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An Airbreathing MACH 7

Development of high-speed transportation systems has played a vital role in the economic and social growth of societies. For future transportation systems new accomplishments must certainly include a continual striving for higher speed, or, more to the point, a reduction in trip time between far-distant cities. The high-speed subsonic transcontinental aircraft is commonplace, and it is only a relatively short wait before the Mach 2 to 3 supersonic transport becomes operational. It is not premature, therefore, to establish higher goals and to determine, for example, if it is possible to provide an intercontinental vehicle which will bring virtually all major cities of the world within two hours' flying time of each other.

The present discussion will deal with some interesting composite design problems which must be considered in order that this goal can be met with vehicles employing airbreathing propulsion systems and which operate in relatively conventional ways from present airports. In particular, the subtle and critical interplay between aerodynamics, propulsion, operational limitations, and performance will be illustrated.

Performance Objectives and Basic Design Philosophy

It is fairly obvious, because of the acceleration and deceleration times involved, that advantageous use of higher speeds compels a consideration of longer ranges. This is illustrated in Fig. 1 which shows the variation of trip time with Mach number for constant trip ranges of from 2000 to 8000 nautical miles. It is immediately apparent that a Mach 3 transport shows appreciable trip time advantage over the subsonic jet airliners for all ranges in excess of roughly 1000 nautical miles. On the other hand, Mach 7 flight does not begin to show significant advantages in trip time over Mach 3 flight until ranges in excess of 3000 nautical miles are considered.

This leads to the conclusion that hypersonic transport aircraft will be most useful in intercontinental travel between principal world cities where a range of 6000 nautical miles would be ample for the great majority of cases. Further increases in speed beyond Mach 7 do not buy significant additional time for ranges up to 8000 miles. This is an interesting result inasmuch as the over-all propulsive efficiency of airbreathing, kerosene-burning engines is maximum at a Mach number very close to 7. The type of engine which is recommended at this speed is an internal, subsonic combustion ramjet.

The very broad Mach number ranges (0 to 7) of operation required of the transport makes

Design of a Mach 7 transport for flights between far-distant cities of the world requires the solution of many major interrelated problems in aerodynamics, propulsion, operational limitations, and performance. The probable use of dual propulsion systems—turbojets and ramjets, research into lift augmentation by ramjets, determinations of flight profiles and trajectories, and establishment of performance parameters are the principal areas of current investigations at APL.

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it necessary to resort to two propulsion systems—turbojets for low-speed operation and ramjets for high-speed operation. A Mach 7 delta-wing configuration incorporating these two propulsion systems, as shown in Fig. 2, was suggested by J. H. Walker of APL. The proportions for a 30,000-lb payload have been nominally established as a 175-ft length, 102-ft wing span, and a 14-ft body diameter. The Mach 0 to 3.6 speed range is achieved by turbojets housed in the rear of the fuselage; air requirements are met by means of retractable two-dimensional diffusers. The Mach 3.6 to 7.0 flight is accomplished by means of twin two-dimensional ramjets located beneath the wings. These external expansion ramjets (ERJ) feature lift augmentation as well as thrust. Further, the external expansion nozzle insures maximum radiation cooling.

Lift Augmentation

Perhaps the most intriguing propulsion feature of the proposed transport design is that of lift augmentation by the ramjet engines. There is much general interest in the concept of lift augmentation, and it is essential, therefore, that we place it in proper perspective. Range R in Fig. 3 is given by the very familiar Breguet equation which shows the direct dependence of R on lift/drag ratio (L/D) and fuel specific impulse (I_f), Eq. 1 of Fig. 3. For the conventional aircraft which derives its lift solely from the relative velocity of the air over the lifting surfaces,

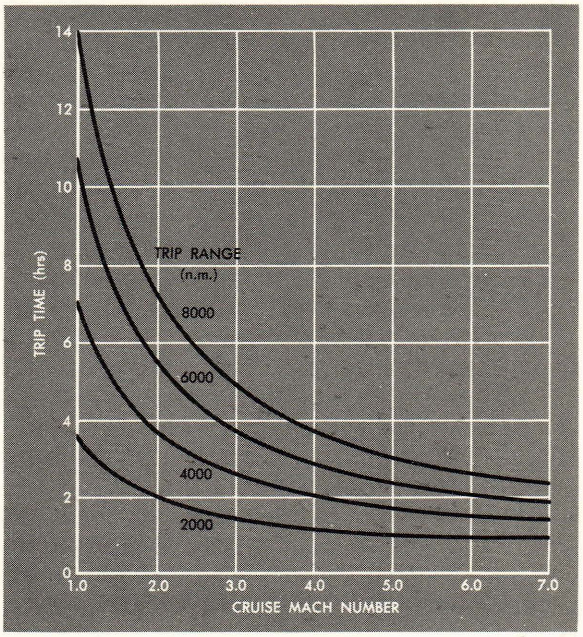

Fig. 1—Variation of trip time with cruise Mach number and trip range for a hypersonic transport. Mach number expresses speed of the aircraft in multiples of speed of sound (1000 ft/sec at 100,000-ft altitude).

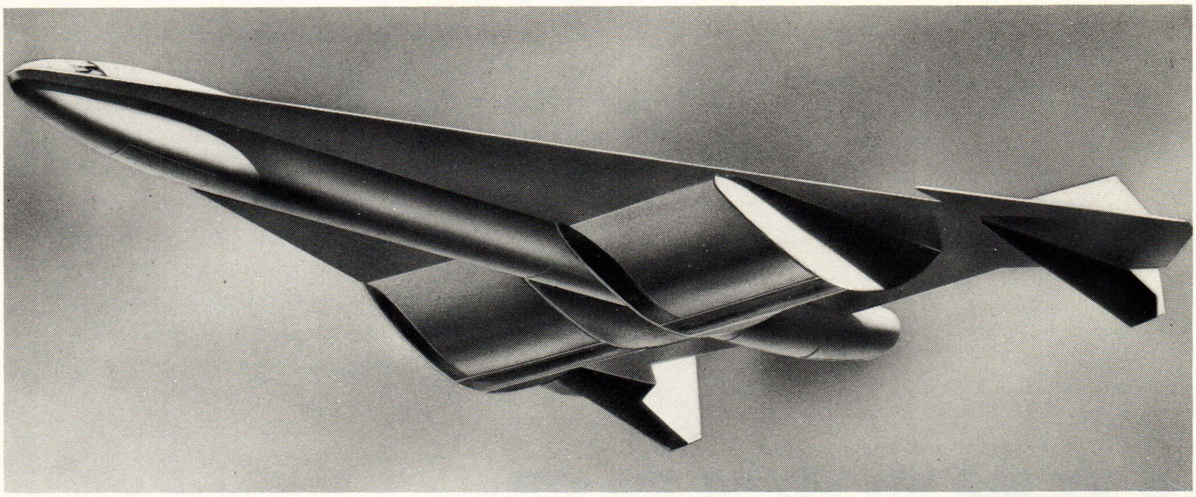

Fig. 2—Artist's concept of the hypersonic transport showing external expansion ramjet diffuser ramps in operating position and turbojet scoop diffuser or air intake in closed position.

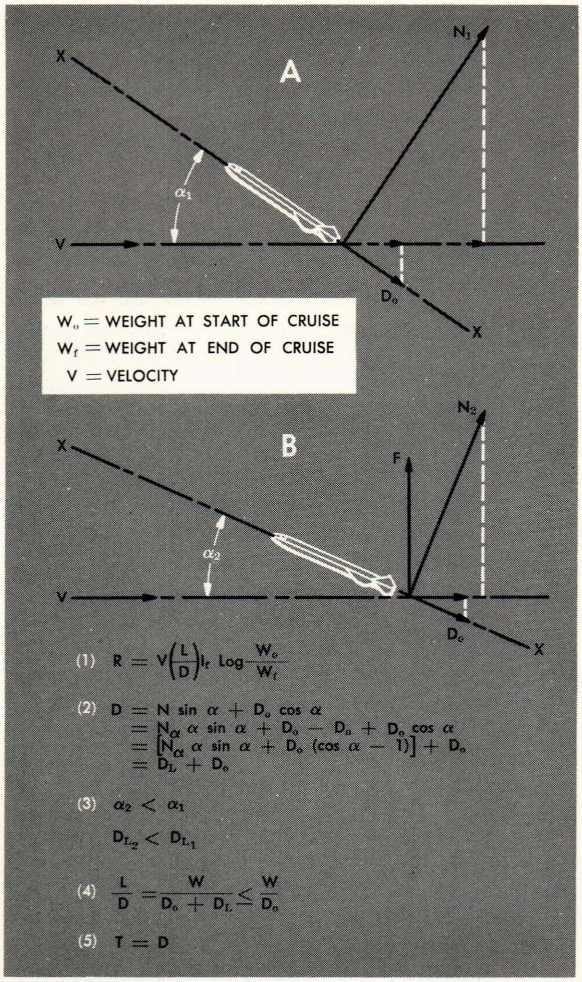

Fig. 3—Diagrams and equations illustrating that lift augmentation can enhance lift/drag ratio and hence range only through its beneficial reduction of aerodynamic drag due to lift.

the normal and axial aerodynamic forces, N and D_o respectively, are as indicated in Fig. 3A. These forces may be resolved in the windward direction to define the drag in accordance with Eq. 2, Fig. 3. Evidently the drag can be expressed as a zero-lift drag (D_o) plus a drag associated with angle-of-attack. The latter is more commonly referred to as the "drag due to lift" (D_L).

If we introduce an additional lifting force F, the force diagram is as shown in Fig. 3B. Since F provides some of the lift to support the weight, the aerodynamic contribution to lift, as reflected in α, can be reduced. Consequently, $\alpha_2 < \alpha_1$, $D_{L_2} < D_{L_1}$. If the lift/drag ratio is expressed in the manner indicated in Eq. 4, it becomes immediately apparent that the augmentation of lift by an additional force can enhance the lift/drag ratio only through its beneficial reduction in the drag due to lift. Further, the upper limit to the lift/drag ratio is given by W/D_o which corresponds to complete lift augmentation. Thus, regardless of the extent of lift augmentation, clean aerodynamic design, i.e., low value of D_o, remains an important design objective.

Lift augmentation can be derived from a variety of sources—centrifugal force, tilting the engines, burning under the wings, etc. Generally, if it comes from the engines the magnitude of the augmentation is constrained in some degree by the requirements of Eq. 5, namely, thrust T equals drag D. That is, the engine is always sized to meet certain thrust-equal-drag requirements, and one must then accept whatever lift augmentation this engine size will provide. Consequently, complete lift augmentation is never

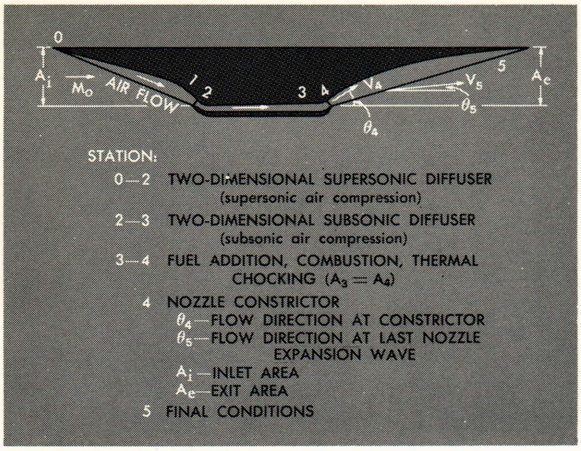

Fig. 4—Schematic diagram of two-dimensional external expansion ramjet illustrating air flow direction and regions of primary interest.

achieved. For the design of Fig. 2, the ramjet contribution to the configuration lift/drag ratio is 12 to 13%.

Propulsive Performance of Mach 7 Ramjet Design

The external expansion ramjet shown schematically in Fig. 4 has a twofold purpose. It is anticipated that the combustion chamber and nozzle temperatures will be quite high (flame temperatures in excess of 5000°R) for Mach 7 flight. The use of as short a cowl as possible and a half-nozzle expansion design are to alleviate these problems, in part, through effective radiation cooling. Also, as indicated above, the use of a half nozzle provides for a certain amount of lift from the high pressures acting over the nozzle section.

The first of the three external expansion ramjet plots, Fig. 5, shows the variation of thrust coefficient C_T with engine geometry A_e/A_i (the ratio of exit area to inlet area), and air flow direction θ_4 at the constrictor for the conditions set forth. These are, namely, Mach 7.0, equivalence ratio = 0.5, pressure recovery = 10%, kerosene-air, thermal choking between equal-area stations 3 and 4, and conditions of dynamic equilibrium in the isentropic expansion nozzle. For each θ_4 the nozzle expansion is carried to the extent of $\theta_5 = 0$. The nozzle exit pressure ratios P_5/P_0 at these points are indicated along the locus $\theta_5 = 0$ curve. The thrust coefficient is as defined in the plot and does not include base drag or boat tail drag (when $A_e < A_i$) or wedge drag (when $A_e > A_i$) of the cowl. This was done to allow a greater flexibility in the use of these data. That is, in certain situations the cowl geometry might be quite conveniently absorbed in the adjacent wing or fuselage structure with favorable drag results. The estimate of thrust includes the losses due to heat addition but assumes complete combustion. The engine is sized for a particular configuration by selecting a value from this graph, equating thrust to drag ($C_T\ P_oA_i = C_D \frac{\gamma}{2} P_oM_o^2\ A_{ref}$) and,

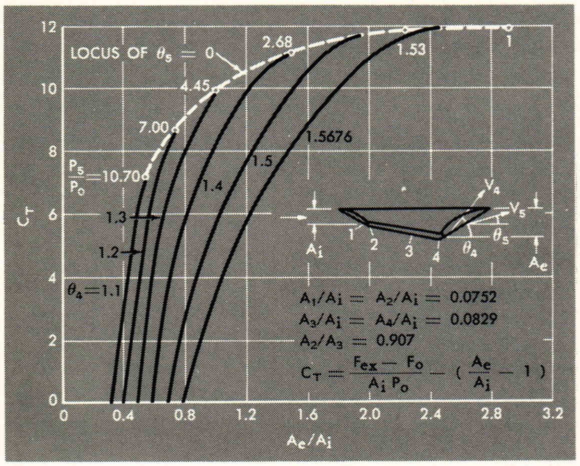

Fig. 5—Curves illustrating variation of thrust coefficient with engine geometry for the external expansion ramjet. A_e/A_i denotes ratio of engine exit area to engine inlet area. The engine sketch portrays a case for which A_e/A_i is greater than 1.0. θ_4 denotes the gas flow direction at the nozzle exit. The "locus of $\theta_5 = 0$" corresponds to final realignment of gas flow in a direction parallel to inlet flow or flight direction.

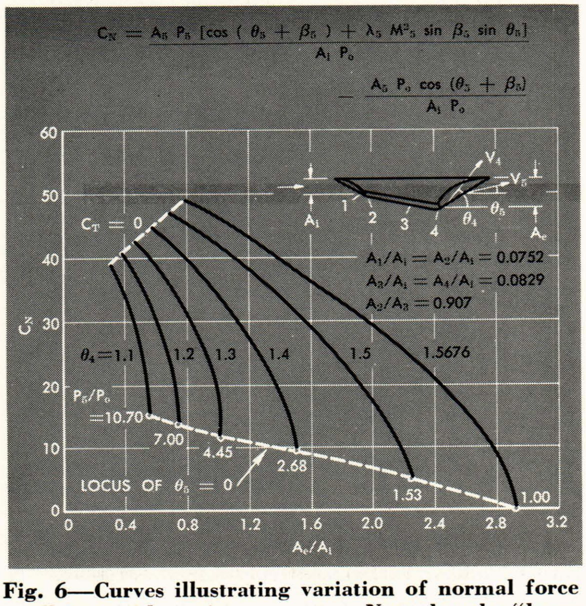

Fig. 6—Curves illustrating variation of normal force coefficient with engine geometry. Note that the "locus of $\theta_5 = 0$" curve corresponds to minimum values of C_N and provides the least lift augmentation.

thereby, solving for a value of A_i/A_{ref} (the ratio of engine area to the configuration reference area). In most of our studies we restrict C_T to the "locus $\theta_5 = 0$" curve and more particularly to an $A_e/A_i = 1.0$.

The second of these plots, Fig. 6, presents the variation of the normal force coefficient C_N as a function of the same parameters and for the same conditions as in Fig. 5. An interesting question now arises as to whether our previously indicated choice for C_T, corresponding to $\theta_5 = 0$ and $A_e/A_i = 1$, is correct; it quite obviously does not afford the greatest lift augmentation and hence, according to the ideas expressed in Fig. 3, a more attractive lift/drag ratio. A justification for the choice is therefore required and is found in Fig. 7, showing the related variation in I_f as a function of θ_4, A_e/A_i, and degree of nozzle expansion P_5/P_o. It is immediately apparent that if one desires a high value of C_N, achieved as noted in Fig. 6, by "backing-off" from the "locus $\theta_5 = 0$" curve, a severe penalty in I_f is incurred. Further, since the C_T and I_f curves are virtually identical in character, a much larger engine, with obvious consequences of weight, drag, and cooling, is implied. Thus, the interplay between engine sizing, lift augmentation, and range is manifest.

Flight Profile

The over-all flight profile of the hypersonic transport is comprised of three equally important phases, namely, climb and acceleration, cruise, and descent and deceleration. Certain

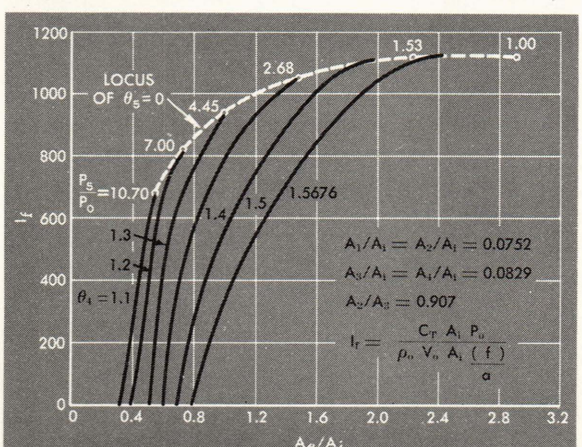

Fig. 7—Curves illustrating variation of fuel specific impulse, I_f, with engine geometry. I_f is a measure of thrusting efficiency of the engine and bears directly on range. Note similarity of this figure with Fig. 5. A small efficient engine requires holding to the "locus of $\theta_5 = 0$" curve and accepting the corresponding minimal lift augmentation in Fig. 6.

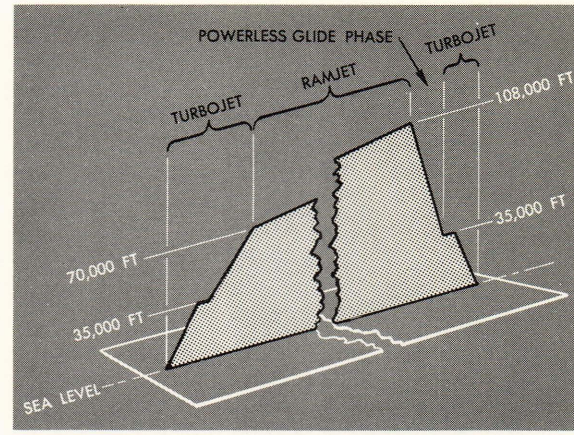

Fig. 8—Over-all flight profile for the hypersonic transport.

operational limitations which arise in the case of the hypersonic transport are not factors in the subsonic transport. The most important of these for our present consideration is the sonic boom problem. An aircraft flying at supersonic speeds generates shock waves that trail from the aircraft in much the same manner as water waves from a boat. There is an abrupt rise in pressure across these waves which can be both physiologically and physically objectionable. The seriousness of these phenomena is a function of aircraft size, Mach number, altitude, winds, and so on. In any event, the flight profile, particularly the climb and descent, must be adjusted so as to attenuate the ground level sonic boom effects.

The selected flight profile starts with a climb and acceleration to 100,000-ft altitude and Mach 7. Cruise at Mach 7 is initiated at 100,000 ft and continues for a Breguet cruise to a nominal 108,000-ft altitude. This is followed by a descent and deceleration, terminating at sea level at Mach 0 (Fig. 8).

Climb and Acceleration Trajectories

Weight estimates and aerodynamic and propulsion data provide a necessary foundation for the consideration, first, of climb and acceleration and, later, of range performance. Consequently, appropriate aerodynamic and propulsion data, together with required atmospheric data, need to be collected, curves fitted, and the trajectories computed by integrating applicable equations of motion with a high speed computer such as the Univac 1103A.

Minimum climb and acceleration time is essential because a Mach 7 transport is a reasonable vehicle if, for a specified range, a sufficient improvement in trip time can be demonstrated to make it worth the effort in overcoming certain economic and technical difficulties. To achieve a minimum climb time, maximum available equivalence ratio, corresponding to maximum propulsive thrust, is always used. The required maximum tangential acceleration a_t, the number of turbojet engines, the size of the ERJ engines, and the gross weight at take-off constitute the principal design parameters. The important performance variables are the climb time, climb fuel, and climb range. The Mach 0 to 3.6 climb and acceleration phase is possibly the most interesting, and we shall restrict our discussion to it.

A precise manner in which the Mach 0 to 3.6 climb and acceleration can be programmed is best understood by examining the illustration of the hypersonic transport climb trajectory (Fig. 9). This shows the variation of altitude with velocity as a function of maximum tangential acceleration a_t called for when using eight turbojet engines and an initial gross weight of 500,000 lb. At the end of the take-off ground run the indicated a_t's are called for and are held until Mach 0.8 is achieved. At this point, in order to avoid the objectionable effects of sonic boom, the tangential acceleration is reduced to zero and the aircraft climbs to 36,000 ft. At this point the initially specified a_t is called for once again. If the thrust during transonic acceleration is marginal or deficient, the configuration will dive and use gravity in order to maintain the required a_t. If, during this activity, the altitude drops below 34,000 ft, a_t is reduced in a systematic manner to regain the lost altitude. When 34,000 ft is once again attained, a_t is systematically worked up to its initially specified value. (It is essential always to bear in mind the above qualification on a_t. For all trajectories the specified a_t represents the maximum but not necessarily a constant value of the tangential acceleration persisting throughout the entire course of the trajectory.) Under certain conditions the process repeats, resulting

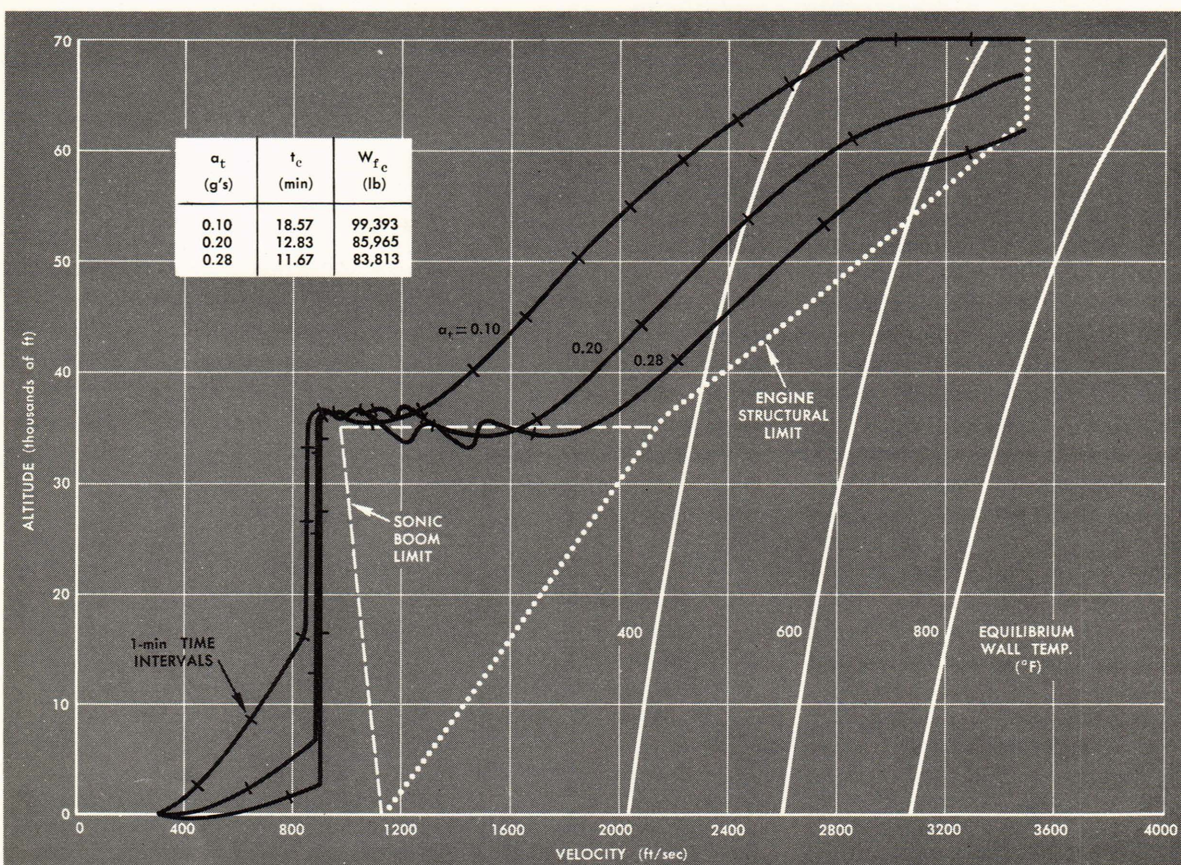

Fig. 9—Typical hypersonic transport climb trajectories in the altitude velocity plane for turbojet climb and acceleration to Mach 3.6 and 70,000 ft. For this flight phase the sonic boom limit presents the most serious over-riding operational limitation.

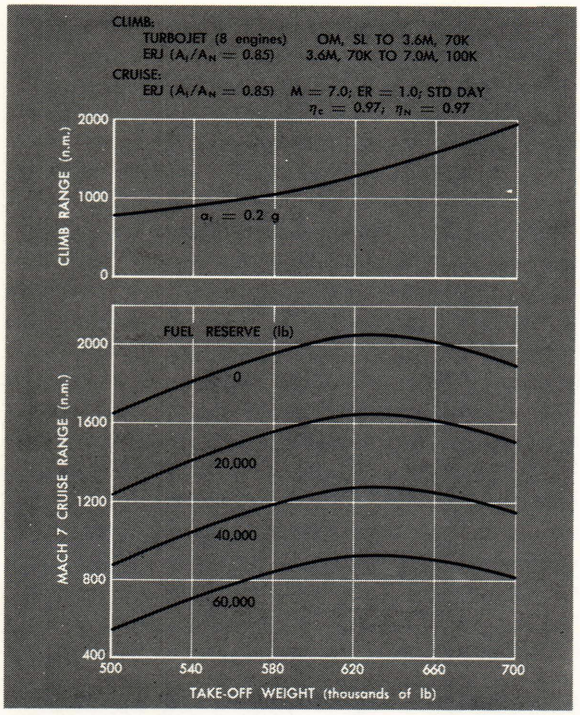

Fig. 10—Variation in climb and Mach 7 cruise range with take-off weight. Concerning cruise curves, fuel reserves of 50,000 lb are considered realistic.

in a few oscillations, as shown in Fig. 9. (These oscillations may readily be eliminated by an alternate programming in the transonic region.) Thereafter the trajectory curves continue and the climb to 70,000 ft is concluded at $a_t = 0$g and Mach 3.6. The switching of propulsion from turbojets to ramjets is accomplished during the latter portion of the climb. At all times the engine structural limit is avoided, and the aerodynamic heating of the structure is relatively low. The time to climb and fuel consumption are indicated in Fig. 9.

The fuel consumed for climb and acceleration for both the turbojet and ramjet flight phases is an appreciable percentage of the total fuel load, and this is reflected in over-all range performance. For example, for a hypersonic transport employing eight turbojet engines and ramjets with a ratio of $A_i/A_{ref} = 0.85$, the total climb fuel consumption varies from 164,000 lb for a 500,000-lb gross weight to 314,000 lb for a 700,000-lb configuration. These fuel consumptions represent 66% and 75% of the corresponding total fuel loads, respectively. The data are for $a_t = 0.2$g which was found to be optimal. The corresponding total climb times and climb ranges are 23.5 min. and 779 nautical miles for the 500,000-lb configuration and 49.9 min. and 1932 nautical miles for the 700,000-lb configuration. Improvements to these fuel consumptions will depend on the invention or development of more efficient propulsion systems and in the realization of configurations of lower aerodynamic drag. Study indicates that, generally, drag accounts for half the total fuel consumption during climb, gravity and acceleration together accounting for the balance.

The effect of gross weight on climb range is shown in the upper graph of Fig. 10. The climb range is appreciable and increases with increasing take-off weight from a value of 779 nautical miles for 500,000 lb to 1932 nautical miles for 700,000 lb. All data are for a near-optimum climb trajectory for which $a_t = 0.2$g.

Cruise

The lower graph of Fig. 10 shows the variation in Mach 7 cruise range as a function of take-off weight and fuel reserve. The cruise range is, of course, dependent upon the fuel available for cruise. The amount of this cruise fuel is, in turn, dependent upon the weight

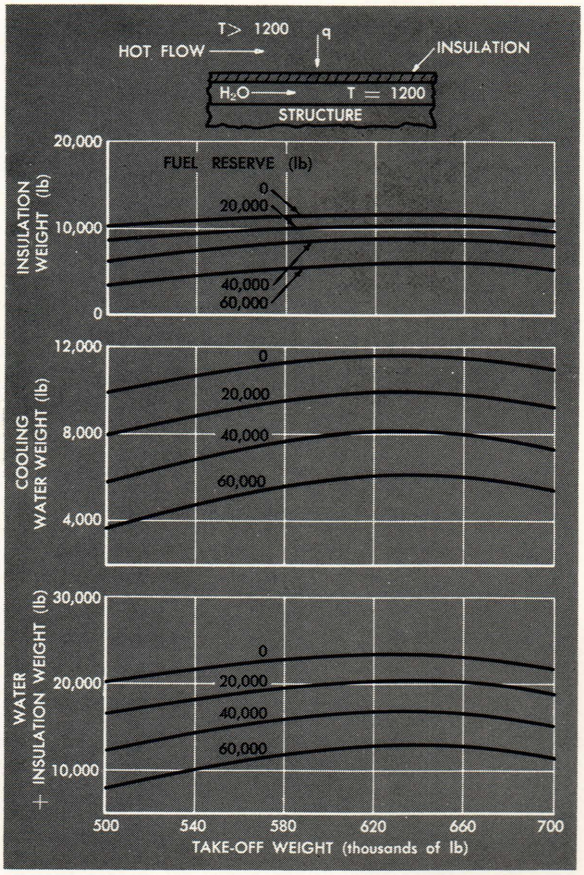

Fig. 11—External expansion ramjet insulation and cooling requirement.

which must be allocated to structure, propulsion, thermal insulation of ERJ engines, fuel reserve, etc. Each of these has been determined; for the case of the ramjet thermal insulation and cooling, the results are illustrated in Fig. 11. The insulation and cooling are designed to maintain the structure at 1200°F. It is evident that for a realistic fuel reserve of 50,000 lb a cooling-water plus insulation weight of about 15,000 lb is required.

Descent

It is planned that the descent from end-of-cruise altitude (approximately 108,000 ft) will be accomplished by means of a powerless glide. During this glide the ramjet engines will be extinguished and retracted. At a nominal Mach number of 1.25 and altitude of 35,000 ft the turbojet diffuser will be let down and the turbojets ignited for a power let-down and landing. The descent altitude and range as a function of descent velocity and lift/drag ratio are shown in Fig. 12. The time required for descent is also indicated. An estimated lift/drag ratio of 5.0 during descent results in a total descent range of 670 nautical miles. The long descent range attests to the very high total energy level of the configuration at end of cruise.

Over-all Trip Performance

Figure 13 illustrates the over-all trip performance of the hypersonic transport as a function of take-off weight and fuel reserve. Trip time, trip fuel, and trip range are presented in the upper, middle and lower graphs, respectively. For a 700,000-lb configuration and a 50,000-lb fuel reserve a trip range of 3600 nautical miles takes 89 min. The total fuel load of the configuration is 418,000 lb.

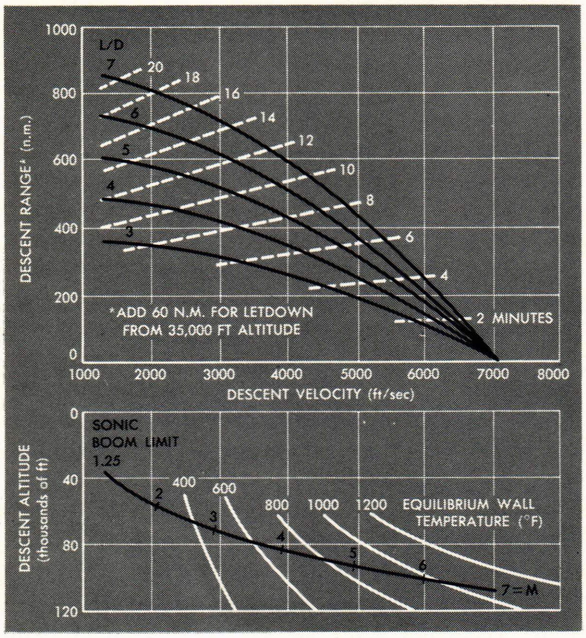

Fig. 12—Hypersonic transport powerless glide range performance. Glide range will generally be on the order of 600 nautical miles.

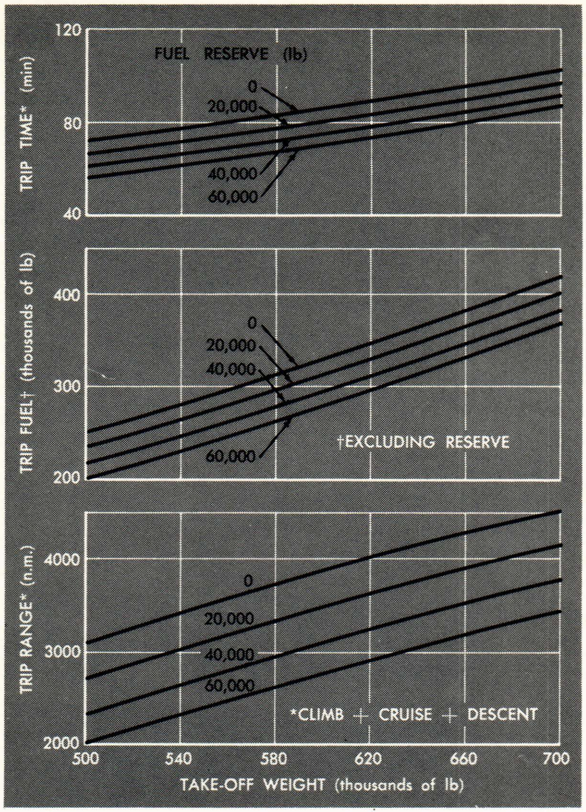

Fig. 13—Hypersonic transport over-all trip performance.

This design has succeeded in achieving a little over half our original range objective of 6000 nautical miles. Further increases in range necessitate a greater proportion of fuel available for cruise than achieved in the presently assumed model. Though not entirely attractive, this might be accomplished through inflight refueling (say, just before transonic acceleration and again after transonic deceleration), by increases in configuration gross weight, and by reducing fuel reserves. Aside from these approaches, however, improvements must await some significant improvements in propulsion and aerodynamic efficiency, progress in cooling and insulation technology, and advancements in structural design. It is anticipated that continued research in these areas will suggest solutions to these problems, thereby increasing the efficiency of hypersonic transportation.