

## SUPERSONIC TRANSPORTS—SOME CONSIDERATIONS OF NONCRUISING PROBLEMS

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### INTRODUCTION

For almost twenty years the jet engine's increase in efficiency with increased forward speed has challenged the aircraft designer and has been the basis for many analyses showing the potential attractiveness of supersonic transport. Analyses based on cruising efficiency have not shown a best cruising speed but have produced advocates of almost any cruising speed between speeds just above the speed of sound and hypersonic cruising speeds almost up to orbital speeds.

Given an earth several times larger than ours, I am sure some of the very high-speed aircraft foreseen in these analyses would have been under development. However, in our real world the very limited market for stage lengths above three or four thousand miles and the relatively large distances covered by normal aircraft in getting up to cruising speed and height and in getting down again mean that vehicles with hypersonic cruising speeds are unable to exploit their full potential, while even aircraft with more modest speeds, say between Mach numbers of 2 and 4, will spend a high proportion of their journey time getting up to speed and down again, particularly on medium range stage lengths. Figure 1 shows just how the acceleration and deceleration phases of flight eat into the cruising phase as speeds increase.

The result of all this is that the practicability of the first generation of supersonic airliners, whose birth pangs are causing so much thought and discussion among research workers, designers, operators, and economists, depends not only on the achievement of aerodynamic and structural designs capable of exploiting high overall engine efficiencies to give highly efficient cruise but on maintaining reasonable efficiency during the climb, descent, holdoff and diversion phases of the flight plan. This point has not, of course, been lost on designers. The designs being considered do strike a balance between

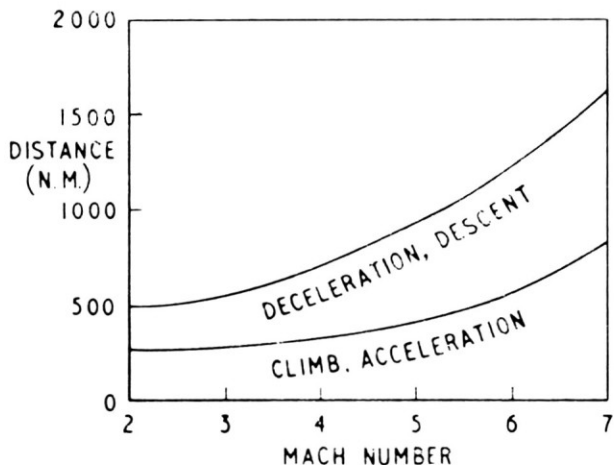


Fig. 1. Distance covered during climb and descent for typical turbojet/ramjet powered aircraft cruising at speeds of between  $M = 2$  and  $M = 7$ .

the efficiencies in the cruising and noncruising phases of the flight. Striking this balance and still achieving an attractive and practical design is an interesting problem and in this paper some of the problems of noncruising flight, particularly climb and descent, are considered. The factors limiting the climb and acceleration phases of the flight are considered, together with the aerodynamic and thermodynamic means of improving the noncruising characteristics and in particular attention is given to possible changes in the climb and descent phases which might result from trying to exploit supersonic transports over shorter ranges.

### THE BACKGROUND—TYPICAL CLIMB AND DESCENT PROCEDURES

To put the problems of climb and descent into perspective it will be worth looking at the way fuel and time is used up in the various phases of a typical transatlantic supersonic transport flight. In Fig. 2 the fuel carried on a transatlantic flight (3,200 nm) is broken down into the fuel used in climb and acceleration; the fuel used in cruise and descent; and the fuel reserves which would probably be carried. For the purposes of preparing the figure the reserves were taken to cover half-hour standoff at 30,000 ft, diversion to an alternative airport, 270 nm from the destination (the diversion starting from low speed and altitude over the destination terminal) plus reserves equal to 5 percent of the block fuel. The figures quoted are typical of transport aircraft cruising at  $M = 2$  and are not sensitive to the details of the design. Figures for an aircraft designed to cruise at  $M = 3$  would not be markedly different. It will be seen that roughly a quarter of the fuel carried is used during climb and acceleration—mostly in the supersonic portion of the climb—about one-half of the fuel is used in the cruise and roughly one-quarter is kept in reserve. Put another way, the fuel used in the climb is one-half the fuel used in the cruise.

The proportion would not change radically between  $M = 2$  and  $M = 3$  but would increase at still higher cruising speeds until for an aircraft cruising at  $M = 5$  for a transatlantic stage length the fuel used in climb and acceleration would equal that used in the cruise.

The climb procedure assumed is to accelerate while climbing to reach  $M = 0.95$  at about 20,000 ft, after covering some 25 nm. Climb at  $M = 0.95$  is continued until a height of between 35,000 and 40,000 ft is reached after covering about 50 nm. The aircraft then accelerates through the speed of sound and continues climbing and accelerating until cruising speed and height,  $M = 2.2$  at between 50,000 and 60,000 ft is reached after covering some 285 nm. The size of the engines used in a supersonic transport intended to cruise in the Mach number range between 2 and 3 are usually fixed by the cruising thrust required, there then being ample thrust for takeoff (with a reserve to enable throttled climb after takeoff to be undertaken to keep noise levels down) and enough thrust for the sort of climb procedure just mentioned, though reheat is desirable to allow transition to supersonic speed to take place higher and so to reduce the intensity of sonic bangs during the climbing phase.

During the typical climb considered, using reheat to reduce sonic bangs, the fuel used in covering the 285 miles traveled while climbing is sufficient to have lasted for 900 nm of cruise. There is thus a loss of 615 nm in range associated with the climb and acceleration. Some of this loss of range is, of course, recovered in deceleration and descent. This recovery is equivalent to 144 nm giving a net loss of 471 nm due to the climb and descent. From the point of view of time the climb and descent occupy 41.7 min, while the distance covered would only have taken 24 min at cruising speed so that 17.7 min are wasted during the climb and descent. If reheat had not been used the loss of range could have been reduced from 471 nm to 332 nm but the time loss would have increased from 17.7 min to 19.7 min. The intensity of the sonic bang is reduced by the use of reheat by about 20 percent and the intensity during the climb is reduced to the same value as during the cruise except for the focusing region at the beginning of the area affected by the bang. Figure 3 illustrates the above points.

A loss of range of 500 or 600 nm and a loss of time of about 20 min is not a negligible price to pay for climb and descent, particularly on stage lengths of 1,000 nm or less, stage lengths down to which a practical supersonic transport

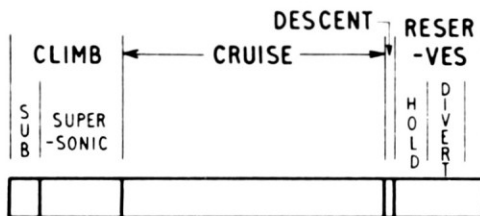


Fig. 2. Distribution of fuel between climb, cruise, descent and reserves for transatlantic flight at  $M = 2$ .

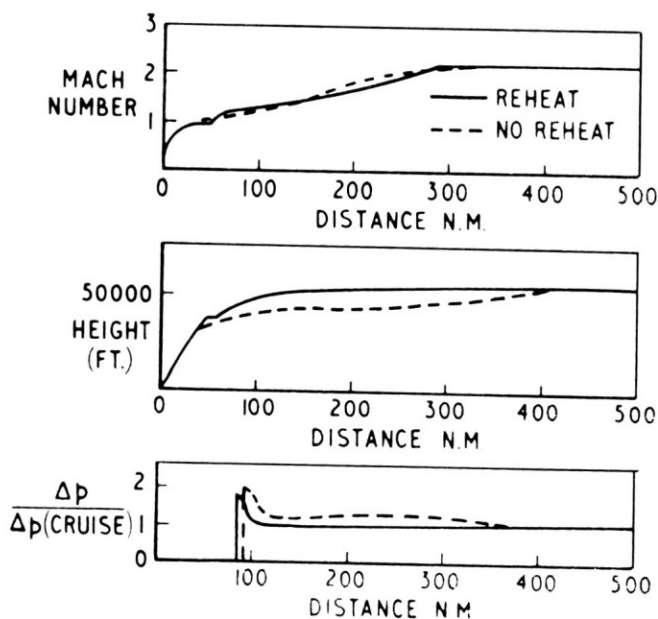


Fig. 3. Typical climb profiles and sonic-bang intensities for  $M = 2$  transport.

should be capable of operating without gross inefficiency. It is therefore worth looking into the question of where the fuel is used and where the time is lost to see where to look for improvements.

Figure 4 shows the fuel used during an acceleration to  $M = 2.2$ , using reheat, and a descent. The fuel used is broken down into that used to overcome drag and that used to build up kinetic and potential energy in the aircraft. It will be seen that the amount of fuel used in overcoming subsonic drag, while not negligible is small and that improvement in subsonic lift/drag ratio is not the key to efficient climb. Most of the fuel used is used at supersonic speeds of about  $M = 1.5$  so that an improvement in supersonic lift/drag ratio at speeds below the cruising speed and of engine specific consumption in this speed range could be valuable. Moreover, since much of the fuel is going into storing up potential and kinetic energy rather than in overcoming drag, improvements in specific consumption are more important than reductions in drag. Finally, though not negligible the fuel consumption in the deceleration and descent is small and there will be no major improvement to come from improving the very high specific consumption of the engines during this phase of the flight.

### NONCRUISING CONDITIONS AND AIRFRAME DESIGN

Studies of possible climb programs for supersonic transports suggest that there is no really major problem in having to fly for extended periods at incidences far removed from those corresponding to maximum lift/drag ratio for the particular Mach number. The problem in reducing drag lies not so much in

arranging to fly at the correct value of the equivalent airspeed throughout the climb as in choosing an aircraft whose curve of maximum lift/drag ratio against Mach number is suitable. A curve typical of slender wing aircraft such as that assumed in preparing Figs. 3 and 4, is shown in Fig. 5, which also shows possible curves for a variable geometry aircraft giving high  $L/D$  at subsonic speeds and also a hypothetical aircraft with high  $L/D$ 's through the Mach number range from 1 to 2.

The amount of fuel used during climb and acceleration to a Mach number of 2.2 has been calculated, the slender wing aircraft using reheat to reduce sonic-bang intensity, and the variable geometry using its higher aspect ratio with

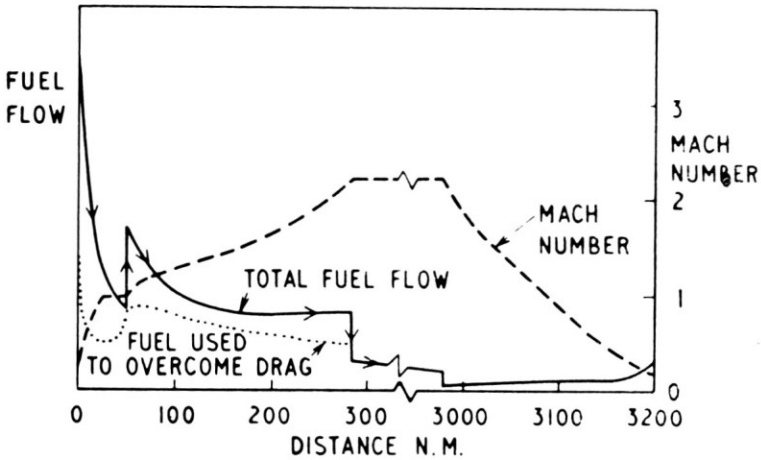


Fig. 4. Fuel flow during transatlantic flight.

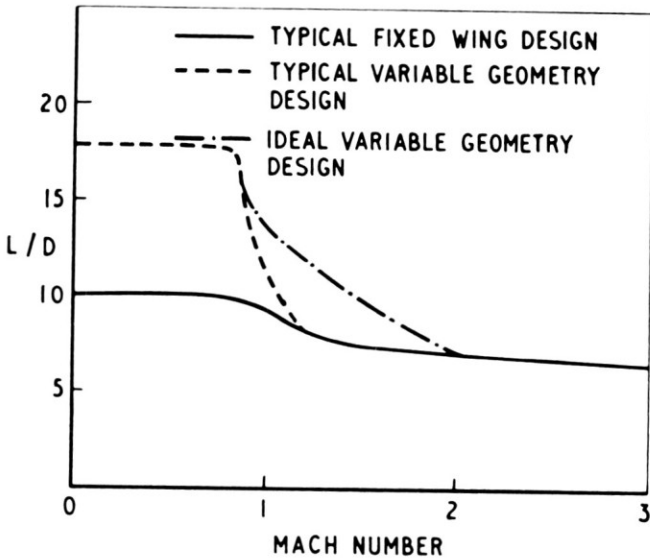


Fig. 5.  $L/D$  vs. Mach number.

wings unswept to continue subsonic climb to an acceptable height. The calculations show that the fuel saving on the climb due to the use of variable geometry is just under 0.5 percent of the all-up-weight of the aircraft, while in the case of the aircraft which maintains high  $L/D$  at intermediate supersonic Mach numbers the gain is about  $1\frac{1}{2}$  percent. These gains are so small that, while they would be well worth having, they could easily be nullified by higher structure weights or small reductions in the cruising efficiency. For example, the gain due to variable geometry in the climb would be more than nullified by a reduction of cruise  $L/D$  from  $7\frac{1}{2}$  to  $7\frac{1}{4}$ . When considering the case for variable geometry it is only fair to add, however, that if the fuel reserves to be carried are specified in terms of a standoff time and a short diversion, all of which would probably be flown at subsonic speeds, plus a percentage reserve, as considered in Fig. 2, the higher subsonic efficiency of the variable geometry aircraft would show to much greater advantage. For the case considered, the variable sweep aircraft would gain  $1\frac{1}{2}$  percent of AUW in the standoff and  $1\frac{1}{4}$  percent in the diversion. The total saving of  $2\frac{1}{2}$ –3 percent is much more likely to be enough to enable an overall advantage to be retained when weight and cruise efficiency are taken into account. It is not possible to decide the case for or against variable geometry on general grounds. The decision turns on precise and delicate balancing of advantages and disadvantages, but it is clear that the choice of fuel reserves and the way they are defined will be an important factor affecting the choice.

Since the drastic changes in aircraft characteristics arising from the use of variable sweep make so small an impact on the total fuel used it is clear that in a fixed wing compromise considerations of  $L/D$  during the climb need play only a very small part in fixing the aerodynamic design.

### CHOICE OF POWERPLANT

An extremely detailed analysis is necessary to choose the right engine for a supersonic transport and all that will be included here is a brief and general discussion of one or two salient points. In fact, the detailed analyses, a typical one being by Sousa, Joy, Smith, and Schmitt,<sup>1</sup> do not lead to a precise set of engine characteristics which are clearly the best. In choosing the right type of engine, despite the fact that typically only about half of the fuel load of the aircraft is used in cruising, it is clear that good specific consumption at cruising speed is of prime importance as is light weight not only of the engine but of the whole engine installation. Secondary, but important, features are good specific consumption at subsonic speeds, high thrust at transonic speeds, and high takeoff thrust. Of these three features the first is important mainly in reducing the fuel reserves required for standoff. The second is important to avoid wasting time and fuel by lingering in the inefficient low supersonic region and to enable the acceleration to supersonic speed to be made high enough to avoid excessively strong sonic bangs. The third is required not so much to give good takeoff performance as to allow reductions in noise by allowing takeoffs to be made

below full thrust and hence with reduced jet velocity. Since the requirement for high thrust for transonic acceleration is not associated with the need for low jet noise or for low specific fuel consumption this is best met by using reheat. The other two noncruising requirements lead to the consideration of bypass engines or turbofans. If the thrust of bypass and nonbypass engines are compared over the speed range it will be seen that for a modest bypass ratio such as 0.5, if the engines are designed to give the same thrust at  $M = 2.2$  the bypass engine will give about 15 percent more thrust at transonic speeds and 20 percent more at takeoff. In specific consumption the bypass engine should be marginally better on the cruise, say 1 or 2 percent, and should be about 5 percent better at high subsonic conditions corresponding to standoff. These figures could, of course, be different in specific cases, depending on the detailed design of the engine and the matching of the components, but they are considered to be fairly typical. On these arguments the noncruising conditions make a strong case for the use of a bypass engine but the larger airflow of the bypass engine for a given cruising thrust implies increased weights of air intakes, exhaust nozzles and other installational items and these, together with the increased weight of the basic bypass engine, more than balance any saving in fuel. With the size of engine likely to be installed, which allows a good deal of scope for choice of takeoff techniques giving reduced noise, takeoff noise seems to be within acceptable limits. This discussion thus leaves us with the conclusion that while cruise considerations favor the nonbypass jet of high specific thrust and low weight and noncruising conditions favor the bypass engine, a bypass engine is unlikely to be justified, unless noise conditions tip the balance.

## ENGINE INSTALLATION CONSIDERATIONS

Clearly the basic case for efficient supersonic transports is undermined if the engine air intakes are not highly efficient in the cruising condition, since the case rests on balancing a loss in lift/drag ratio at supersonic speeds against an increase in engine efficiency and an efficient intake is vital to engine efficiency at supersonic speeds. All efficient intakes involve multishock systems and the choice of intake type lies between types with all the supersonic compression outside the intake, all inside the intake mouth or mixed internal/external compression types. It should be possible to design intakes of any of these types to give a high pressure recovery for design Mach numbers in the range between 2 and 3, but intakes with internal compression, having much smaller lip angles, should have smaller drags in the cruising phase. To offset this, the starting and control problems of external compression types are simpler and high-pressure recoveries with the low-drag, internal-compression types depend on successful and efficient control of the boundary layer inside the intake. Recent work in the United Kingdom has pointed the way to improving the effectiveness of boundary-layer bleeds within the intake by better detail design of bleed slots, and by taking into account the cross flow drift and nonuniform development of the boundary layers on the intake walls. However, from the

point of view of the cruise efficiency (including considerations of both pressure recovery and drag) no clear decision can be made between the attractions of external compression intakes and mixed external/internal compressions types.

We now turn to the noncruising performance of air intakes, and consider whether this should play a determining part in choosing the right type of intake. Consideration will be concentrated on rectangular intakes, appropriate to engines mounted on the surface of a wing or body rather than the circular types more appropriate to pod mounting. The first point to emphasize is the lack of matching between the intake and the engine. This is illustrated in Fig. 6, which shows the engine demand and the airflow available from an intake, if running full. It will be seen that at low supersonic Mach numbers a great deal of air must be spilled from the air intake and that this problem is more serious for designs aimed at higher cruising Mach numbers. This mismatching is dealt with in two ways—either by taking in more air than the engine needs and discharging it through spill doors, or by spilling air round the intake lip. In general, it is more efficient and leads to lower drags if the air is taken in and discharged through vents rather than spilled around the intake lip, but there are practical limits to the design of large spill vents. This means that, with the large amounts of excess air available at low supersonic Mach numbers, both methods have to be used, and it would not be unusual to design for half the air to be spilled around the intake lips and half to be passed through spill vents.

While it is relatively straightforward to estimate the drag due to spilling reasonable quantities of air around the intake at high supersonic speeds, it is more difficult to estimate the drag due to spilling large quantities of air at transonic and low supersonic speeds and there are not a great many tests on which to base such estimates. In this study use will be made of some tests and

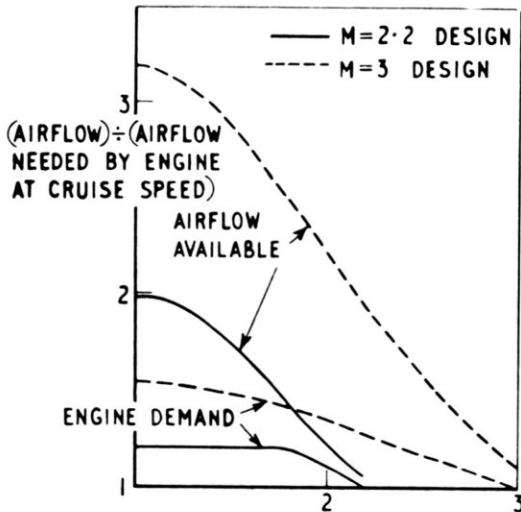


Fig. 6. Curves showing airflow required for engine below cruising speeds and airflow available from an intake taking the full flow of a streamtube matching the intake area.



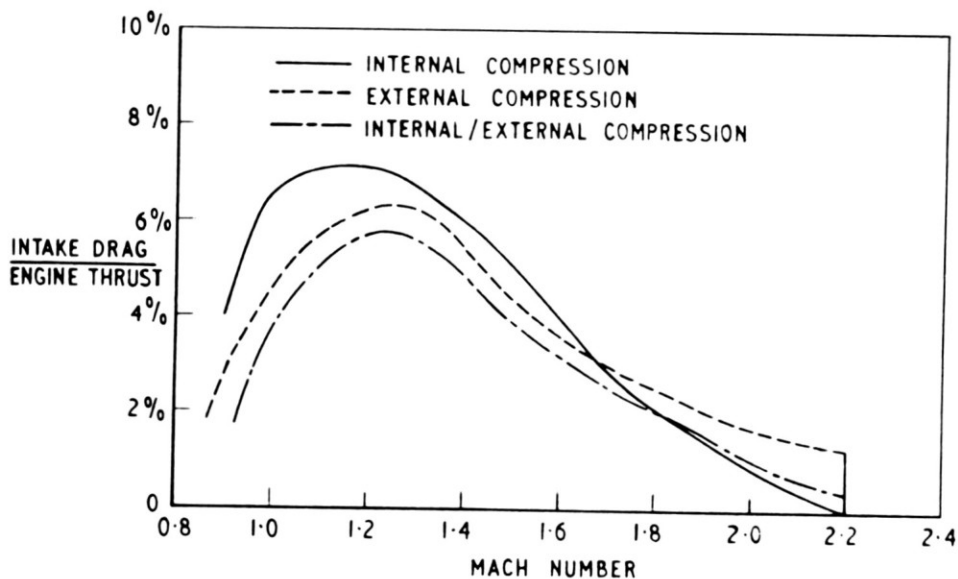


Fig. 7. Intake drags for different types of intakes designed for cruising at  $M = 2.2$ . Half the spillage at off-design speeds assumed through spill vents and half round the intake lip.

an analysis carried out by B. R. Leivers<sup>2</sup> of Rolls Royce Ltd. on behalf of the Ministry of Aviation. These tests showed that the spillage drags for different Mach numbers could be correlated using transonic similarity principles. For intakes with fairly steep cowl angles (corresponding to all or at least part external compression) the transonic and low supersonic drags do not appear to be very sensitive to cowl shape. The drags of such intakes are lower at these speeds than the internal compression types of intake with nearly streamwise lips. This can be explained by the fact that with a fairly steep cowl the preentry drag corresponding to the pressures on the preentry streamline are to some extent offset by a suction force on the cowl lip, while in the case of a streamwise cowl lip very little axial force can be generated by suction on the cowl.

Using the method of analysis mentioned and the spillage quantities appropriate to a Mach 2.2 engine from Fig. 6 and assuming half the excess air to be spilled around the cowl lip, intake drags have been calculated over the speed range from  $M = 1$  to 2.2 for different intake designs. The results are shown in Fig. 7. The high peak drags amounting to 6 or 7 percent of the engine thrust for Mach numbers between 1 and 1.4 are noteworthy. Similar calculations for the case where all the unwanted air was spilled around the cowl lip showed a prohibitive drag of 10–15 percent of the engine thrust. Looking at the results to see if they suggest ways in which the noncruising conditions affect the design of the intake it is clear that particularly in cases where there is not much margin of thrust for transonic acceleration the all internal compression type of intake is to be avoided. The results shown in Fig. 7 also suggest that the best overall compromise will be an intake with a combination of internal and external compression, but the accuracy of the generalized analysis, and the experimental

results on which it is based, is not high enough for any definite conclusion to be drawn. More detailed analyses would have to be based on tests of particular intake designs and engine installations, since the general conclusions are affected by the size of the engine in relation to its air swallowing capacity and the extent to which it is buried in the aircraft.

## **POSSIBLE CHANGES IN THE CLIMB AND DESCENT PATTERNS, WITH SPECIAL REFERENCE TO SHORT RANGE OPERATIONS**

### **GENERAL REMARKS**

We have shown above that the conventional approach to the supersonic airliner led to climb and descent procedures which cost some 18 min of wasted time and the equivalent of almost 500 nm in wasted fuel. Since some 600 nm are covered in getting up to speed and down again, it also means that on stage lengths below about 1,000 nm little use is being made of the good characteristics of the aircraft. It seems therefore worth considering whether there are any possibilities of cutting this wasted time and fuel and of making shorter stage lengths attractive.

As a start to this consideration, we will consider the various limits imposed on climb procedures. There are limits on the EAS, set by consideration of aerodynamic loads and aeroelasticity, limits on the altitude at which supersonic speed may be reached set by sonic-bang considerations, limits to acceleration set by passenger comfort and limits set by the powerplants and the thrust available. The wasted time of 18 min mentioned above is relative to an impossible ideal in which the aircraft is instantaneously given cruising speed and altitude and instantaneously stopped at the destination. Let us start by seeing how the limitations on the accelerations which a passenger can stand affect how close we can come to the impossible ideal. We can take it that given suitable seating arrangements it is the total acceleration on the body which must be limited so that more rapid acceleration is acceptable when moving downwards or horizontally than when moving upwards. If we accept as a reasonable limit that passengers should not be exposed to total acceleration loads exceeding 10 percent excess  $g$  then the acceleration allowable varies with the direction of motion as shown in Fig. 8. This shows how much larger the allowable component of acceleration is for level flight than for steep angles of climb. If in fact drag, EAS limits, sonic bangs and so on were neglected and flight consisted of level acceleration to cruise speed and equally rapid deceleration, the time lost compared with that for infinite acceleration and deceleration would only be  $2\frac{1}{2}$  min and the distance covered in acceleration and deceleration would be 50 nm.

### **THE AVOIDANCE OF SONIC BANGS DURING CLIMBING FLIGHT**

Turning now to sonic-bang limitations, it is worth noting that there is one class of aircraft which does not give sonic-bang problems despite going supersonic at fairly low altitudes, namely, ballistic missiles, where the steep angle

of climb throws the shock waves clear of the ground. It is worth looking at the ways in which steep angles of climb can eliminate or reduce sonic-bang problems. The refracting effect of the normal atmosphere and the directional effect of an inclined flight path can be combined to give Fig. 9. In this figure if a point corresponding to a given height and a given Mach number is selected, the line joining this point to the origin has a slope corresponding to the minimum angle of climb for sonic-bang-free operation. It will be seen, as is well known, that quite steep angles of climb are necessary if sonic bangs are to be avoided and that the requirement to climb steeply to avoid sonic bangs and fly as near level as possible to allow maximum acceleration conflict.

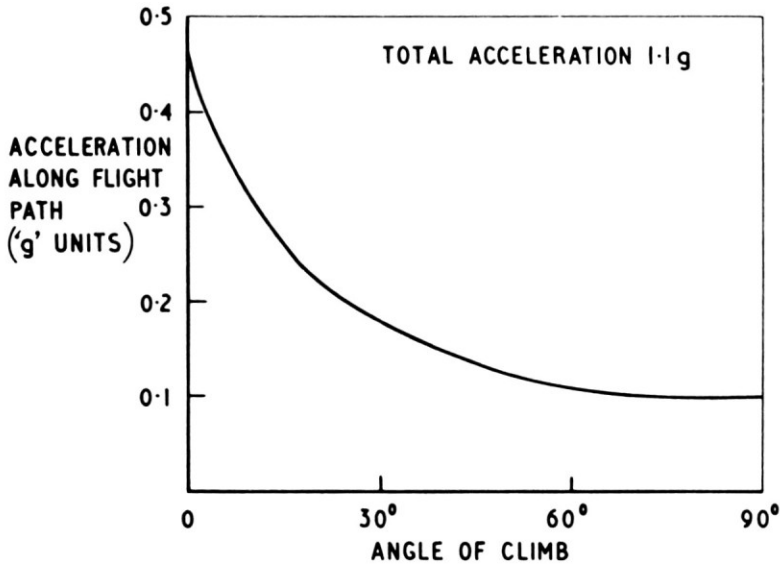


Fig. 8. Acceleration along flight path vs. angle of climb, for total acceleration limited to 1.1 g.

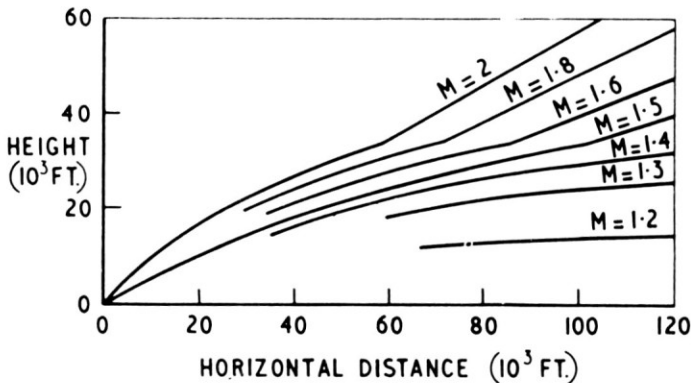


Fig. 9. Curves showing minimum angle of climb to avoid sonic bangs in supersonic climbs.

The next step is to consider the type of climb which might be possible if the aim is to reach cruising speed and height as quickly as possible without making a sonic bang. Such climbs have been considered, using Figs. 8 and 9 as a basis and a climb such as that shown in Fig. 10 results. Although the acceleration along the flight path is limited by the angle of climb required to values appreciably below those allowed in level flight by our 1.1- $g$  limit on total acceleration, it is still a rapid climb. Using this climb to 55,000 ft, followed by acceleration to  $M = 2.2$ , the assumed cruising Mach number, cruise conditions are reached in  $3\frac{1}{2}$  min. A distance of 36 nm is covered and the lost time, compared with cruising for the same distance, is only  $1\frac{3}{4}$  min, compared with  $1\frac{1}{4}$  min for the ideal acceleration in level flight mentioned above. This climb involves some increase in EAS compared with conventional climbs but the maximum EAS reached, 650 knots, is not impracticably high. The snag is, of course, the very high thrust required from the engines and the problem of transition from climbing to level flight without discomfort for the passengers.

### TRANSITION FROM CLIMBING FLIGHT TO LEVEL FLIGHT

A quick transition from climbing to level flight could be made by rolling the aircraft on to its back, pulling over sharply (acceleration due to turning being about  $2g$  so that the resultant acceleration on the passengers would be about the normal  $1-g$  value) then rolling right way up again at the completion of the transition. Such a maneuver seems in practice a quite unacceptable procedure, although theoretically it could be carried out without any undue loads on the passengers. We therefore revert to considering simple bunts starting from some point during the supersonic climb whose steepness is fixed by the requirement that no sonic bangs shall reach the ground. By throttling back the engines at a height below that set as a limit below which no shock wave produced must reach the ground, the steepness of climb can be reduced and the speed reduced in such a way as to continue avoiding sonic bangs. When a sufficient height is reached so that the sonic bang can be allowed to reach the ground without exceeding the acceptable strength, full thrust can be applied and accelerating flight continued as the aircraft turns over into level flight. If, for reasons of passenger comfort, flight paths are ruled out in which the

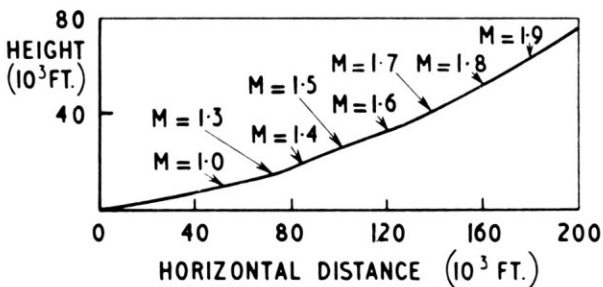


Fig. 10. Maximum acceleration climb, free of sonic bangs. Limiting total acceleration 1.1  $g$ .

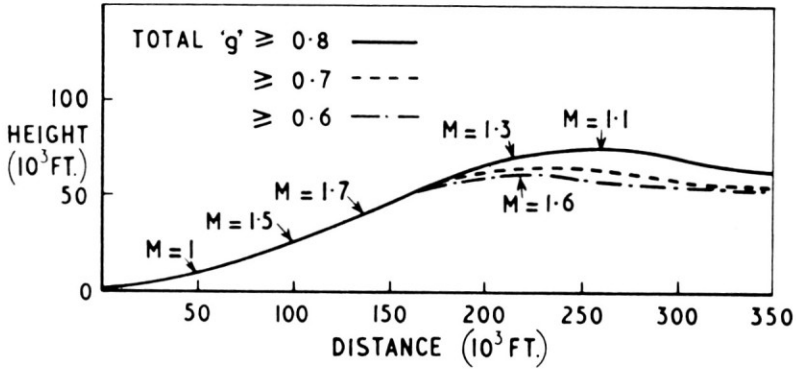


Fig. 11. Flight paths showing transitions, from sonic-bang free climb to 40,000 ft, to level flight at 55,000 ft, for various limits on minimum acceleration loads on passengers.

total acceleration, limited in the earlier part of the flight to less than 1.1 g, is not allowed to go below some limiting value which might lie in the region of 0.8 or 0.9 g, calculation of possible flight paths shows that the aircraft will overshoot its cruising height by a large amount. For a limit of 0.9 g the overshoot is so large that the aircraft would stall before completing transition. Alternatively, if large overshoots are to be avoided the transition would have to start from so low a speed and altitude that all the advantage of the high speed climb would be lost. Figure 11 shows examples of transition from climbing to cruising flight with various limits set on the minimum values of total acceleration. It will be seen that a limitation of 0.8 g leads to an unacceptable flight path, and that a limit of about 0.6 g is required if the problem of transition from climbing to level flight is to be made really tractable. While little is known of passengers' reactions to steady flight for periods of the order of half a minute at less than 1 g the acceptable value seems likely to be nearer to 0.9 g than 0.6 g. So far we have considered only flight paths lying in one plane and the answer to the problem of turning over sufficiently quickly from the climb to level flight without subjecting the passengers to unacceptable accelerations would appear to lie in combining the transition with turning flight, or more probably an S-bend. By using this device of combining a bunt leading to negative accelerations in one plane with a turn leading to positive accelerations in a plane at right angles to the first it would seem possible to accept transitions which without simultaneous turns would lead to, say, 0.6 g acceleration without subjecting the passengers to unpleasant accelerations. Heading changes in the sort of maneuvers involved might be typically of the order of 20°. Careful consideration of the exact combinations of turns and bunts would be required to avoid or minimize any focusing of shock waves over local regions on the ground.

**THRUST REQUIRED FOR RAPID CLIMB**

If we return now to considering the thrust required for the sort of accelerated climbs we have been considering we find that the thrust of powerplants of a

size fixed by cruising considerations could with the full use of reheat provide ample thrust for the low-altitude parts of the climbs but that at higher altitudes it is difficult to provide enough thrust. For example, the thrust required for the optimum climb described above, before considering the problem of transition from climbing to level flight, is shown in Fig. 12, where the thrust required is split into the parts required to overcome drag, to balance the component of weight acting along the flight path in the climb, and to accelerate the aircraft along the flight path. Notable are the very large thrust requirements arising from the steepness of the flight path and the peak in the thrust requirement arising from the interplay in air temperature and speed which demand a very steep climb early in the supersonic acceleration if sonic bangs at ground level are to be avoided.

With a good supersonic inlet and an efficient exhaust nozzle the thrust of a jet engine rises very rapidly with increasing forward speeds between Mach numbers of 1 and 2, particularly when reheat is being used, as is shown in Fig. 13. The reheated thrust at  $M = 1.5$  is four times the unreheated sea level static thrust, while at  $M = 2.2$  with reheat over six times the sea level static thrust is obtained. The thrust available during the climb illustrated in Fig. 10, using full reheat, is shown in Fig. 14 (with the thrust requirement of Fig. 12 superimposed) for the case where the sea level static thrust of the unreheated engines is 0.5 times the weight of the aircraft. This is towards the top end of the range of thrusts likely to be installed in supersonic transports but is not unreasonable.

A series of calculations has been carried out to explore the effect of different thrust levels and different starting points for the transition from climb to level flight. For simplicity it has been assumed that where extra thrust is required it is provided by extra engines of the same thrust and fuel consumption characteristics as the normal engines, though in practice this would not be a sensible approach.

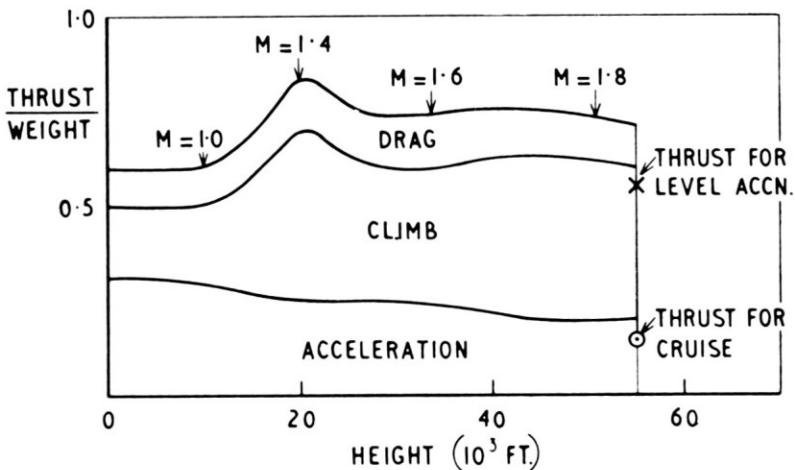


Fig. 12. Thrust required for maximum acceleration climb shown in Fig. 10.

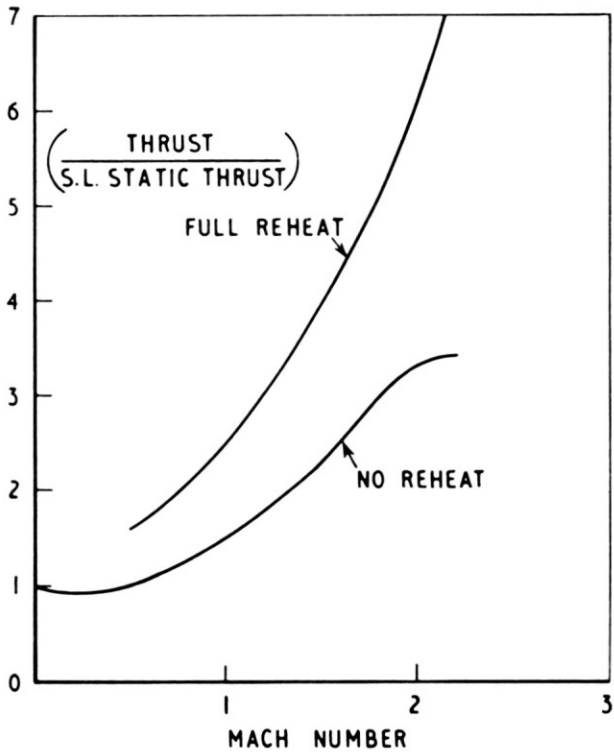


Fig. 13. Thrust vs. Mach number for typical turbojet for  $M = 2.2$  cruise.

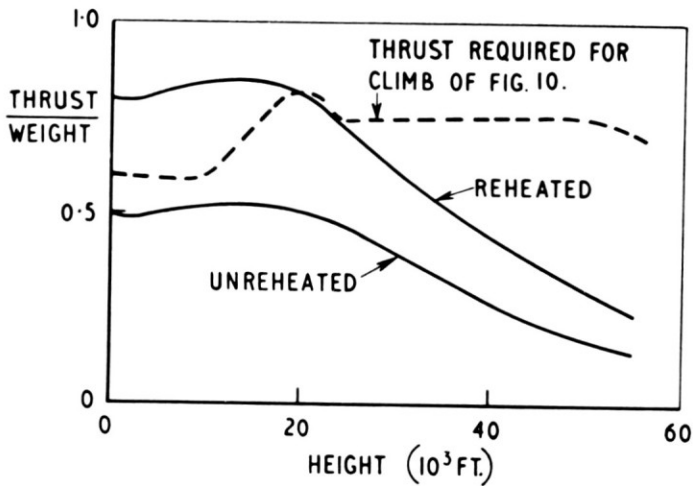


Fig. 14. Thrust characteristics of engines during climb and acceleration.

The results of these calculations are given in Table I. The thrust augmentation ratio quoted is the ratio of the thrust of all engines, or cruise engines plus boost engines, to the thrust of the cruise engines chosen to give a static thrust of half the weight of the aircraft. Cruising height assumed was 55,000 ft and speed  $M = 2.2$ . All rapid climbs had reached cruising speed and height within 100 nm from start of flight, the standard climb however takes 285 nm to reach cruising height and speed. These results show that the time taken in the climb is not significantly different for any of the rapid climbs considered though naturally delaying the start of transition to level flight causes a marginal increase in time taken. Extra thrust available gives negligible reduction in time taken, but extra thrust does allow the height below which the sonic bangs do not reach the ground to be raised quite appreciably. It will be seen that without any extra engines the use of full reheat allows a rapid supersonic climb to be made without making sonic bangs from a lower height than in the normal climbs appropriate to long-range flights with acceleration to supersonic speeds taking place in level flight. A thrust boost of 1.25 allows the height below which no sonic bangs reach the ground to be raised to about 45,000 ft, while a thrust boost of 1.5 allows this height to be raised to about 55,000 ft. Any higher degree of thrust boost is clearly pointless in an aircraft designed to cruise at 55,000 ft; however, a thrust boost of 2 would enable suitable aircraft to operate without producing sonic bangs during the climb up to more than 60,000 ft.

TABLE I.

Max. thrust augmentation ratio	Height of start of transition	Height below which sonic bangs do not reach ground	Time to 100 nm	Time to 285 nm
Ideal climb ignoring problems of thrust and transition	55,000	55,000	6.6	15.5
Normal climb	—	37,000	11.3	22.6
1 (i.e., no thrust augmentation)	30,000	38,500	6.8	15.7
1.25	30,000	38,500	6.8	15.7
	35,000	41,000	7.2	16.1
1.5	30,000	38,500	6.8	15.7
	35,000	41,000	6.8	15.7
	40,000	47,000	7.2	16.1
	45,000	52,000	7.2	16.1
2.0	30,000	38,500	6.7	15.6
	35,000	41,000	6.7	15.6
	40,000	47,000	6.8	15.7
	45,000	52,000	7.0	15.9



SONIC BANG INTENSITIES FOR RAPID CLIMB

The sonic bangs produced on the ground during climbs of this kind have been calculated and are plotted in Fig. 15 and compared with the sonic bangs produced during the normal climb plotted earlier in Fig. 3. For simplicity and greater generality, the pressure jumps have been made nondimensional by dividing by the pressure jump at the start of the cruise. One characteristic of all supersonic-bang patterns in an atmosphere with normal temperature gradients is a focusing effect leading to louder bangs just at the edge of the region affected by the aircraft. Only crude estimates of the extent of this region are possible but it appears that for the maximum acceleration climb a considerably smaller region would be affected than for the normal climb. It will be seen that the rapid-climb techniques described offer significant possibilities for reduction of sonic-bang intensities during climb and acceleration.

THRUST BOOST

Without making a detailed analysis, it is not possible to estimate precisely the weight penalty which would be involved in providing thrust augmentation by auxiliary engines but a weight penalty of 2 percent of AUW for a 25 percent thrust augmentation or a 4 percent penalty for a 50 percent augmentation obtained from simple retractable engine installations with simple inlets and exhaust nozzles is probably in the right street. Thrust boost by rockets though possibly convenient in many ways is a doubtful proposition, since extra thrust is required for periods of the order of one or two minutes and the weight penalty

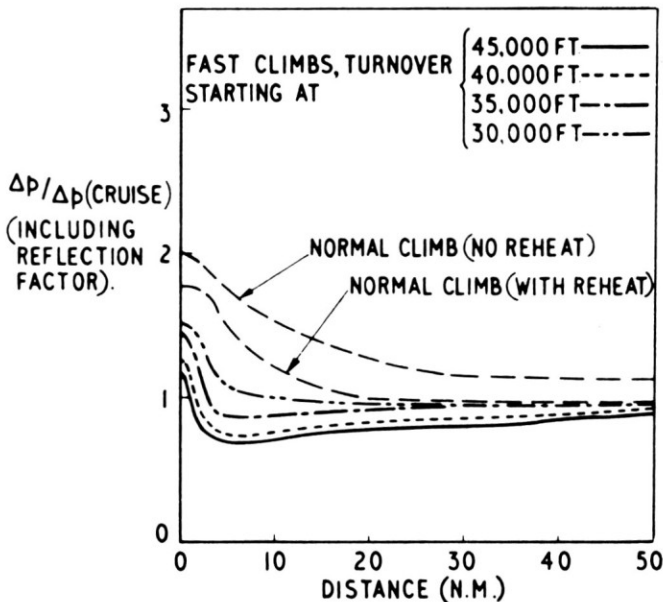


Fig. 15. Pressure jump in sonic bangs vs. distance along ground under the flight path for different climb techniques, with first point at which sonic bang is heard taken as origin.

in fuel would almost certainly be considerably larger than the weight of auxiliary engines and the fuel they would use. However, the small rocket required would not be awkward to stow.

When considering thrust boost we remember that at transonic and low supersonic speeds the variable intakes required for efficient operation over the speed range had to spill a lot of air—either by preentry spillage or through spill vents in the subsonic diffuser—and it is natural to speculate on the possibilities of providing thrust boost in the intermediate speed ranges where it is mostly needed by either burning fuel in this air or by feeding it to lightweight auxiliary engines. From the quantities of air being spilled over the speed range, it seems just possible that extra thrust roughly equivalent to a 25 percent thrust boost might be obtained. Whether this approach of using the spilled air is a practical proposition cannot be determined without detailed engineering studies, but it may merit further consideration. In conventional climbs supersonic speed is reached at about 35,000 ft. It appears that the degree of extra thrust required to allow rapid climbs to be continued free of sonic bangs to heights well above this can be obtained in various ways with a weight penalty which would not be serious, in short-range flights at least. In fact, when the fuel used in the various different types of climb are compared it is found that in the rapid climbs the larger proportion of the flight done at high speeds where the overall propulsive efficiency of the engine is higher more than outweighs the worse specific consumption from the extensive use of reheat. The fuel used to climb and accelerate to cruising height and speed and to reach a point 285 nm from the start of the flight (the end of the conventional climb) is about  $11\frac{1}{2}$ –12 percent of the all-upweight using conventional techniques, with reheat used to raise the height of transition to supersonic flight. The corresponding figure using the unconventional rapid climb technique is  $8$ – $8\frac{1}{2}$  percent. This saving is thus of the same order as the likely penalty due to providing extra thrust desirable in a rapid climb to reduce the sonic-bang nuisance.

## DECELERATION AND DESCENT

If we now turn to the question of deceleration and descent, the normal aim is to get what range one can out of the kinetic and potential energy of the aircraft in an extended glide. A typical gliding descent from  $M = 2.2$  at 60,000 ft is shown in Fig. 16. For short-range operations, however, the time lost and distance covered in such a procedure may mean that it is not the best approach. If our aim is to get as near the destination as possible at cruising speed and height before slowing down and descending as quickly as possible, a very rapid descent can be made. A near optimum descent was found to take 6 min and to cover just over 30 nm giving a time wasted of 2.7 min. However, this descent would have involved an airbrake of up to 900 ft<sup>2</sup> effective area being available on an aircraft with 200,000 lb landing weight. If we remember that one characteristic of slender-wing aircraft is that they can be made controllable up to very high incidences and down to very low values of lift/drag ratio, we find that such an aircraft, by exploiting these characteristics, can slow up quickly using

induced drag and make a quick steep descent. In Fig. 16 a deceleration and descent is shown based on the assumption that the aircraft can be stabilized at a high incidence corresponding to an  $L/D$  of about 2. Using this technique allows a descent to be made in  $8\frac{1}{2}$  min compared with  $16\frac{1}{2}$  min for the maximum  $L/D$  gliding descent. Time wasted, relative to cruising to the destination is 5 min, compared with over 8 min for the maximum  $L/D$  descent, and descent can start 100 nm later. There is, of course, a price to be paid in fuel used but this amounts to only  $\frac{1}{3}$  percent of the all-upweight.

BLOCK SPEEDS AND JOURNEY TIMES

As an example of what these rapid climb and descent procedures mean in terms of block speeds and journey times Figs. 17 and 18 show distance/time curves for climb and total journeys. From Fig. 17 it will be seen how important the rapid climb and acceleration technique could be in short range operations. An aircraft with Mach 2.2 cruising speed and rapid acceleration would be between 100 and 150 nm ahead of an aircraft using normal climb techniques after some 300 or 400 miles had been covered, and even a Mach 3 aircraft using normal climb techniques would not catch up until the aircraft had covered about 900 nm, thus quick acceleration and climb may often be more important than top speed in medium range operations. Figure 18, which shows the total journey time from takeoff to landing, again emphasizes the way in which rapid acceleration and deceleration can give significant savings of time over the range from, say, 200- to 800-nm stage lengths, and that the case for Mach numbers above 2.2, which with normal climb and descent does not become significant until stage lengths of 2,000 nm are reached, is not significant even with extreme rapid climb and descent techniques below about 800 nm. The same data is plotted in a different form in Fig. 19, which makes it clear that if rapid climb and descent techniques can be made possible then a Mach 2.2 aircraft can exploit its speed down to stage lengths of 200 nm. The time savings on such short ranges will probably be of little interest to the passenger though on 300-500 miles stage lengths they are not negligible. The time savings could be of interest to an operator in putting

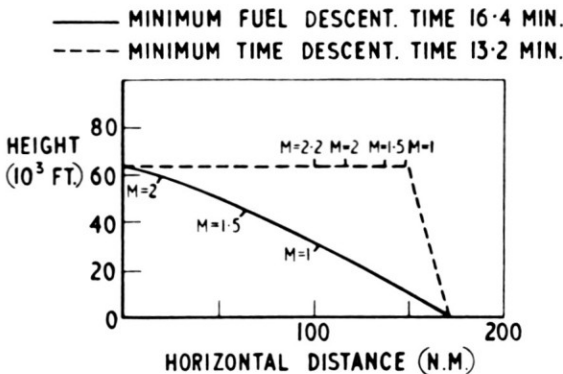


Fig. 16. Comparison of alternative flight paths for descent from  $M = 2.2$  at 64,000 ft.

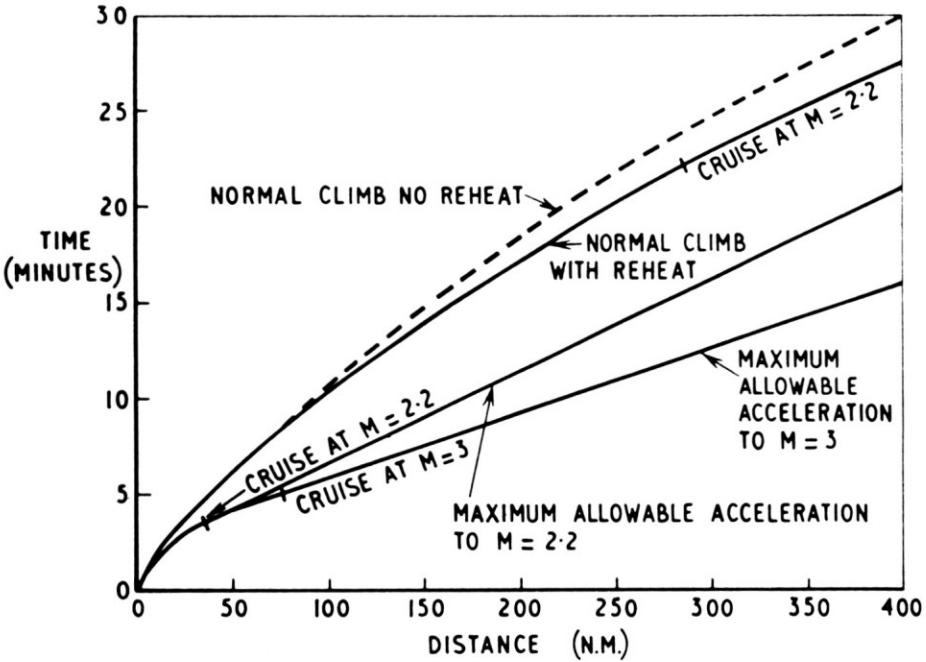


Fig. 17. Distance/time curves for climb and acceleration phases of supersonic transports.

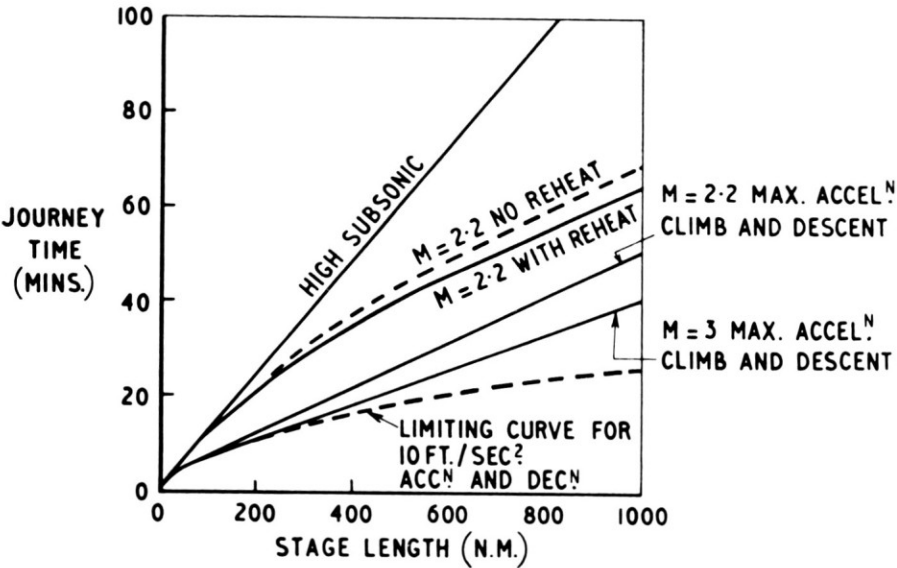


Fig. 18. Journey time vs. stage length for aircraft, using different climb and descent techniques and different cruising speeds.

up the earning power of the aircraft if the turnaround times could be kept short enough. For example, on routes made up of a mixture of stage lengths of 200, 400 and 600 nm a Mach 2.2 aircraft using the rapid climb and descent techniques discussed could fly 16 percent more miles than a normal Mach 2.2 aircraft, and 38 percent more miles than a subsonic aircraft allowing 45 min turnarounds or 21 and 50 percent if turnarounds could be made in only 30 min.

### CONCLUDING REMARKS

On the whole, this paper shows that the noncruising conditions are important and play a significant part in determining the compromises involved in the design of aircraft. It would be wrong, however, to swing from the extreme of regarding cruising efficiency as all important to the other extreme of concentrating on the noncruising conditions. It has been shown that far more fuel is used in supersonic climb than in subsonic climb, and that the penalties for departing from the optimum lift coefficient during the climb are small. The case for variable geometry is not easily decided but appears to depend on the specification of reserves and the amount of subsonic flying involved in standoff rather than on improved efficiency during the normal planned flights. The high drag of engine installations at transonic speeds can be an important factor in the choice of engine installations, and more data on this facet of air-intake design is needed.

Since aircraft drags are inevitably higher at supersonic speeds than at subsonic speeds and the high efficiency of the propulsive system (and high productivity) which make supersonic transports economic improve steadily with speed, in looking for improvements in noncruising characteristics the aim must be to spend as little time as possible in the lower supersonic speed range and to reach cruising speed and height as quickly as possible.

Following up this thought, the possibility of saving time, and thus increasing productivity, and of reducing the sonic-bang problem, by using rapid supersonic

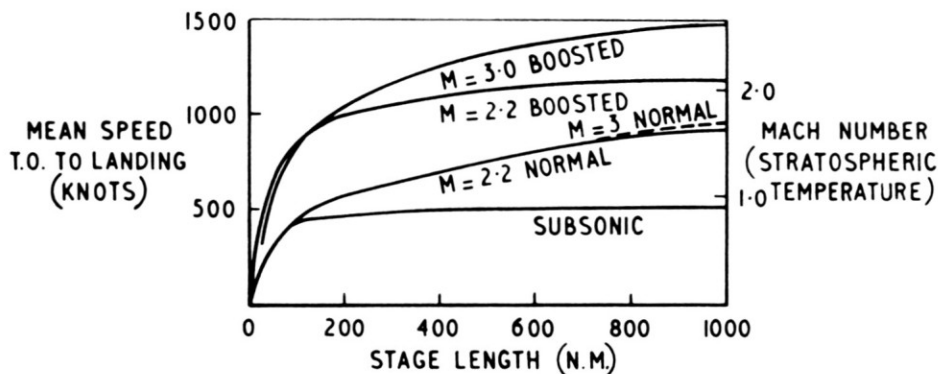


Fig. 19. Block speed vs. stage length for various aircraft having normal and rapid acceleration and deceleration procedures.

climb techniques made possible by high-thrust engines and some degree of thrust boosting has been explored. Possibilities of exploiting supersonic speeds down to stage lengths of two or three hundred miles have been found. A superficial study of this kind cannot answer the question of whether these concepts could lead to economically attractive aircraft, but there is no doubt that supersonic transports when introduced will tend to penetrate the transport market to lower stage lengths than was envisaged in early studies and further study may be justified.

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2. Leivers, B. R., "Transonic Drag of Two Dimensional Wedge Intakes; Model Tests in the A.R.A. Transonic Wind Tunnel," *Rolls Royce Technical Report Ref. TAS/WFW. 10/BBM*, December 1959.

*Discussor:* Helmut Langfelder, Messerschmitt AG im EWR-Süd

Der Hinweis des Vortragenden, dass der Einlauf für ein überschallflugzeug nur aufgrund einer Genauen Kenntnis der Triebwerksdaten sowie der Flugplans ausgewählt werden kann und dass daher allgemeine überlegungen keine sicheren Schlüsse zulassen, ist sicher Richtig-Erstaunlicherweise wird aber in Fig. 6 gezeigt, dass der Einlauf im kritischen Betriebspunkt bei niedriger Machzahl mehr Luft liefert als das Triebwerk schluckt. Bei Einlaufen nicht-variabler Geometrie ist einer im Allgemeinen das Gegenteil der Fall, nämlich dass der Einlauf bei grosser Machzahl zu gross ist wenn er im Transonik-Bereich ausreichend Luft liefert. Überlauf-Widerstand entsteht also besonders bei den Höheren Machzahlen. Durch Beipast kann er allerdings Sehr Stark verringert werden. Ein variabler zwei-dimensionaler Einlauf kann in einem grossen Machzahl bereich, jedenfalls bis  $M_a = 3.0$  gut an das Triebwerk angepasst werden. Das im Vortrag angegebene anwachsen des Einlaufwiderstandes in niedrigen übergenau sollte daher nicht auftreten.

(*Author did not reply.*)

*Discussor:* G. H. Lee, Handley Page Limited, London, N.W. 2, England

Mr. Nicholson's paper contains many useful ideas and suggestions. I am particularly interested in his suggestion of the fast climb technique.

The time saved by this method is certainly valuable for short range cases and the fact that fuel can also be saved may make the technique of importance for long range operations where a quite small fuel saving could represent an appreciable increase in payload since this is normally such a small percentage of the all-up weight.

Designers will have to repeat the study with a view to determining the cost optimum of the reduction in direct operating cost that could be achieved by using fast climbs. Because of the great importance of powerplant cost in direct operating cost (not only first cost but also maintenance costs of engines are high) it often happens that the cost minimum does not correspond to the weight minimum. It may well pay to adopt a solution in which the all-up weight and perhaps the fuel weight are greater than the minimum if, by so doing, a smaller powerplant can be installed.

Finally, I would like to ask a question about the main speeds shown in Fig. 19. These are referred to as block speeds, but as far as I can see, the speed of 480 knots quoted for the high subsonic airplane for a 400 nautical mile stage length is much higher than can be achieved using the A.T.A. method of estimating block speed which, for this case, would give about 335 knots; this is due to the need to include time for taxiing, standoff time, etc. What is the actual basis of the speeds quoted and are the supersonic speeds assessed in exactly the same way as the subsonic speeds?

*(Author did not reply.)*

