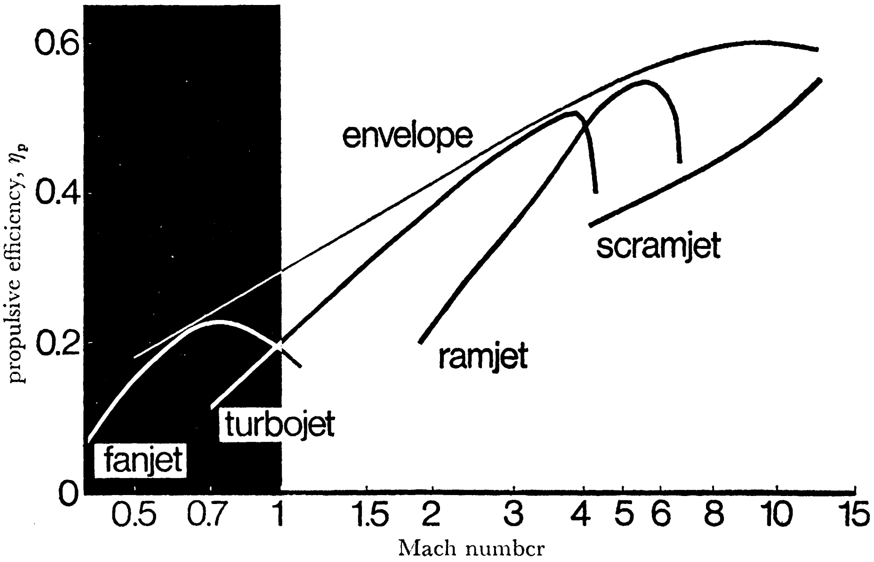


FIGURE 12. Propulsive efficiency against Mach number.

The ram-jet engine, a powerplant without rotating parts and the scram-jet, which is a supersonic burning version of the ram-jet, are both outside the scope of this paper.

As was the case in selecting the optimum aircraft configuration described in figure 11, there is a similar conflict of interest between the supersonic cruise and low-speed requirements in the choice of powerplant. This choice, together with the powerplant intake and nozzle systems, will be described later, when technical solutions are discussed. The envelope line on this curve shows that provided the right choice is made of the characteristics of the turbo-jet engine, the propulsive efficiency increases with speed over the range in which we are interested. This characteristic is therefore a compensation for the falling value of aerodynamic efficiency with increase of speed and it has a cancelling characteristic, as can be seen in the Breguet formula.

4.4. *Overall vehicle efficiency*

The overall effect of these considerations on the total aircraft performance in cruise is exemplified by the specific range factor, which is proportional to the cruise fuel consumption.

Figure 13 shows the same three classes of aircraft on the same Mach number base. The ordinate is the product of the characteristics shown on figures 11 and 12; aerodynamic efficiency $L/D \times$ propulsive efficiency η_p.

The sharp fall-off in vehicle efficiency just below Mach 1.0 is restored to comparable levels on a broad plateau in the region of Mach 2.0–3.0. There are signs of the possibility of another region of useful efficiency at sub-orbital speeds, but this is beyond the subject of this paper.

Hence, by choice of the optimum aerodynamic shape and engine thermodynamic cycle, a specific range factor can be achieved supersonically which is as good as and possibly better than the best subsonic one.

The final choice of speed in the Mach 2.0–Mach 3.0 band is in practice determined by other factors – notably the choice and state of knowledge in using and working the structural materials of the vehicle, bearing in mind the elevated temperatures in which they have to operate, which vary in proportion to the square of the flight speed.

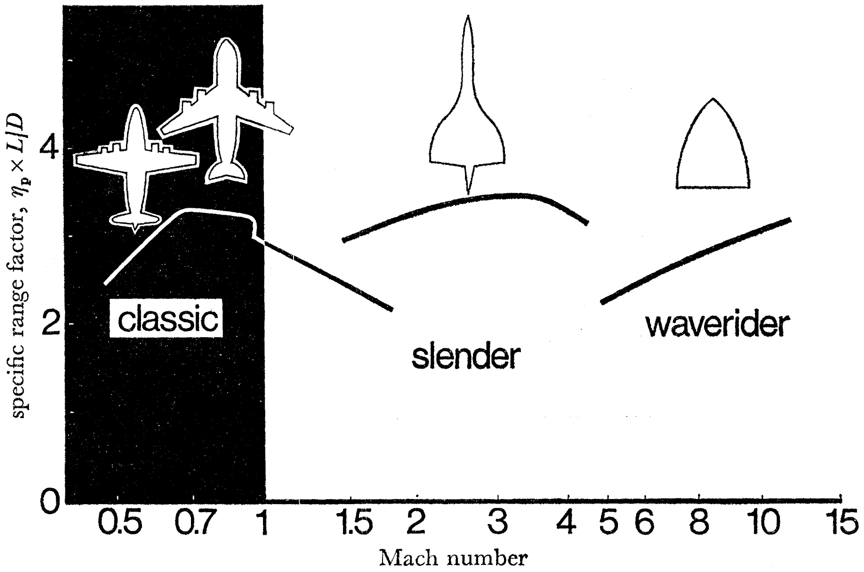


FIGURE 13. Overall vehicle efficiency.

4.5. *Components of drag*

Having discussed the variation of lift/drag ratio with Mach number and observed the sharp reduction around Mach 1.0, it is instructive to examine the components of the drag of an aircraft at both subsonic and supersonic speeds (table 2).

There are two main components in the subsonic regime; drag due to skin friction, which is roughly proportional to total surface area; and drag due to lift, which is associated with the trailing vortex system and is proportional to $\text{lift}^2/\text{span}^2$.

In supersonic flow it is generally true that recompression can only take place through a shock wave, which is a narrow zone of pressure discontinuity and energy dissipation. It can be shown that this characteristic gives rise to a further component of drag, which is known as wave drag. This manifests itself in two ways; zero lift wave drag, which is a function of the aircraft shape and is generally proportional to $\text{volume}^2/\text{length}^4$; and the wave drag due to lift, which is generally proportional to $\text{lift}^2/\text{lifting length}^2$. These are in addition to skin friction and vortex drag of the same type as for subsonic aircraft.

It is clear therefore that for a supersonic aircraft there is a conflict of requirements. Ideally it needs to be a long aircraft with a large span, with a long lifting length and small total area. However, this conflict is only one special expression of the whole new class of problems which are introduced by supersonic flow conditions and their associated shock waves. These phenomena are among the basic reasons for the difference in design philosophy and techniques between subsonic and supersonic aircraft.

4.6. *Supersonic drag*

Many of the differences between the configurations of subsonic and supersonic aircraft result from the phenomenon of the drag associated with the formation of shock waves. The fundamental difference in the mechanisms of airflow in the two speed regimes places severe limitations on the choice of both airframe configuration and powerplant.

The air flowing past a body at subsonic speeds produces a drag force as a result of the friction between the air and the body's surface. This is shown in figure 14 as the skin friction drag

TABLE 2. COMPONENTS OF DRAG

component	generally proportional to	subsonic	supersonic
skin friction drag	total surface area	small area	small area
zero lift wave drag	$\frac{\text{volume}^2}{\text{length}^4}$	—	long aircraft, moderate span
vortex drag	$\frac{\text{lift}^2}{\text{span}^2}$	large span	large span
wave drag due to lift	$\frac{\text{lift}^2}{\text{lifting length}^2}$	—	long wing

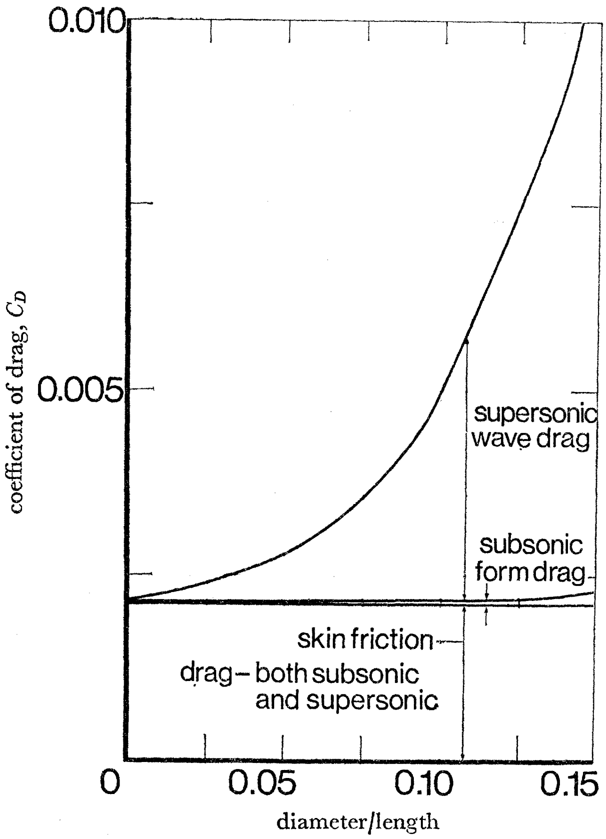


FIGURE 14. Components of drag. $C_D = D/\frac{1}{2}\rho V^2 S$ (where D is drag force, ρ is air density V air speed, S wetted area).

component. In addition, a further pressure or form drag results from the disturbance of the airflow caused by the passage of the body. The greater the 'fatness' of the body (or diameter/length ratio plotted on the abscissa) the greater is the form drag. However, this is only a small addition to the skin friction drag and increases only slowly with body thickness over the range of shapes of practical interest.

At supersonic speeds the situation is very different. The skin friction drag is similar in magnitude to that for the subsonic case, but the form drag is now largely shock-wave drag and its magnitude increases very rapidly with body thickness, approximately in proportion to the square of the thickness. As a result, practical supersonic shapes have to be more slender than their subsonic counterparts, if the drag is to be kept down to a level which does not degrade the aircraft's economic performance at supersonic speed.

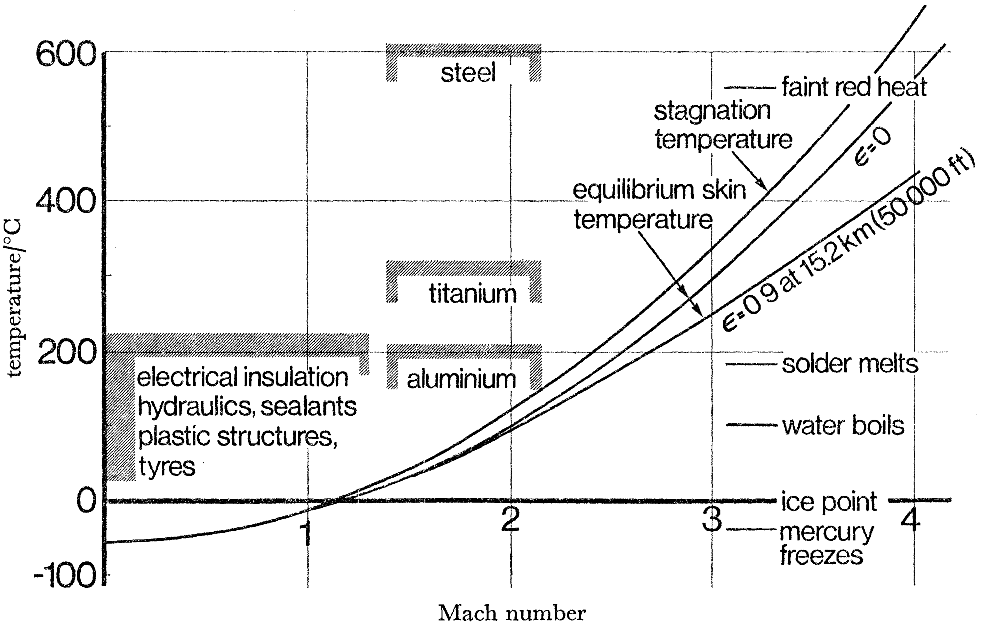


Figure 15. Spectrum of materials.

This concept of slenderness also needs to be applied to the wings of a supersonic aircraft, but here there is conflict with a further drag component – called induced drag (or lift-dependent drag). As the latter description implies, it is the drag vector of the lift force acting approximately normal to the wing. Induced drag varies as a function of wing span, decreasing in magnitude for a given lift with increasing span. Therefore the slenderness required of the supersonic shape must be modified to optimize the configuration to achieve as high an L/D as possible – as required by the Breguet range formula.

In the practical aeroplane, this optimization cannot be idealized for the cruise condition only and a further optimization is required in respect of the low-speed requirements of the vehicle, for which, as has already been shown, a relatively high proportion of the aircraft's fuel is used on a typical mission.

4.7. *Spectrum of material properties at elevated temperatures*

Figure 15 shows the curves of stagnation and equilibrium temperatures plotted against Mach number, together with bands showing approximations to the limits of engineering usefulness of materials.

The significant new factor to be considered in the choice of material for the s.s.t. is the mechanism of kinetic heating at high flight speeds. The air adjacent to the surface of an aircraft (within the boundary layer) is suddenly accelerated to the aircraft velocity. At the forward extremities, this is brought about by normal forces with negligible heat transfer, making the process an isentropic compression. The work done by the accelerating forces increases the energy of the air and appears as an increase in temperature to the total or stagnation temperature. Aft of the stagnation points, the air is accelerated by viscous forces, under conditions in which heat transfer may occur within the boundary layer. Under these non-isentropic conditions the total temperature will not be achieved and in its place the reference temperature is taken to be the 'adiabatic wall', or zero heat transfer temperature. This is the equilibrium temperature which would exist in an ideal insulated surface having zero radiative heat exchange. In practice this ideal temperature is further modified by the conditions in the particular part of the boundary layer under consideration.

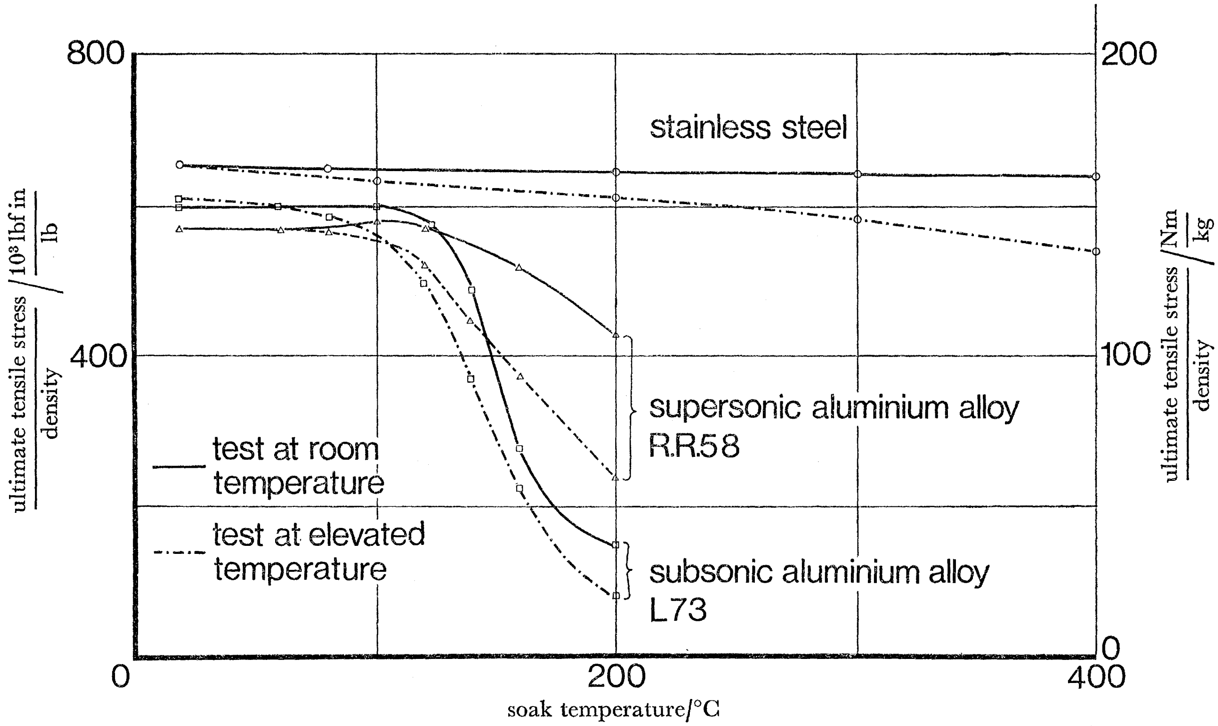


FIGURE 16. Material properties (after 20000 h soak).

For laminar flow the recovery factor is about 0.85 and for turbulent flow 0.88–0.90, so that the temperature achieved would be 85 and 88–90 % respectively of the theoretical values.

In addition to heat transfer by forced convection, there are further exchanges at the surfaces by radiation. This effect is important where the skin temperature is high and the heat transfer coefficient is small, as in high-speed flight at high altitude.

The effects of kinetic heating on the structure may be divided conveniently into three classes, namely the effect of high temperature on material properties, the effect of high temperature on structural elements and the effect of high temperature gradients within the structure. Only the primary factors which led to the selection of the basic structural material are discussed here.

4.8. *Reason for the choice of aluminium alloy*

Having established that Mach 2 would be a very worthwhile cruise speed for a supersonic transport aircraft, the use of aluminium alloy for the structure became a possibility. Aluminium had been used for several generations of aircraft and experience was also available in both small short-range supersonic aeroplanes and large long-range subsonic transports. To face the great technological challenge of long-range supersonic flight with a new basic structural material for the airframe seemed most unwise.

The outstanding difference between an s.s.t. and all that had gone before it was the long and intensive airline life requirement, 12–15 years or about 50000 flying hours. The skin and airframe are not, of course, at this temperature for the whole of this time and 30000 h is regarded as sufficient for 'hot' testing. (This represents some three years work in the laboratory.)

The dominant characteristics to be taken into consideration in selecting the particular aluminium alloy for the structure were:

(1) the tensile strength and proof stress retained after prolonged exposure to the highest temperature encountered;

(2) the creep strength in terms of the limiting creep stress for 0.1 % permanent strain;

(3) the fatigue endurance of a notched specimen with the steady load limited to 25 % of the tensile strength;

(4) crack propagation.

4.9. *Hiduminium R.R.* 58: *the ultimate choice*

With these criteria in mind, comparative tests were made on several alloys (figure 16) – notably L 73 (Duralumin), 2024-T81 (Duralumin with high magnesium content) and Hiduminium R.R. 58 (of the Y-alloy family containing nickel). Although in most respects these three materials did not differ greatly from each other, in fatigue tests on notched specimens at 120 °C R.R. 58 was notably superior and was accordingly chosen. However, R.R. 58 was not a new alloy, having been known (as its designation suggests) in the aero-engine field for over 30 years. The impellers of the original Whittle jet engines installed in the Gloster Meteor fighter had been forged from this material.

5. TECHNICAL SOLUTIONS

5.1. *Resolution of shape*

In common with any aircraft, the shape of a supersonic airliner is dictated by the requirement of the design missions. The plurality of mission is important because adequate flexibility of operation is unlikely to be obtained by concentration on a single design mission. For example, with an s.s.t., the need to carry out missions with long subsonic sectors must be considered. As already discussed, the operational environment varies considerably over the surface of the globe, and 'ideal' solutions for 'cold' equatorial and 'warm' polar routes are different. These requirements are inevitably more or less conflicting and must be resolved. For the s.s.t. they are generally more acute than for subsonic aircraft.

There are two main methods of resolution and compromise:

(1) by the use of major variable geometry in order to optimize the aircraft for each flight phase more or less independently;

(2) by attempting to achieve a compromise fixed-geometry configuration giving an adequate overall performance and reaching at least minimum acceptable levels in each basic flight phase.

Some of the major problems of the first approach are mechanical complexity and weight, aircraft stability in the extreme configurations and during transition and limitation on the overall configuration (limited choice of spanwise engine location).

The nature of the compromises involved in the second method depends on the specific nature of the task that has been set – in particular on the size, range and cruise Mach number which have been chosen. For this reason it is difficult to make very general statements in this area and the discussion which follows is based on an aircraft of generally Concorde type (figure 17).

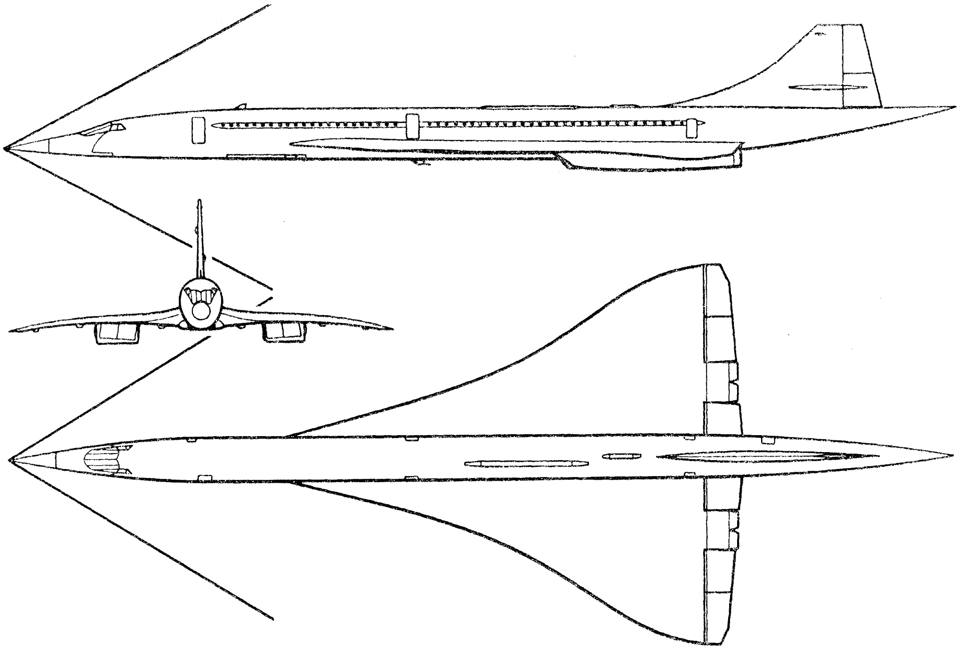


Figure 17. Bow shock waves (Concorde).

It can be shown that very good lift/drag ratios can be achieved at moderate supersonic speeds with aircraft that are aerodynamically slender – where the sweepback of the wing leading edge is greater than the complement of the Mach angle (greater than arccos $(1/M)$).

From the very nature of the slender-wing concept, it is readily apparent that the wing, fuselage and nacelles are interdependent and that the aerodynamic design must be integrated with the requirements of the structure, systems and production engineering.

Since supersonic aircraft have to conform to subsonic standards in the vicinity of airfields, no single speed can be taken as the design speed – supersonic design is very important, but subsonic and transonic requirements must also be given proper attention.

5.2. *Wing planform development*

Figure 18 illustrates the steps taken to match the ideal wing planform shape for cruise efficiency with the low-speed stability requirements to reach a compromise solution. Each of the shapes shown has the same plan area and is therefore capable of holding a certain amount of fuel.

Starting from the simple triangular delta shape (*a*), with about 69° of sweepback giving a Mach number normal to the leading edge at cruise of about 0.8, the first development takes the form of reducing the leading edge sweep as much as possible (*b*), but considerations of supersonic wave drag set some rather hazy limit to the minimum sweep. For this first step a sweep of 57° is taken, which results in nearly sonic flow at Mach 2.0 (i.e. the cone angle of the shock wave is the same as the angle of sweep) and supersonic at Mach 2.2. However, reducing the root chord has several adverse effects; it worsens the area distribution giving higher wave drag, increases the wave drag due to lift by reducing the chord over which the lift is distributed and moves the centre of gravity (c.g.) of the fuel too far aft in relation to the aerodynamic centre.

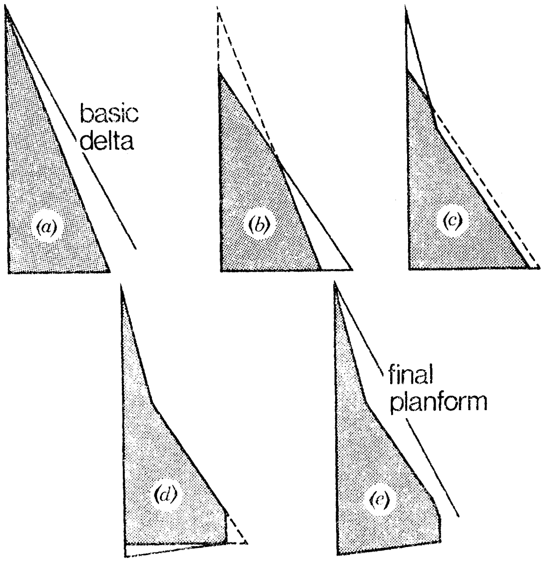


Figure 18. Wing planform derivation.

To compensate for these effects, the next step is to add a small highly-swept fillet at the wing leading edge (*c*). This is important in that it enables the c.g. of the fuel to be brought forward without the aerodynamic centre being much affected on a low wing configuration.

Finally, two changes are made which eliminate a tendency to loss of stability at high incidence, which exists on planform (*c*). The shape is cropped at the tip and the trailing edge is swept forward (*d*). The final ogival-delta planform (*e*), when leading edge discontinuities are eliminated, bears little resemblance to the original simple triangular delta planform shape (*a*). Although the leading edge is supersonic at the position of minimum sweepback, the supersonic wave drag has not suffered significantly and the final shape of the low-speed pitching moment curve is entirely satisfactory.

5.3. *Fuselage shape*

The question has frequently been raised as to why Concorde does not have a so-called 'wide-body' fuselage. The following discussion puts this argument into persepective, while surveying the principal design considerations involved.

In order to minimize supersonic wave drag, the fuselage length/diameter ratio of Concorde is 21.6, resulting in a cross-section optimized for four-abreast (two-and-two) seating. It is significant to note that this ratio for the proposed Boeing 2707 s.s.t. was 21.4.

The pressurized volume of the Concorde fuselage is 239 m^3. If we consider Concorde to be flying at 18.3 km and pressurized to restore the equivalent cabin altitude to 2.44 km, the difference between the weight of air in the cabin and the air displaced by the aircraft is approximately 182 kg. (Corresponding figures for the Boeing 2707 were: pressurized volume approximately 759 m^3 and weight difference at 18.3 km; 636 kg.)

Comparison of the fuselage design of an s.s.t. with that of a wide-body subsonic jet (the Boeing 747 fuselage diameter of 6.71 m.) is salutary. With a length/diameter ratio of 21.6, Concorde would have to be 144.78 m long with this width of fuselage – compared to the present length of the Boeing of only 68.58 m. Assuming that a similar proportion of the fuselage volume would be pressurized to that in Concorde, there would be 3030 m^3 of pressurized space. This would result in a weight difference at 18.3 km of approximately 2542 kg (just 2.54 tonnes).

Considering the capacity of such an aircraft, the 298-seat Boeing 2707 s.s.t. would have 2.55 m^3 of pressurized air per passenger, whereas the Boeing 747, with 374 passengers, has a pressurized volume of 963 m^3, which allows 2.58 m^3 per passenger. (Note that this volume of pressurized air also includes that in baggage-hold areas.) The wide-body s.s.t. with 3030 m^3 of pressurized air would therefore be ideal for approximately 1180 passengers. On landing, the Concorde pilot is 12.2 m above ground level at the point of touchdown. Assuming a similar angle of incidence for the wide-body version on landing, the pilot would have his wheels touching the ground when his altimeter read 30.5 m!

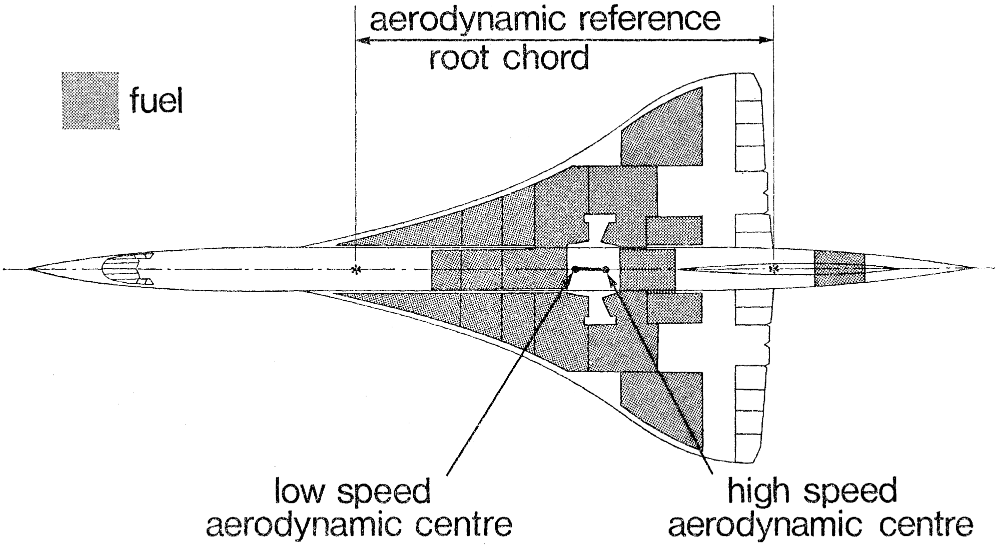
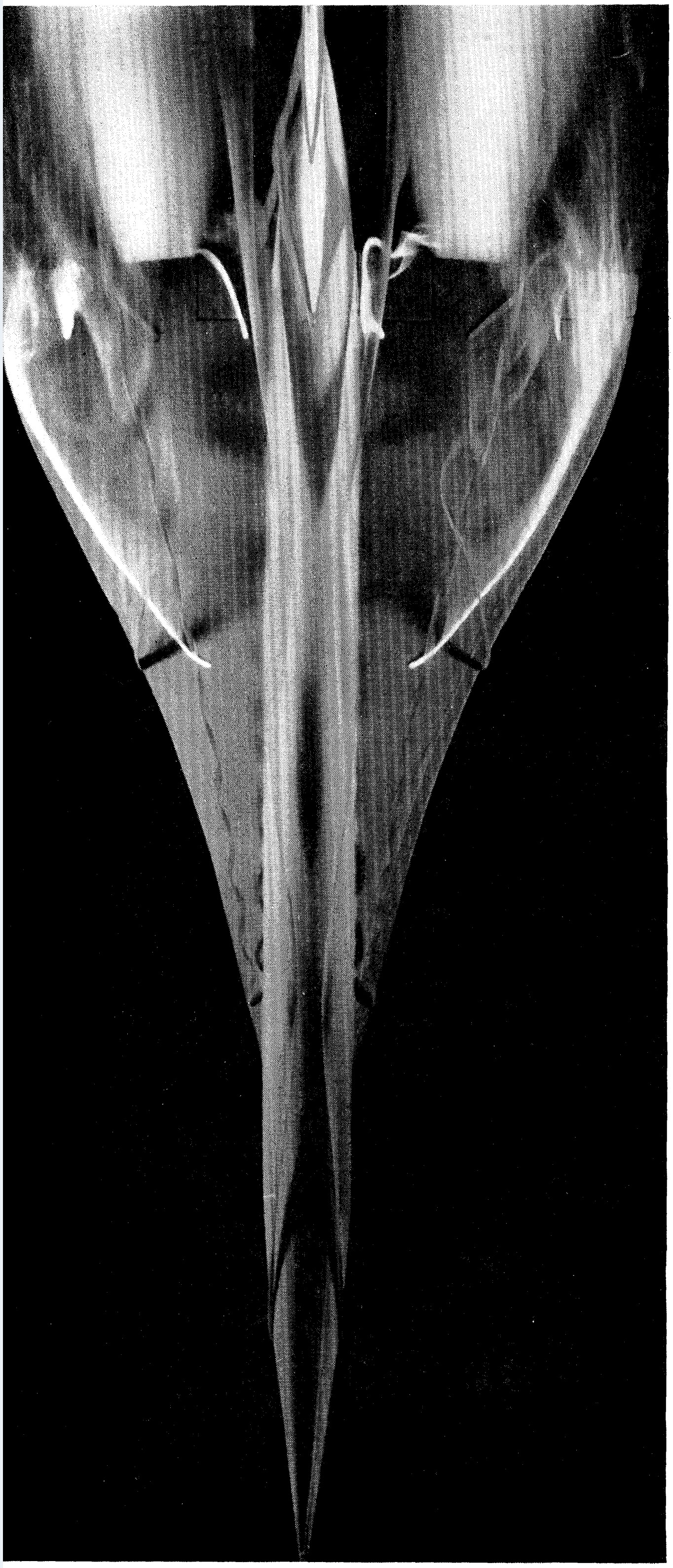


FIGURE 20. Aerodynamic centre.

5.4. *Vortex flow*

It has been shown that a slender-wing aircraft with a highly-swept leading edge is one very attractive form of supersonic aerodynamic shape. It is also a requirement for low supersonic drag that the leading edge of the wing should be relatively sharp and not rounded as on subsonic aircraft.

At low incidences the flow will follow even a relatively sharp leading edge and normal attached flow results. However, as the incidence increases, because of the high sweepback, it does not do so in a random manner, but in a controlled way, to form a vortex above the wing surfaces. This vortex is continually energized and increases in size along the wing from root to tip, leaving the leading edge near the tip to swing and run streamwise. (Both views in figure 19,



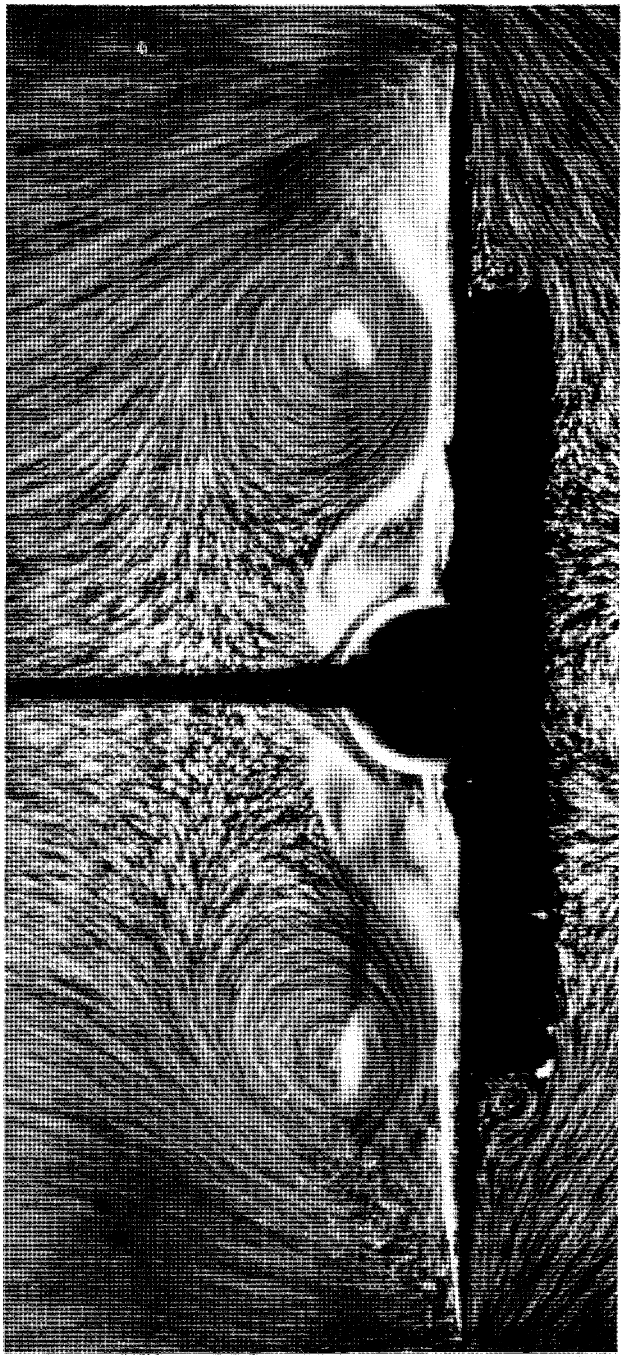


FIGURE 19. Vortex flow (two views).

plate 27, are of a model in a water tunnel, the upper with dyes issuing from holes in the wing, and the lower showing a section at the trailing edge of the wing, using aluminium particles in the water and a narrow light beam for illumination.)

It is characteristic of vortices that they have low pressure within them – and it is found that there is a low-pressure region on the wing in the area under the vortex. This low-pressure region increases the lift of the wing above that which it would have in attached flow, which is generally advantageous, as it gives increased overall lift. However, it also means that the pressure field, and therefore forces and moments on the wing, are sensitive to the exact position and strength of the vortices. It is essential therefore that the vortices should develop steadily and be stable and insensitive to sideslip, otherwise non-linear and erratic pitching- and rolling-moment derivatives would result. Considerable design effort and ingenuity have gone into achieving the desired situation on Concorde, involving fine adjustment of both the planform and wing camber near the leading edge. (The mechanism and benefits of this phenomenon stemmed from the pioneering work at the Royal Aircraft Establishment (R.A.E.) at Farnborough in the mid-1950s, under the most able leadership of Morien Morgan, who was also Chairman of the Supersonic Transport Advisory Committee (S.T.A.C.) formed in 1956 to initiate British research towards a practical s.s.t.)

5.5. *Aerodynamic centre movement*

As the airflow over a lifting body becomes supersonic, the aerodynamic centre moves aft, creating balance and stability problems for the designer of a practical aircraft.

In his classic paper 'A New Shape in the Sky' (*J. R. Aeronaut. Soc.* 1972) Sir Morien Morgan highlights the principal theoretical and experimental development work which led to the choice of a basic shape having 'manageable aerodynamic centre shift with Mach number' properties.

At supersonic speeds the drag produced by the deflexion of trailing edge controls can be excessive and it follows that in the mean supersonic cruise condition the aircraft must be arranged to be trimmed with substantially zero control deflexion. Additionally, it must have an adequate level of static longitudinal stability. Taken together, these two requirements imply two things; the resultant of all lift forces acting on the aircraft must pass close to the aircraft centre of gravity when the controls are not deflected and the centre of gravity must lie ahead of the supersonic aerodynamic centre by a given amount during the cruise.

However, as already stated, the supersonic aerodynamic centre lies considerably farther aft than the subsonic aerodynamic centre. Typical values are subsonic 53 % C_0 and supersonic 60 % C_0, where C_0 is the aerodynamic reference chord. These positions for Concorde are shown in figure 20 and the shift is about 1.83 m.

Considerable effort is required to arrange that the centre of gravity of the aircraft at low speed lies ahead of the subsonic aerodynamic centre, but having achieved this, it lies much farther ahead of the supersonic aerodynamic centre. In fact, if the c.g. were to remain in this forward position, the longitudinal stability would be excessive.

5.6. *Aerodynamic centre control by fuel transfer*

It is therefore desirable to move the aircraft c.g. aft along the wing chord for the supersonic cruise condition and in Concorde this is achieved by transferring fuel between front and rear trim tanks (figure 21.) This diagram should be read in a clockwise direction, starting at the zero fuel weight (z.f.w.) point in the bottom left-hand corner.

Fuelling the aircraft increases its weight and the c.g. moves slightly aft to about 51.5 % C_0, as shown by the left-hand sloping line with arrow. As the aircraft takes off and climbs subsonically, the fuel weight decreases and the aircraft c.g. moves slightly farther aft. During transonic acceleration, fuel is transferred to the aft trim tank, bringing the c.g. rearwards to about 57 % C_0 at the beginning of the supersonic cruise (time to transfer fuel is about 20 min), where it remains essentially constant for the supersonic part of the flight. As fuel is burnt the weight of the aircraft is decreasing along the downward arrow on the right-hand sloping line. With deceleration to subsonic speed at the end of the cruise, fuel is transferred forward, as shown, so that the correct c.g. position for subsonic flight is achieved before approach and landing, when the path to c.g. shift returns to the z.f.w. point.

It should be noted that by this fuel management technique, all the uplifted fuel is usable, the only penalty being the loss of a small amount of tank volume at take-off in the aft trim tank.

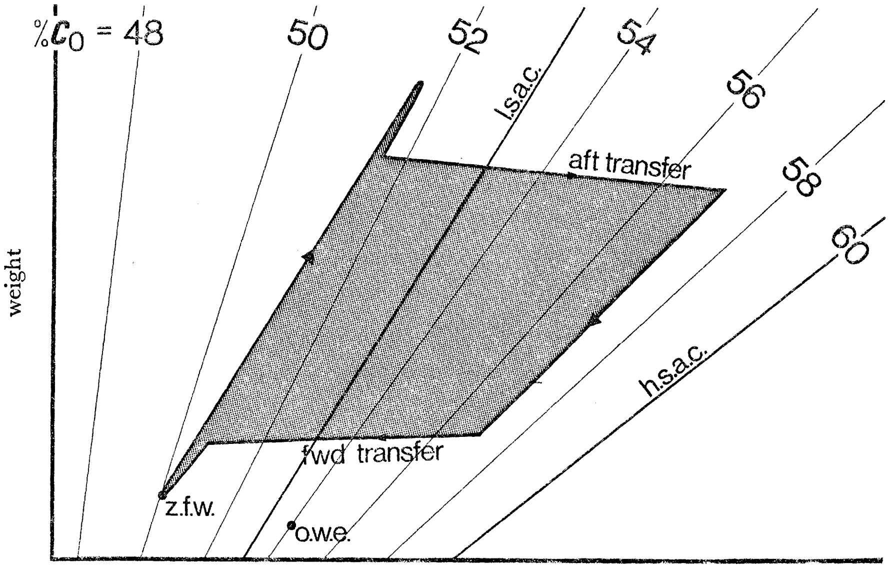


FIGURE 21. Aircraft trim by fuel transfer.

5.7. *Powerplant installation*

Special problems arise in the installation of engines in supersonic transport aircraft, since all turbofan and turbojet engines require the air velocity at the compressor entry to be uniform and appreciably less than sonic. For aircraft cruising at less than Mach 1 a very simple air intake geometry is quite adequate. However, an aircraft cruising at twice the speed of sound requires a much more complicated variable-geometry intake, to recover the kinetic energy of the area and to avoid excessive spillage drag.

In the same way, the simple fixed-geometry jet nozzle of the subsonic civil aircraft is no longer suitable for an aircraft which has about twice the speed range and cruises at higher altitudes. To enable it to do this efficiently, a variable-area primary nozzle is required. Further, in order to obtain efficient propulsion from the jet at the highest jet pressure ratios (15:1 at the cruise), a divergent nozzle section is required downstream of the throat of the propelling nozzle. This is provided on Concorde by two variable-area nozzles (primary and secondary), one located within the other.

Figure 22 shows the principal modes of operation of the intake and propelling nozzles for Concorde.

At low speed the problem is to get sufficient air to the engine and an additional amount is drawn in through auxiliary intakes. In normal cruise the principal design aims are efficient compression, minimum drag and a good velocity distribution at the engine face. It is in this phase that the automatic regulation of the intake plays its main part, making adjustments to the ramp angle to maintain efficient operation under varying conditions of flight. The whole process is one of continuous compression from the front of the intake to the last stage of the engine compressor, giving an overall pressure ratio of about 80:1. This is of the same order as a diesel engine and accounts for the high efficiency of supersonic powerplants. It is a breakdown in this compression process which constitutes an engine surge.

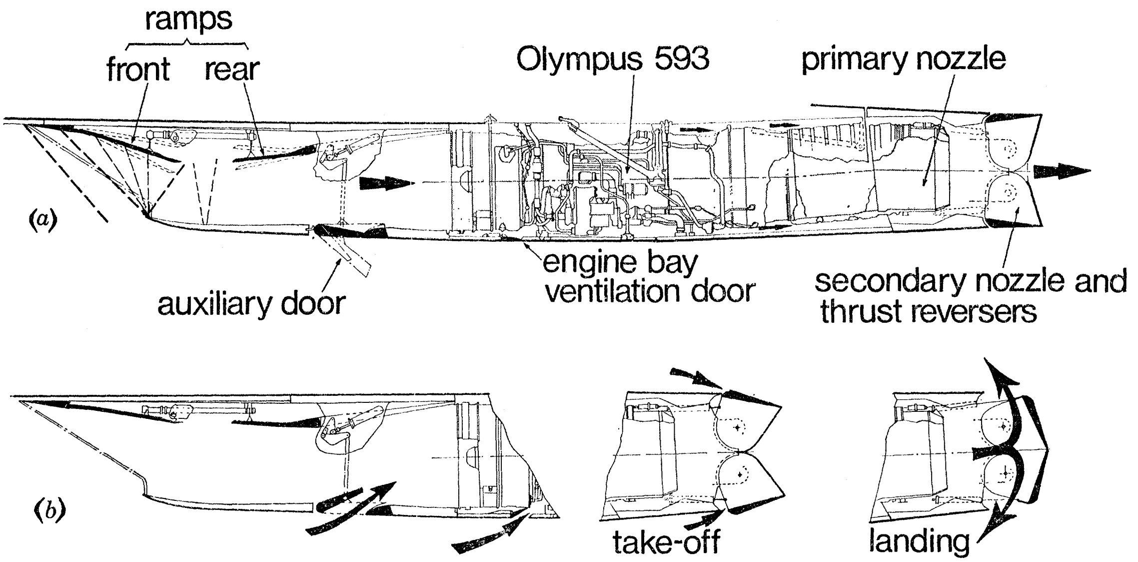


Figure 22. Power plant installation. (*a*) Cruise and descent; (*b*) Take-off and landing.

5.8. *Engine intake mechanism*

Intake design is dictated primarily by the requirement to slow the incoming air from the cruise Mach number to around Mach 0.5 at the engine face. For Concorde this is accomplished by the creation of a series of shock waves, each successive shock slowing and turning the airflow. Most of these shocks are produced on the external compression surfaces, the first coming from the front wedge of the intake and the next from the leading edge of the hinged front ramp. They are followed by a fan of smaller isentropic compression shocks generated along the movable surface of the front ramp. This shock pattern slows the air but also turns it downwards and away from the horizontal. In order to return the airflow to the horizontal, the sharp lower cowl lip has been shaped to produce an internal compression final shock which turns the flow back to within 5° of the intake centre-line, leaving the final correction to the subsonic diffuser section of the intake.

At take-off the intake is opened to provide maximum airflow, the hinged upper ramps are raised and the auxiliary door in the base of the intake opens inwards. At the same time the secondary flow doors are closed, to prevent reverse-flow in the intake. (These doors open again at about 370 km/h to provide additional engine-bay cooling.)

During climb the auxiliary 'blow in–blow out' door in the bottom of the intake begins to close, thereby reducing the airflow to the engine. At about Mach 0.7 the door closes completely.

From Mach 1.3 to the ultimate cruise Mach number the upper ramps are progressively lowered, the forward ramp fixing the shock waves at the front of the intake. The engine-bay door, open at take-off, is closed and the bay is cooled by air drawn from the intake throat through the ramp bleed slot.

To prevent windmilling and aerodynamic confusion if an engine has to be shut down in supersonic flight, the upper ramps are lowered further and the auxiliary door is opened outwards to spill the incoming air.

Like all supersonic powerplant intakes, the inlet does not function in isolation, but in a highly complex interaction with the engine and exhaust system.

5.9. *Engine exhaust nozzle operation*

At take-off, with afterburner on, the reverser-nozzle buckets are brought to an angle of 20° from the horizontal, at which position a convergent final nozzle is achieved, with additional air induced through the uncovered tertiary air inlets. This provides the optimum nozzle expansion ratio. During the initial climb, the buckets are further closed to 30°, making the nozzle even more convergent. For the climb and fly-over phases, where noise abatement is most important, the re-heat is turned off, the bucket angle reduced to 10° and the retractable spade silencers deployed.

The transonic acceleration between Mach 0.9 and about Mach 1.6 is achieved by re-lighting the afterburner and modulating the buckets between 10 and 0° ('stowed').

At supersonic cruise, with re-heat off, the nozzle buckets are at 0°, giving a divergent final nozzle with no tertiary airflow. (The tertiary air inlets are closed by the nozzle buckets when the latter are in the 0° – fully open – position.)

For thrust reversal, the buckets are brought together (to meet at 73° bucket angle), thereby deflecting the exhaust forward. This mode of operation may be used throughout the flight range to dump thrust, as an airbrake.

The critical importance of the design of the engine exhaust system can be appreciated when it is realized that 1 % change in efficiency is equivalent to 204 kg of payload.

5.10. *Flight envelope design speeds*

The operating speed of Concorde is limited in terms of airspeed (V_{MO}), Mach number (M_{MO}) and stagnation temperature (T_{MO}) as follows; V_{MO}, 982 km/h at 13.33 km and above; M_{MO}, 2.05, and T_{MO}, 400 K. (MO, maximum operating.)

Depending upon altitude and atmospheric temperature, any one of these three limits may be dominant and constitute the design cruising speed (V_{C}).

The design diving speed $V_{\mathrm{D}}/M_{\mathrm{D}}$ is greater than $V_{\mathrm{MO}}/M_{\mathrm{MO}}$ by a margin which is adequate for unplanned upsets and atmospheric disturbances from flight at V_{C}.

The design manoeuvre speed V_{A} is the lowest speed at which an abrupt pull-up manoeuvre of 2.5 g can be carried out, the maximum lift coefficient used being compatible with the value demonstrated for satisfactory flying qualities in normal flight.

5.11. *Design loads*

The design load factors for Concorde are the same as those for current transport aircraft ($+2.5g$ and $-1g$), conventional factors also being applied for the dynamic effects of gusts, landing and taxiing.

5.12. *Aeroelasticity and flutter*

The speed–altitude regime within which the aircraft operates (subsonic, transonic and high-altitude supersonic) imposes conditions of flight and manoeuvre which cannot be resolved by studying the aeroelasticity of the airframe as simply 'rigid' or 'flexible'. Consequently, all conditions of flight have been studied and characteristics have been established in both flexible and rigid modes.

These investigations of flutter speed, using computers and dynamically similar models for both symmetric and asymmetric flight conditions, have clearly shown that the aircraft possesses no critical flutter speed. This fact has now been confirmed by extensive flight-testing on the full-scale aircraft.

5.13. *Structural design philosophy*

The design of a long-range supersonic transport demands new techniques and conventional forms of construction have had to be modified to meet the new requirements.

All the familiar criteria of subsonic aircraft design have still to be considered – in particular those which result from fail-safe and fatigue considerations.

5.14. *Weight criteria*

The fuel load requirement associated with long-range supersonic transport operations brings empty weight sensitivity into sharp focus and emphasizes the importance of structure weight. To save weight, machined components are used extensively, to allow a more exact correlation of shapes and thicknesses to the stresses which modern methods of calculation can now define precisely. Although some parts, when finished, weigh only one-tenth or one-twelfth as much as the original billets, the time saved in assembly balances raw material and machining costs, resulting in a method of construction which is highly competitive, particularly with modern automatic tape-controlled machine tools. Comparative studies show a weight saving of up to 20 % for machined structures, when compared with the more conventional fabricated structures.

5.15. *Kinetic heating considerations*

Although the higher structural temperatures of supersonic flight have been contained by the use of R.R. 58 as the basic material, new solutions were required from a structural point of view, due to differential thermal expansion. For example, transient thermal stresses generated in a wing rib or spar web during supersonic acceleration or deceleration might reach values similar to those generated by normal flight loads, unless suitable precautions were taken.

Various advanced construction methods have been used to avoid a weight penalty, such as machined, corrugated members which allow some distortion, braced, pin-jointed structures and 'criss-cross' pattern members, with large machined recesses forming a lattice. The last two designs, which are widely used throughout the structure of Concorde, offer very good accessibility for maintenance of the interior of the wing, especially in fuel-tank areas.

Other consequences of the higher temperatures are joint creep phenomena, which become particularly important in multi-jointed assemblies. In order to alleviate this problem the structural design has minimized the number of assemblies and used one-piece components as far as possible. This is why certain centre-wing skin panels attain lengths in excess of 6.71 m.

5.16. *Structural problems peculiar to the s.s.t.*

While thermal aspects are the most noticeable structural problems peculiar to the s.s.t., they are not the only ones. On subsonic aircraft there tends to be a predominant load direction in the wings, associated with span-wise bending. In the case of the s.s.t. with its large wing of low aspect ratio, this is no longer the case and the structure is much more of an 'egg box', with spars and ribs carrying loads of comparable values. This has led to the need to develop new methods of structural analysis.

The s.s.t. wing is not only large but very thin, so that torsional stiffness is low. This, combined with large trailing-edge controls and the fact that the aircraft flies right through the transonic range under conditions of high dynamic pressure, highlights the potential problem of flutter.

The wing also constitutes a fuel tank for more than 60 % of its surface area, which tends to accentuate temperature differences between various parts of the structure.

5.17. *Testing*

All these considerations, and the analogous ones in the aircraft systems, are the subject of extensive full-scale facsimile testing in Britain and France. This, combined with the very searching powerplant and flight development programmes in the two countries, means that Concorde will be the most thoroughly researched and tested airliner ever to enter commercial airline service.

6. Ecological considerations

It would not be possible to write a paper on the s.s.t. without some discussion of the environmental aspects. Much – probably too much – has been written and said on the subject, often by those whose objectives were by no means of pure scientific inquiry. No attempt is made to argue the environmental case – merely to indicate areas in which our knowledge is good, the areas of doubt and to show what steps can be and are being taken to meet the known problems and resolve the doubts.

The environmental impact of any transport aircraft can be divided into three areas; low-level pollution, community noise and the sonic boom and stratospheric pollution.

The entirely new problems introduced by the s.s.t. are the sonic boom and exposure to cosmic radiation.

6.1. *Low-level pollution*

Aircraft are one of the cleanest forms of mechanical transport, giving lower pollution per passenger-mile than any other type of transport vehicle, except for electric vehicles using nuclear-powered generating stations as their prime source. The total contribution of all jet aircraft to atmospheric pollution is less than 1 % (figure 23), so that if it has any significance at all, it must be because of the peculiar nature of its distribution.

The exhaust pollutants of a jet engine are generally similar to those of any other engine burning fossil fuel, namely CO_2, CO, H_2O, SO_2 and NO_x. Under normal operating conditions the CO emission is small, but NO_x is significant because of high local flame temperatures; at idle the CO content rises because of reduced combustion efficiency.

The values for the s.s.t. are not significantly different from those for subsonic aircraft. However, since the fuel consumption of a pure jet is greater than that for a fan-jet engine of the same thrust, particularly during re-heat operation, the absolute quantities of pollutants produced are higher.

The total contribution of all aircraft to atmospheric pollution has been shown to be small. Even near large airports, where there is not only a high concentration of traffic, but where much time is spent with the engines operating inefficiently at idle, the pollution does not rise to the level of that of the cities served by the airports. Nevertheless, reduced pollution by improved operating techniques and improved combustion systems is potentially possible and these improvements will apply just as significantly to the s.s.t. as to conventional aircraft.

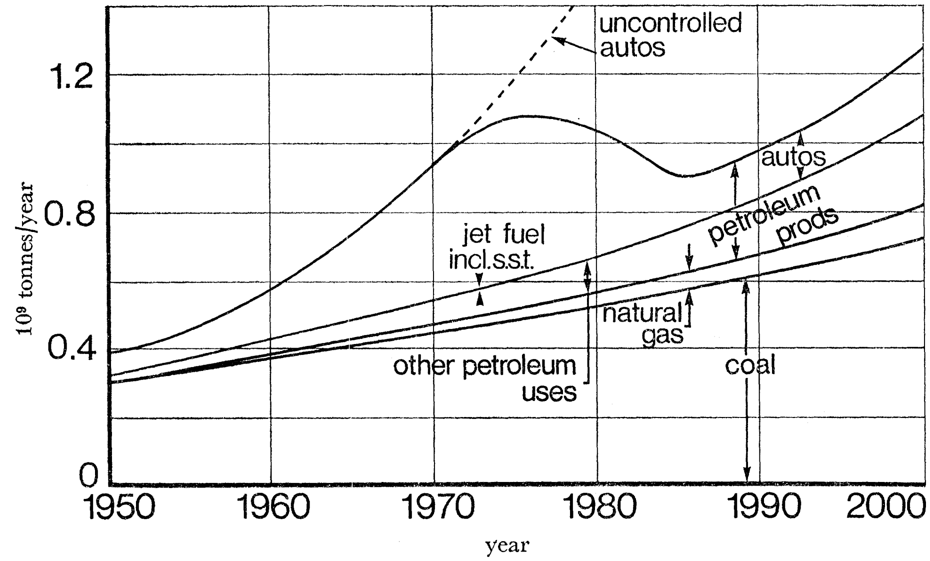


FIGURE 23. World pollution generation.

A notable example of success in this area is the almost complete elimination of exhaust smoke in the production standard Concorde by the incorporation of a new-design vaporization-type annular combustion chamber, which ensures more complete combustion of the fuel-oxidant mixture (figure 24, plate 28).

6.2. *Community noise*

The noise produced by an aircraft near the ground is, with great over-simplication, a function of aircraft height, installed power and engine cycle and engine specific thrust. The first two are obvious. The third arises from the fact that at high jet velocities (at least where the turbomachinery noise is not significant) the noise produced by the engine is proportional to something between the sixth and eighth power of the jet velocity and the source noise therefore increases with specific thrust.

It is clear therefore that the s.s.t. is at an inherent disadvantage by comparison with subsonic aircraft, since we have already seen that the subsonic lift/drag ratio will be relatively poor and that supersonic flight demands engines of high specific thrust.

The designer has a number of weapons available to help relieve this difficult position.

(i) Fly-over noise after take-off can be reduced by increasing the height by the use of high thrust–weight ratio, but at the expense of some increase in noise on the airfield itself.

(ii) Approach noise can also be reduced by increased height arising from the use of steep approach paths – this procedure cannot, however, be unilaterally adopted by s.s.ts, since ground guidance is still required.

(iii) The lift/drag ratio can be improved by detail design and by various forms of variable-geometry, ranging from swing-wings to flaps on both the leading and trailing edges.

(iv) Direct silencing of the jet must be used. Because of the vital importance of cruise nozzle efficiency, any silencers must be retractable; in some ways this helps, since once the need for retractable silencers is accepted, it is possible to contemplate those which have a far higher effect on nozzle efficiency than would be acceptable in a fixed installation. (It appears to be a broad general rule that the more effective a silencer is, the bigger the thrust losses it causes.)

(v) The specific thrust in the throttled cases can be minimized by using the variable-area nozzle to run the engine at the minimum practicable pressure ratio.

(vi) When all this has been done to reduce the jet noise, it may be found that the turbomachinery noise makes a significant contribution, particularly on approach. Under these conditions, sound absorption treatment may be given to the jet pipe and possibly the intake.

Although none of these measures may individually produce a dramatic noise reduction comparable to the change from low by-pass engines to the big fans on subsonic aircraft, together they can produce a very useful degree of silencing.

In spite of all these ameliorative measures, it seems that it will be extremely difficult to reduce the noise of an s.s.t. to the level achieved by the new generation of high by-pass-engined subsonic aircraft by the use of any current technology. Some useful further improvement is certainly possible, but large gains will require the development of new technologies, probably in the direction of multi-mode operation of the powerplant.

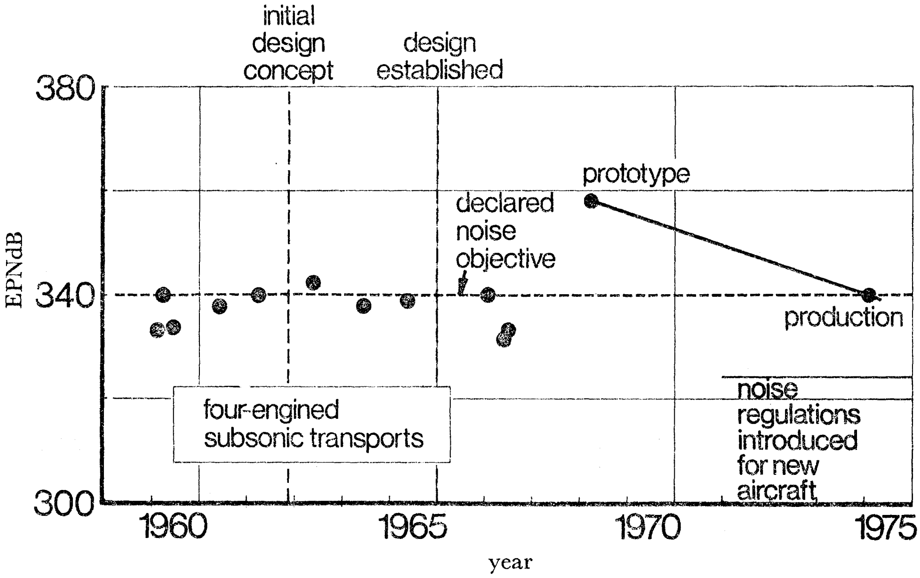


FIGURE 25. Airfield noise comparison.

The declared noise objective for Concorde has always been that the total noise level would be no worse than today's big fleets of four-engined long-range subsonic airliners (figure 25). Whereas the prototype Concordes (without silencers) do have a higher community noise than this objective, it has already been demonstrated that the production standard Concorde total noise figure (340 EPNdB) meets this target. However, new attitudes and regulations are now on the horizon for lower levels to be achieved for new aircraft. A massive and continuing programme of noise research is expected to yield further attentuation, which will certainly go a considerable part of the way towards bringing Concorde noise levels in line with these new requirements.

6.3. *Sonic boom*

The sonic boom is a further manifestation of the shock wave broadly associated with the bow wave of the aircraft, giving a sudden pressure rise followed by a steady rarefication to below ambient pressure, which is in turn followed by a second shock that re-establishes ambient pressure.

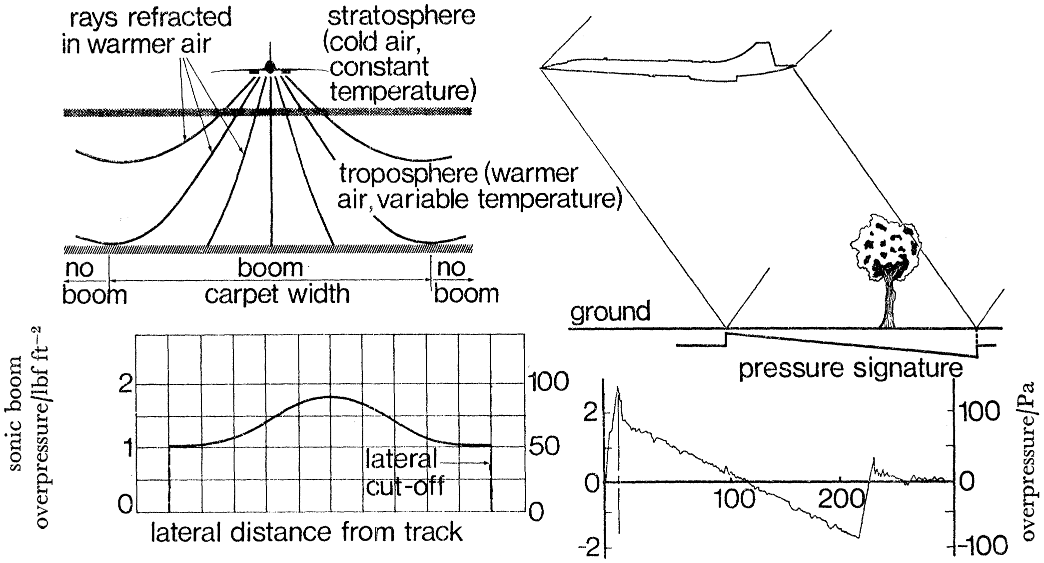


FIGURE 26. Sonic boom.

This simple picture (figure 26) is true for an aircraft flying under steady conditions in a uniform atmosphere. In the real atmosphere, with temperature and wind gradients and turbulence, the simple N wave is often blurred (or even totally dissipated if the aircraft Mach number is below about 1.15), while manoeuvres or acceleration of the aircraft can cause a focusing effect, giving pressure rises of several times the corresponding steady-state value.

The effects of a sonic boom, particularly the psychological ones, are also a function of aircraft size, since both the sharpness of the initial pressure rise and the delay between the two shocks are very significant. It is for this reason that many of the simulated tests, with either small military aircraft flying at relatively low altitude, or even explosives, are suspect when applied to s.s.ts.

However, the considerable data obtained from Concorde, both in the United Kingdom in 'Exercise Trafalgar' on the West Coast route and in France, has shown that the probability of damage from sonic boom is very low and has suggested that the annoyance factor is much lower than has often been suggested. Nevertheless, all present planning is on the basis that supersonic flight over populous areas will be prohibited.

6.4. *High-altitude atmospheric circulation and pollution*

The area in which there has been great controversy on the alleged effects of pollution by the s.s.t. is that of stratospheric flight.

Before discussing the nature of this controversy, it should be noted that flight in the lower stratosphere is not confined to the s.s.t. – it is currently being carried out on a regular basis by both military aircraft and subsonic jet transports. By 1990 the contribution from the projected supersonic fleet will be about equal to that of the subsonic civil fleet. Nevertheless, the effect of this pollution is almost certainly a function of height and the generally higher altitudes of the s.s.ts make their separate consideration essential.

The heavy line in the centre of figure 27 denotes the tropopause, which is the normal limit of convective activity, although occasionally highly-active cumulo-nimbus formations may exceed average tropopause levels. Figure 30 also indicates the mid-latitude discontinuities in the tropopause, which are associated with jet-stream phenomena and through which stratospheric air and any contaminants associated with it, are discharged into the troposphere by the Hadley cell systems. These cells are caused by upwelling air in tropical regions of the troposphere being carried through the cold layer of the equatorial tropopause – typically 190 K – into the stratosphere.

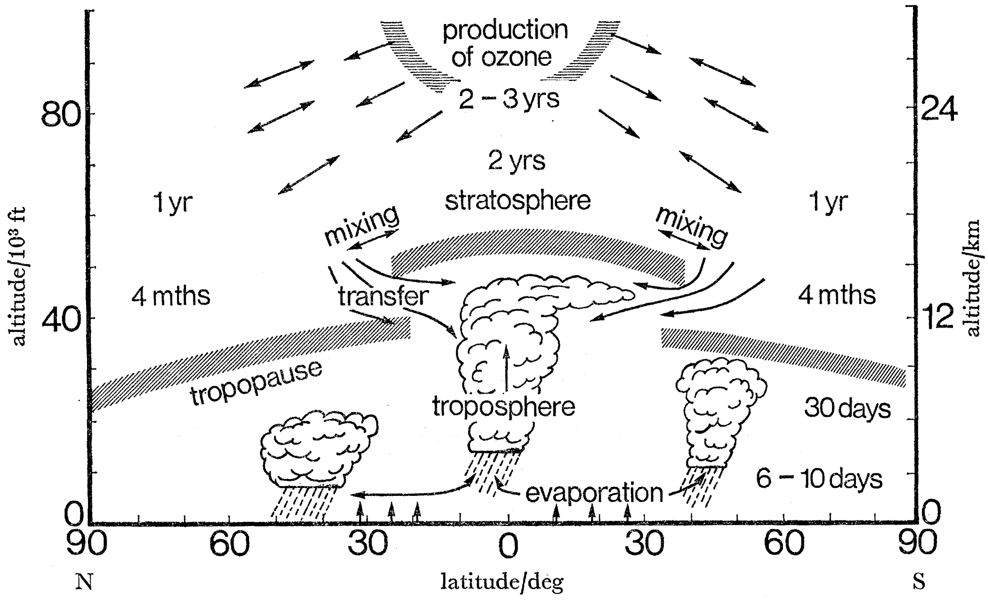


FIGURE 27. Atmospheric circulation.

The pole-wards flow of air in the stratosphere from the tropical cells and to a lesser extent the equatorial flow of the high-latitude cells, give the residence times for stratospheric air shown in figure 27. At mid-to-high latitudes embracing Concorde cruise levels, the residence time is about four months while in equatorial regions it is about nine months. These figures are to be compared with residence times in the troposphere of a few weeks.

While the troposphere is dominated by convective activity, the stratosphere is dominated by photochemistry, resulting in the production of ozone, predominantly as shown around 30 km altitude above the equatorial tropopause. The ozone diffuses downwards and pole-wards, so that the layer of maximum density occurs just above the tropopause. Therefore, in regions where subsonic jets may penetrate the tropopause, they can also affect the ozone layer. In the case of Concorde, the maximum concentration of flights occurs in regions where residence time is quite short; consequently, contaminants cannot build up to large concentrations over a long period.

It is now generally agreed that neither the H_2O nor the CO_2 emissions from an s.s.t. represent an environmental threat, although both have been suggested. The various sulphate residues have also caused concern, because of their ability to form nucleation particles. The Junge Layer in the region of 18–20 km altitude represents a natural concentration of such particles; their source is not wholly clear, but volcanic eruptions must play a major part. The quantities of matter injected by them are so great, in comparison with any foreseeable contribution by aircraft, that this aspect appears most unlikely to be a real problem. The increasing use of low-sulphur fuels further reduces the importance of the subject from a general pollution point of view.

The final aspect is that of interaction between the exhaust products and atmospheric ozone, in particular between the oxides of nitrogen and ozone. The importance of this lies in the absorption by the ozone layer (which is formed in the region above 20 km and steadily reduced by photochemical action, until the ozone content is negligible below the tropopause) of a biologically active region of the ultraviolet spectrum below 320 nm. Although it is not wholly proved and the quantitative relation is in doubt, there is broad evidence of a correlation between naturally-occurring ultraviolet dosage and skin cancer. Any mechanism which could cause major changes in the ozone content of the stratopshere is therefore a cause of concern.

The problem is extremely complex. Not only are the appropriate photochemical equations complex and the dynamic parameters not yet well established, but it is now clear that for any reasonable estimates to be made, the large-scale (and probably medium-scale) dynamics of the atmosphere (figure 30) must be included as well. It now seems very probable that the original cataclysmic estimates of the effects of an s.s.t. were much in error. However, the problem of getting a good estimate of the order of the probable change remains – and this is still a major area of research.

In summary, one thing is certain; the evidence from volcanic eruptions has shown beyond doubt that the stratosphere is self-cleansing and monitoring is therefore a total safeguard against danger. There remains the problem that natural variations in the content of the upper atmosphere appear to be large, compared to any changes that s.s.ts are likely to cause, but more data is required before the fleet sizes become large; extensive monitoring is in hand.

(Since this lecture was prepared Concorde prototype 002 has flown seven flights specifically programmed to monitor the upper atmosphere at high northern latitudes. This initial investigation, carried out in collaboration with the National Physical Laboratory, involved nearly 20 h flying – over half at supersonic speeds – and included two supersonic night flights.)

6.5 *Cosmic radiation*

At high altitudes the shielding effect of the Earth's atmosphere against cosmic radiation is greatly reduced and since the radiation can have harmful biological effects, it presents a potential problem.

As far as the galactic component of the radiation is concerned, the dose-rate, even at s.s.t. altitudes, is relatively low and the increase over that experienced by passengers in subsonic aircraft is fully compensated for by the reduced flight time. The real difference between the s.s.t. and subsonic aircraft lies in the relatively sudden large increases in the solar component associated with solar flares. The solution to this problem adopted for Concorde is to carry on the aircraft a dose-rate meter, which gives the crew a preliminary warning when the rate reaches a certain level and a further 'action' warning at a higher level, at which time the pilot descends to a safe altitude. The precise values of these levels are still under discussion, but the tentative 'action' level has recently been lowered to 50 mrem/h.

From data collected over many years, it can be shown that even if the 'action' level were to be set considerably lower, the number of occasions on which aircraft would have to descend would still be very small indeed.

The on-board dose-rate meter will be supplemented by a World-wide warning system based on the 'Solterwan' network, with its headquarters at Boulder, Colorado, U.S.A., which will alert crews and air traffic control (A.T.C.) authorities to the possibility of an occurrence. This, combined with the fact that a descent does not have to be made with extreme urgency, should avoid any A.T.C. hazards due to s.s.ts descending into the airspace of subsonic aircraft.

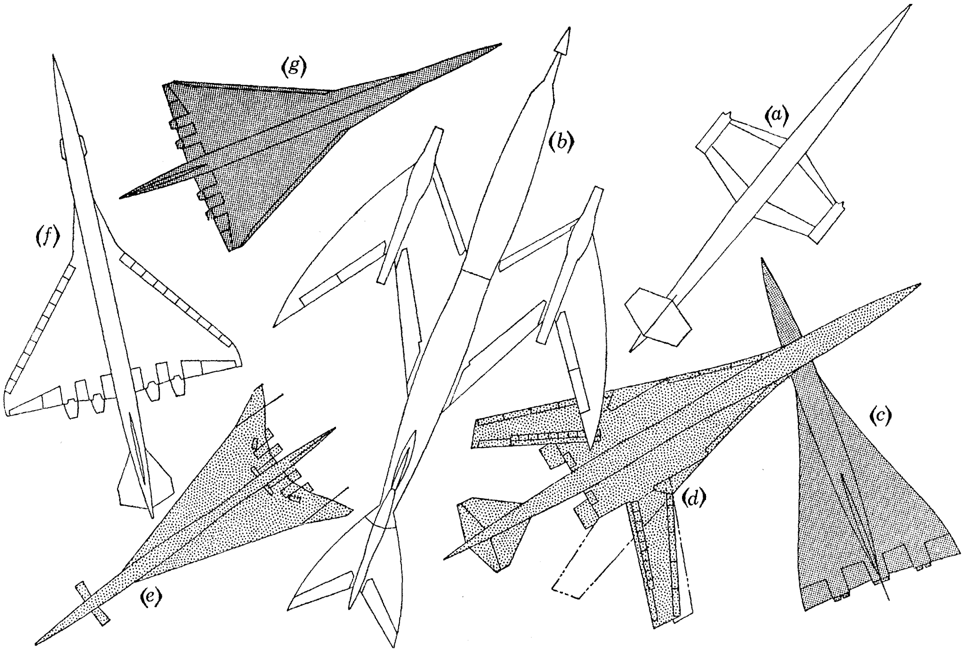


FIGURE 28. Montage of paper aeroplanes.

7. STUDIES AND REALITIES

Having reviewed the technical aspects of supersonic airliner design, mainly as they have evolved in the Anglo-French Concorde, it is salutory to take a brief look at some of the shapes and principal features of the various 'paper' studies from which Concorde emerged and those involved in the ill-fated U.S.-s.s.t. programme.

The montage of shapes in figure 28 shows:

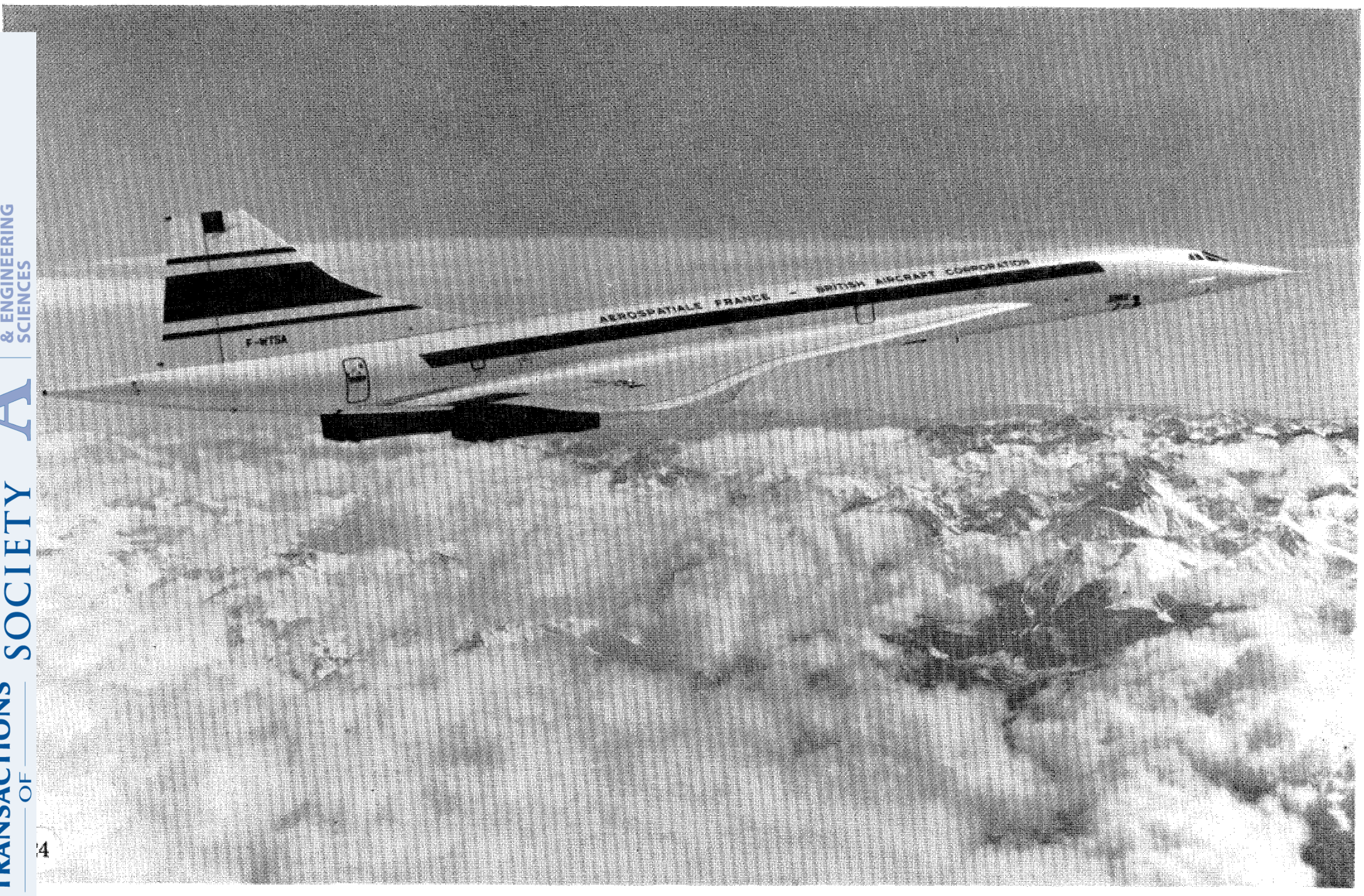
(*a*) typical tail-aft layout used for estimating the performance of a supersonic airliner (R.A.E. Discussion group 1954);

(*b*) M-wing proposal by Armstrong Whitworth for a Mach 1.2 transport submitted to the Supersonic Transport Aircraft Committee (S.T.A.C.) *ca.* 1956;

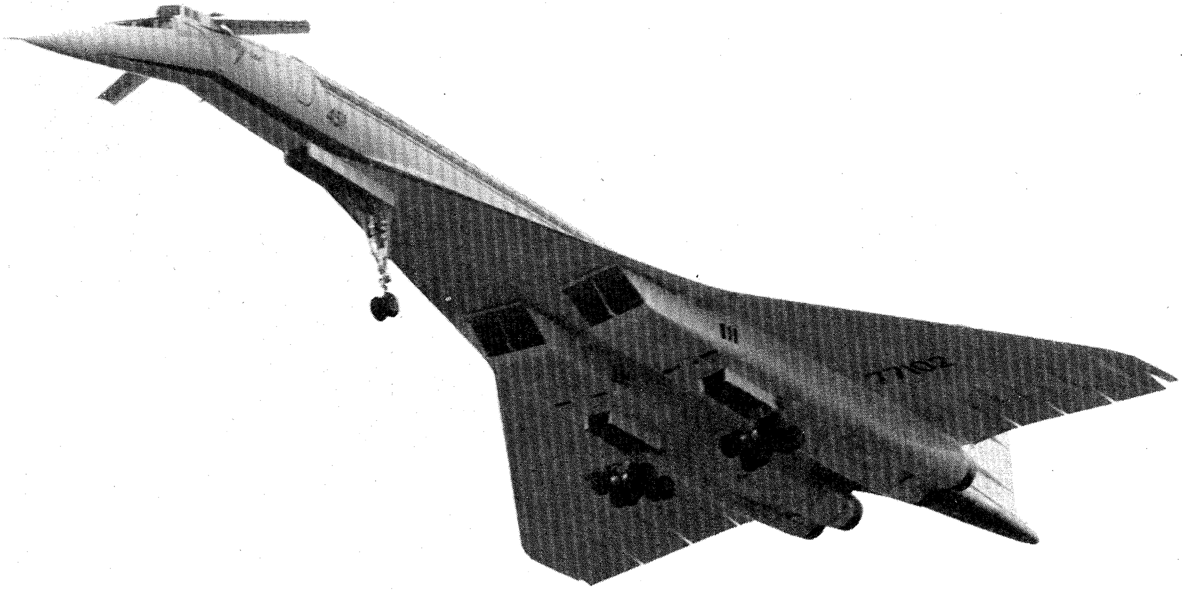
(*c*) British feasibility study predecessor of Concorde; Bristol six-engined design for trans-atlantic routes carrying 122 passengers (1960);

(*d*) Boeing variable-geometry aircraft (B 969-404); first finalist in the 1968 U.S.-s.s.t. configuration competition;

(*e*) second configuration finalist, again by Boeing (B 969-320) – a modified 'arrow wing' configuration;



4



30

FIGURE 24. Concorde 02 (without smoke).
FIGURE 30. TU-144 (production).

(*f*) third configuration finalist by Boeing (B 969-302) which was the forerunner of the B 2707-300 that came nearest to fruition (cancelled 24 March 1971) after the expenditure of 1.1 billion dollars of U.S. taxpayer public funds;

(*g*) Lockheed L 2000-7 A double-delta contender for the U.S.-s.s.t. competition, which was eliminated in favour of the Boeing family of designs.

The clear message from this is the dominance of the slender delta-wing shape as the most practical for an s.s.t.

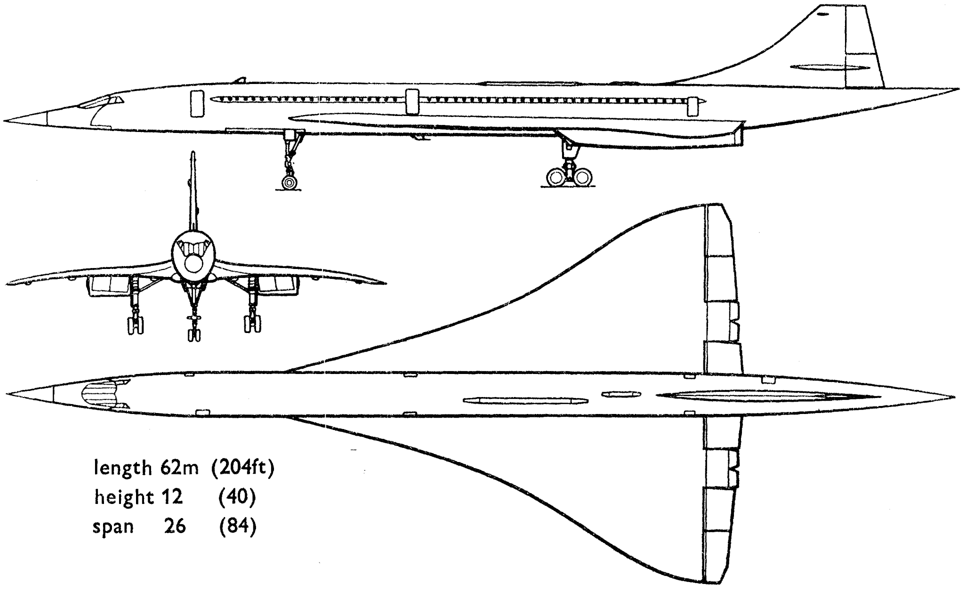


FIGURE 29. Concorde (general arrangement).

7.1. *The Russian Tupolev TU-144 s.s.t.*

The remarkable similarity between the Anglo-French (British Aircraft Corporation–Aérospatiale) Concorde and the Russian Tupolev slender delta s.s.ts which have actually been built is evident in figure 29 and figure 30, plate 28, and in the following brief comparison.

Both are about the same size and designed for essentially the same operational performance.

	Concorde	TU-144
span	25.56 m	28.80 m
length	61.66 m	65.70 m
a.u.w.	174630 kg	181440 kg
engine ratings	4 × 17260 kgf static thrust	4 × 19960 kgf static thrust

Little is known of the detail design and development of the Russian solution, but the following *résumé* of modifications between the TU-144 prototype and production aircraft is an interesting complement to the main part of this lecture, which has been derived mainly from the technology of Concorde.

(1) Increased length of forward fuselage – both the drooped nose section and the fuselage section ahead of the wing, giving greater fineness ratio. Windows added to the droop nose to improve visibility in the cruise position.

(2) Wing refinements now feature extensive camber, twist, droop and anhedral.

(3) Engine nacelles moved outboard and the rectangular inlets of the prototype now of square cross-section.

(4) Nose landing gear moved forward and now retracts forwards into the fuselage, instead of rearwards into a fairing between the nacelles on the fuselage centre-line.

(5) Main landing gear now retracts into the nacelles, instead of into the wings.

(6) Addition of nose-mounted canards – the Russians call them 'cherub wings' – which retract to lie along the outside of the upper fuselage.

(7) Seating capacity now quoted as 140 (increase of 20 over the prototype).

(8) Unconfirmed reports suggest that the original Kuznetzov NK-144 turbofans have reduced by-pass ratio. This would be no surprise, since at the 1971 Paris Show Soviet officials said that the TU-144 was designed originally around turbofan engines, because Aeroflot route studies indicated that they would be flying the aircraft at subsonic speeds for about 40% of the time. For future applications involving high sustained supersonic cruise, the aircraft may well be fitted with 'leaky' turbojet engines.

8. Conclusions

I have tried to give an indication of some of the problems that have beset those who are intrepid enough to embark on designing civil supersonic transports.

In conclusion, I can only say what I think we have achieved in the work which has been done in Britain and France on the Concorde, although I daresay it would be safe to assume that a number of the claims I make could also be made with equal truth by the Russian Tupolev design team, in relation to their TU-144.

In summary, we have achieved our overall objective – to fly twice as fast as today's jets and still behave like any other aircraft.

The many people who have now flown in Concorde have commented that its passenger comfort is at least as good as any other airliner in which they have travelled.

Handling characteristics are sufficiently straightforward for airline Captains to have found it no more difficult to fly than today's subsonic jets; some say it is easier.

We have demonstrated in many parts of the world that Concorde is perfectly capable of operating in the existing air traffic control system and into existing airports, in all weather conditions. When one bears in mind the massive runway extensions which the Boeing 707 and the Douglas DC 8 made necessary in the 1960s, this is something of an achievement.

We have also done our best to reduce the impact on the environment and I believe that we have succeeded.

Looking back over the twelve or more years that I have been working on Concorde, it would clearly have been difficult to tackle such a massive challenge as a uni-national programme, but it has been considerably more difficult as a bi-national one. On the other hand, we have had the advantage of the extra resources of two great aerospace nations and there is no doubt that the pre-flight testing which has gone into Concorde is far greater than that of any previous commercial aircraft; it was the lack of relevant military experience which made this necessary.

The extensive flying that we have done has confirmed the validity of the estimates and assumptions that were made to what I would regard as an unusually high degree. This, I believe, may well be due to the anxiety of each team to justify in great detail the technical decisions and judgements that they were required to take. As a former Chief Designer, I find this a difficult admission to make, but I believe that it is an important factor in Concorde having met its performance predictions so closely. However, I am glad that we have not had an American competitor breathing down our necks while this complex and demanding design process has been going on, because if we had had this, there would not have been time to spend months in settling an issue which traditionally would have had to have been done in days.

On a very general front, I consider that we have done much to cement Anglo-French relations and to demonstrate that international collaboration on high-technology projects can be made to work successfully. On the diplomatic front, the engineers working on the Concorde programme were at one time just about the only British and French people speaking to one another.

For the future, I see stretching before us an expanding era of supersonic travel in the speed band between Mach 2.0 (2100 km/h) and Mach 2.7 (3000 km/h). I have tried to indicate in this Review Lecture that the technical problems associated with supersonic travel at twice the speed of sound have been largely resolved. I believe that there will now be a 30-year progression of developments stemming from the first generation s.s.ts now established – in the same way that the initial commercial jets have been logically developed up to the high-capacity types such as the Boeing 747 of today.

On behalf of those whom I have had the privilege to lead in the Concorde programme, and all those who have helped to initiate the supersonic age of air travel, I am grateful to the Royal Society for the opportunity to present some of the technical aspects of designing and developing supersonic civil transports.

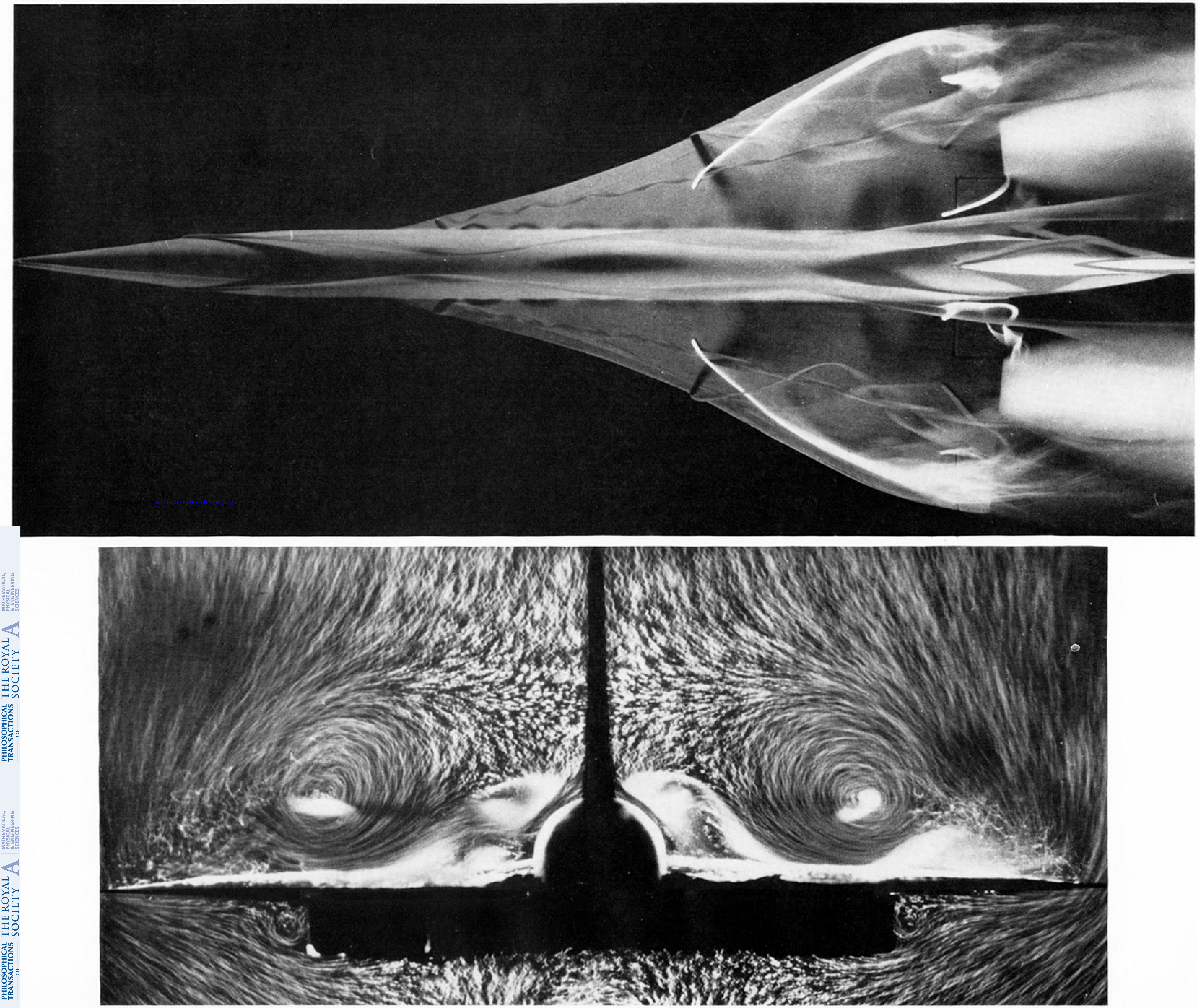


FIGURE 19. Vortex flow (two views).

24

30

FIGURE 24. Concorde 02 (without smoke).
FIGURE 30. TU-144 (production).