AERODYNAMICS FOR SPACE FLIGHT

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AERODYNAMICS FOR SPACE FLIGHT

by

E. P. Williams
Carl Gazley, Jr.

The state-of-the-art of hypersonic aerodynamics is reviewed. Special attention is given to the problem of aerodynamic heating, particularly as it affects hypersonic flight vehicles.

INTRODUCTION

Planetary atmospheres comprise such a small part of space that one may well wonder why aerodynamics is even included in an introduction to astronautics. Fortunately, for the aerodynamicist at least, the earth's thin atmosphere gives rise to some very vital problems in space flight, particularly if you wish to recover your man, dog, or data-capsule intact. Furthermore during passage through the atmospheres of the earth or other planets hypersonic speeds are encountered by satellite, lunar, or interplanetary vehicles. Consequently, for better or worse, hypersonic aerodynamics is inherently connected with astronautics and even subsonic and supersonic aerodynamics will be involved in a manned recovery system.

Strictly speaking, we should use the term 'gas-dynamics' rather than 'aerodynamics,' since our consideration is not limited to the earth's atmosphere. Furthermore, due to chemical effects, the 'air' we are concerned with in hypersonic aerodynamics may be quite different from our customary ideas of air. However, we shall assume 'aerodynamics' does not preclude gases other than air.

In this lecture on aerodynamic flight we would like to review some typical hypersonic vehicles and show how they fit into the flight spectrum; to outline the characteristics of hypersonic and free molecule flows, and to consider aerodynamic heating. Later lectures will look in more detail at the prime problem of atmospheric entry* and entry design.**

VEHICLES

First let us consider typical hypersonic vehicles. Perhaps the most widely publicized vehicle, and the one of greatest international interest, is the long-range ballistic missile. From an aerodynamicist's viewpoint, the distinguishing characteristic of a ballistic vehicle is that it operates at zero lift. The missile is accelerated up to speed by a rocket motor or by some other launching device and then left to coast under its own momentum as modified by aerodynamic drag and the acceleration of gravity. A typical ICBM trajectory for 5500 n mi range is shown by Fig. 9-1. Its 22,500-ft/sec velocity at burnout is not much less than the 26,000 ft/sec required to maintain a satellite in its orbit. Thus, a long-range ballistic missile approaches satellite speeds and a considerable portion of its weight is supported by centrifugal force.

Although aerodynamics is concerned with only a small part of the trajectory of a long-range ballistic missile, namely the shaded area simulating the earth's atmosphere in Fig. 9-1, it is a most vital part. The important aerodynamic effects occur, of course, on re-entry. The skin temperature rise during ascent is only about 600°F; but it is a major design problem to keep the skin from literally melting, vaporizing, or burning away during re-entry.

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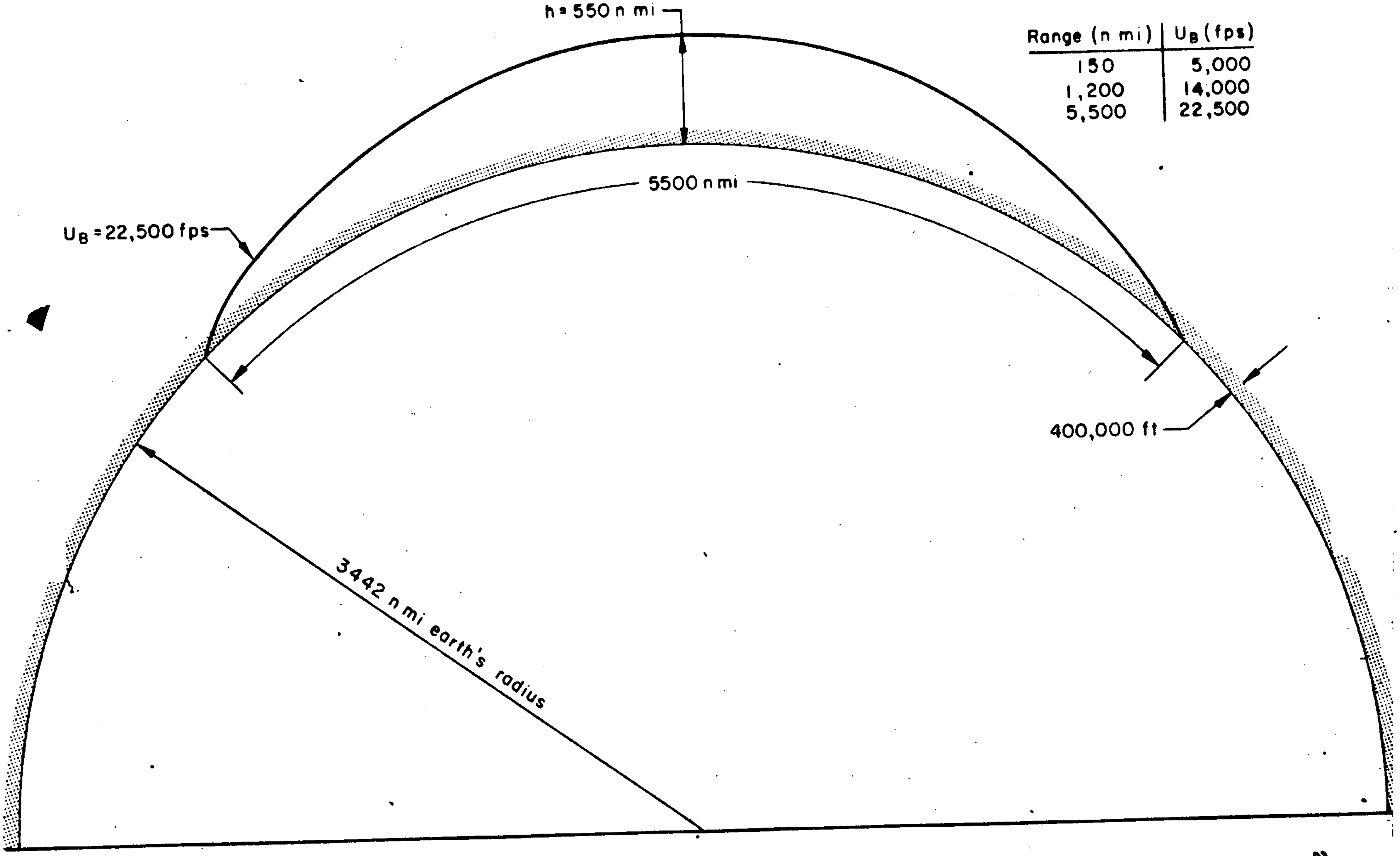
*Lecture 10 by C. Gazley, Jr. Also P-1322, The Penetration of Planetary Atmospheres.

**Lecture 11 by D. J. Masson.



Range (n mi)	U_B (fps)
150	5,000
1,200	14,000
5,500	22,500

Fig. 9-1 —Ballistic trajectory

The inefficiency of the long-range ballistic vehicle is indicated by the fact that for a 5500-mi range the useful payload amounts to only about one per cent of the initial gross weight.

The glide rocket,(1) although it is not so widely publicized as the ballistic missile, is perhaps a more interesting vehicle to the aerodynamicist. First, it stays within the earth's atmosphere and, second, its range is directly proportional to its lift-drag ratio. Although not a true cruising type vehicle, the glide rocket is much more closely related to the conventional airplane than is the ballistic rocket and is a more likely vehicle for manned hypersonic flight and for recovery of a man from space. The glide rocket is boosted up to initial speed and altitude by a one- or two-stage rocket, much like a ballistic vehicle. It is then tilted over into a glide path and glides back to earth, losing speed and altitude as it descends. For increased accuracy and to avoid too low an impact speed, the flight path of the glide bomber is usually terminated in a ballistic dive. A typical flight path is shown by Fig. 9-2. Note that the vertical scale is considerably expanded, and that the entire glide-rocket flight is within the atmosphere.

A typical glide-rocket configuration is shown by Fig. 9-3. It is a high-fineness-ratio, streamlined vehicle because of the importance of lift-drag ratio. The flat-bottom-body and drooped nose provide the best lift-drag ratio in the hypersonic regime.(1) The flares at either side of the body are essentially wings which increase the lift-drag ratio.

The efficiency of the glide rocket versus the ballistic rocket is illustrated by the fact that for two vehicles of the same gross weight and payload the ballistic rocket will go only about one-third as far as the

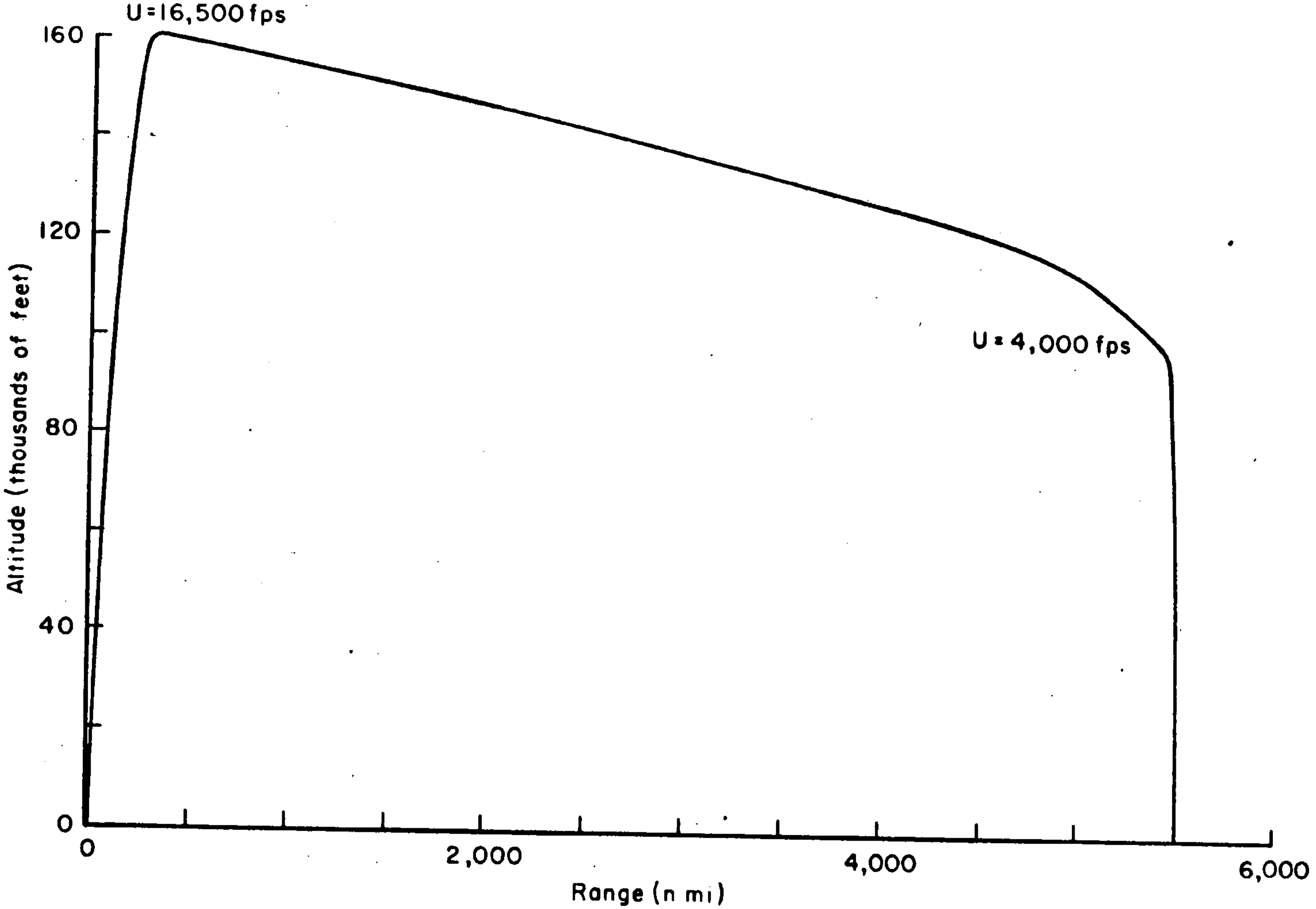
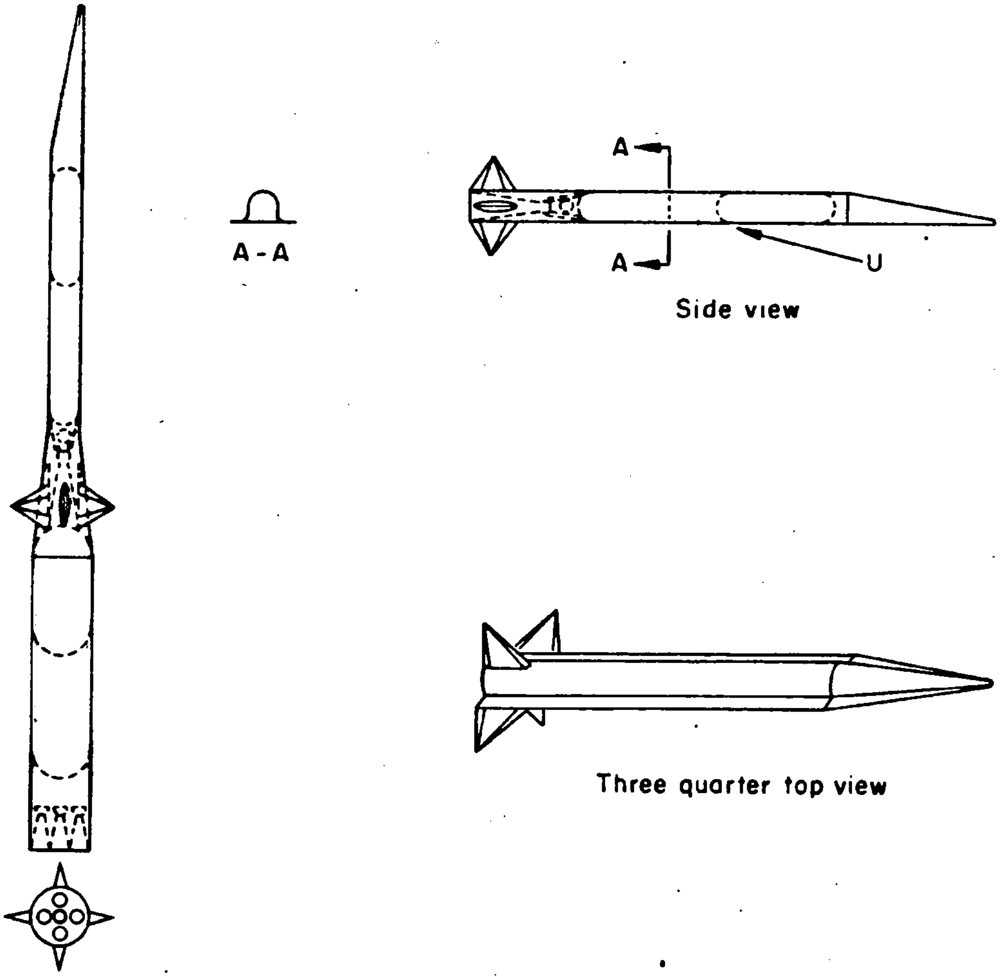


Fig. 9-2 —Glide path



Side view

Three quarter top view

Fig. 9-3 —Typical glide rocket

glide rocket; or, for the same range and payload, the glide rocket will weigh only one-third as much.(2) A more impressive way to look at it is that if the ICBM were converted to a glide rocket of the same range and initial gross weight, the payload could be 8 to 10 times as great. However, guidance, vulnerability, and other factors outweighed flight-mechanics efficiency and dictated the choice of the ballistic missile as the first strategic rocket bomber. Figure 9-4 shows typical hypersonic vehicles, drawn approximately to the same dimensional scale, with their boosters: ICBM, IRBM, glide rocket, and the explorer and Vanguard satellites. Sputnik, not shown, presumably is comparable to the ICBM.

A manned glide rocket involves essentially the same design considerations for the glide portion of its path, with only the added complication of a conditional compartment for human occupancy. However, the powered ascent and the landing must be modified for human tolerance and safety. The take-off acceleration of a typical unmanned glide rocket or ballistic rocket starts with about 1/2 g above gravity and increases to about 7 g as the fuel is burned. For an inhabited vehicle, the maximum take-off acceleration could be reduced to a tolerable limit - perhaps 4 g - by extending the time of powered flight, i.e., accelerating more gradually.

The terminal portion of a manned vehicle must involve essentially a conventional airplane landing or a parachute recovery, so that tolerable decelerations occur. Ballistic re-entry, except for very shallow descents, involves decelerations above human tolerance. Glide path descents, however, are accompanied by very low decelerations--usually less than one g. While power-on landings appear to present no insurmountable problems, as has been demonstrated by current VTOL aircraft, the weight penalty for a rocket vehicle would probably be excessive.

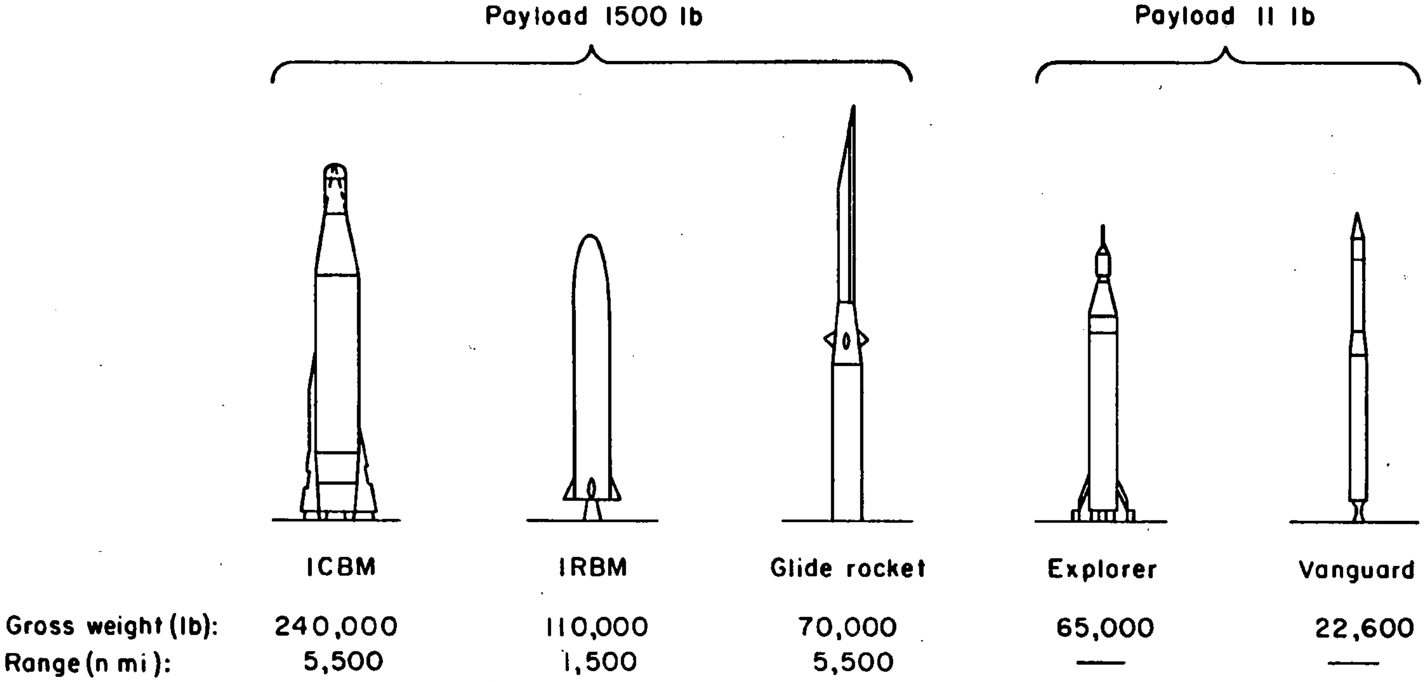


Fig. 9-4 —Typical hypersonic vehicles

As indicated by these brief considerations, hypersonic airplanes would appear to be primarily of the boost-glide type - essentially an extension of the current series of X-airplanes. It is expected that development of a hypersonic cruise aircraft must wait the advent of an efficient sustaining power plant, such as a hypersonic ramjet.

The initial ascent flight paths of space craft will be almost identical with those of ballistic and glide rockets; space craft re-entry is discussed in a following section.

FLIGHT SPECTRUM

As you have noticed, hypersonic vehicles seem to fit into one of two categories: first, cruise- and glide-type vehicles which depend upon aerodynamic lift to support at least part of their weight and must therefore stay within the earth's atmosphere, and second, ballistic missiles and satellites which require no aerodynamic lift and therefore operate mostly out of the atmosphere. The range of flight speeds and altitudes considered possible for steady earth flight is shown by the corridor of continuous flight in Fig. 9-5. In the region above the corridor the dynamic pressure is too low to provide sufficient lift, while below the corridor the aerodynamic heating rates cause excessive skin temperatures. For construction of this chart, the maximum allowable skin temperature was considered to be about 2000°F and the dynamic pressure (necessary for lift) was assumed to be near 80 lb/sq ft. The upper limit of the corridor is relatively insensitive to the dynamic pressure, and even doubling the required dynamic pressure does not cut off the corridor. The effect of centrifugal force due to the vehicle following the curvature of the earth is included. At 15,000 ft/sec, centrifugal force supports one-third of

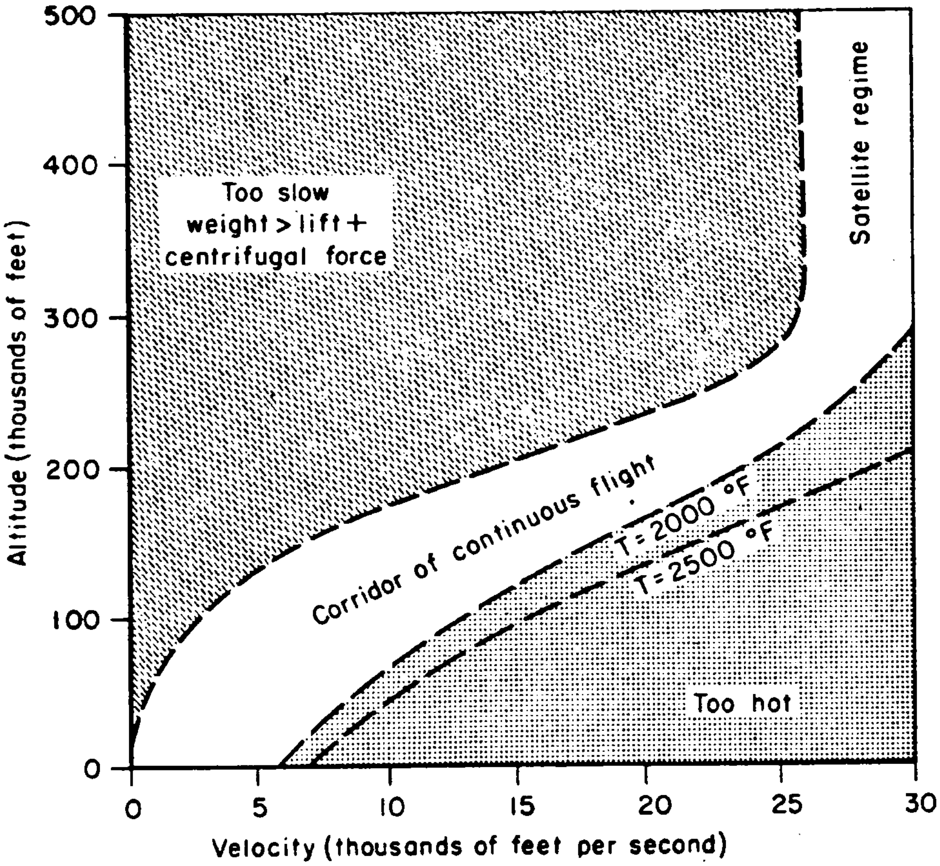


Fig. 9-5 —Flight spectrum-corridor of continuous flight the weight of the vehicle; at 18,000 ft/sec, it supports one-half; and, of course, at 26,000 ft/sec, centrifugal force balances gravity and the vehicle is in a satellite orbit.

The lower limit of the corridor of continuous flight is unfortunately quite sensitive to the allowable skin temperature. As you can see by extrapolating from 2500 deg and 2000 deg, a 1500 deg limit would cut off the corridor at less than satellite speeds. However 2000 deg is believed indicative of present design capability with high temperature alloys.

A cruise-type aircraft could be built to fly anywhere within this corridor. Glide rockets, including those re-entering from satellite orbits, will, of course, descend along this corridor. A typical flight path is shown in Fig. 9-6. Notice that the ICBM ascent path stays well out of the high-temperature region; but upon re-entry, the ICBM dips into the hot region below the continuous flight corridor. The IGY satellite or Vanguard re-entry trajectory lies close to the upper boundary of the continuous flight corridor. Although its re-entry from around 200,000 ft takes only four or five minutes, it happens that nearly equilibrium skin temperatures are reached. It could reach the earth intact if its skin were made of a high-temperature alloy rather than magnesium.

The continuous flight temperature boundary was based upon radiation equilibrium. Below this boundary aerodynamic heating is greater than can be disposed of by radiation, and the skin temperature rises. This is illustrated by the middle part of Fig. 9-7. Eventually the skin temperature rise is great enough to cause melting or vaporization, as indicated by the right-hand side of the figure. At that point we are forced to use one of the cooling systems discussed in the paper on entry design.*

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*Lecture 11 by D. J. Masson.

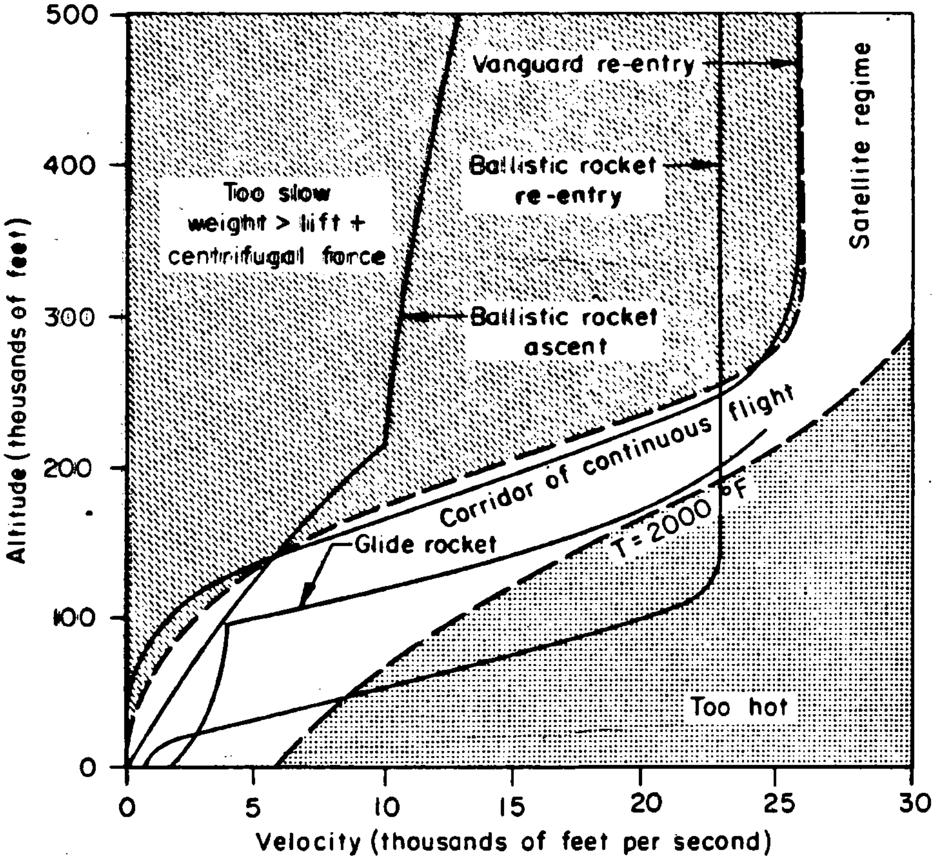


Fig. 9-6 — Flight spectrum-flight paths

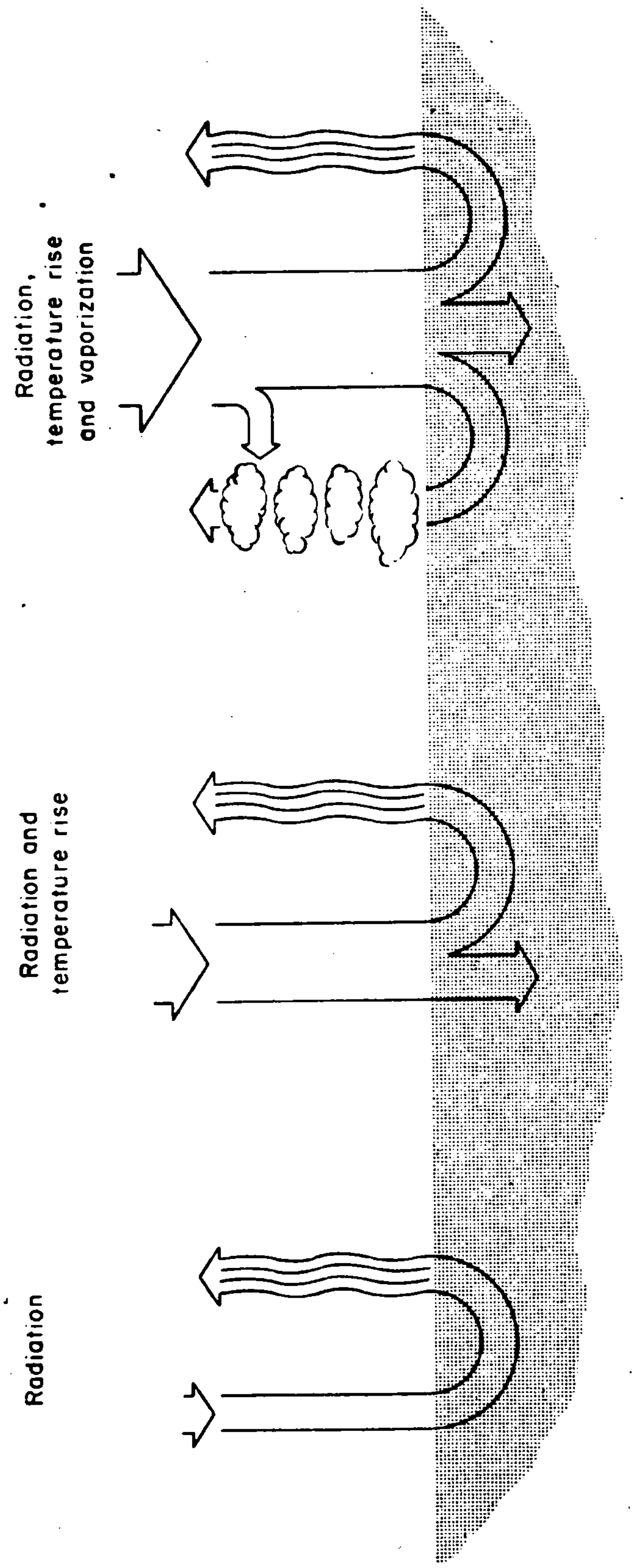


Fig. 9-7 —Surface heating

A continuation of the flight spectrum chart is shown by Fig. 9-8. Lunar vehicles require about 35,000 ft/sec, while interplanetary vehicles leaving or returning to the earth have velocities of about 37,000 ft/sec - the earth's escape velocity. Meteor velocities may exceed 200,000 ft/sec. The vaporization boundary designates the region beyond which nearly all materials (except impervium) vaporize. It is not, of course, as precise a limit as the continuous flight radiation boundary. Although the ICBM dips into the hot region, it stays safely above the vaporization boundary. Likewise, a recoverable space craft must stay out of this region. A small meteor on dipping beyond this boundary loses appreciable mass by vaporization and sloughing, thus changing its weight-to-drag ratio and modifying its trajectory to bring it back above the vaporization region. A larger meteor or fireball with greater weight-to-drag ratio will strike the earth before emerging from this region. Figure 9-8 illustrates one of the most difficult aerodynamic problems of space flight - that of entry or re-entry into a planetary atmosphere.

HYPERSONIC FLOW

Since the aerodynamics of space flight is inherently hypersonic, we might try defining the word 'hypersonic' or at least relating it to the lower speed regimes with which you may be more familiar. Unfortunately the distinction between super- and hypersonic flow is not as clear-cut as the line between sub- and supersonic flow. To the layman the latter is the velocity of sound (which the aerodynamicist calls Mach one), and to the mathematician, it is the point at which the equations shift from elliptic to hyperbolic. Now, hypersonic flow for the mathematician starts when the differential equations become predominantly non-linear. But this

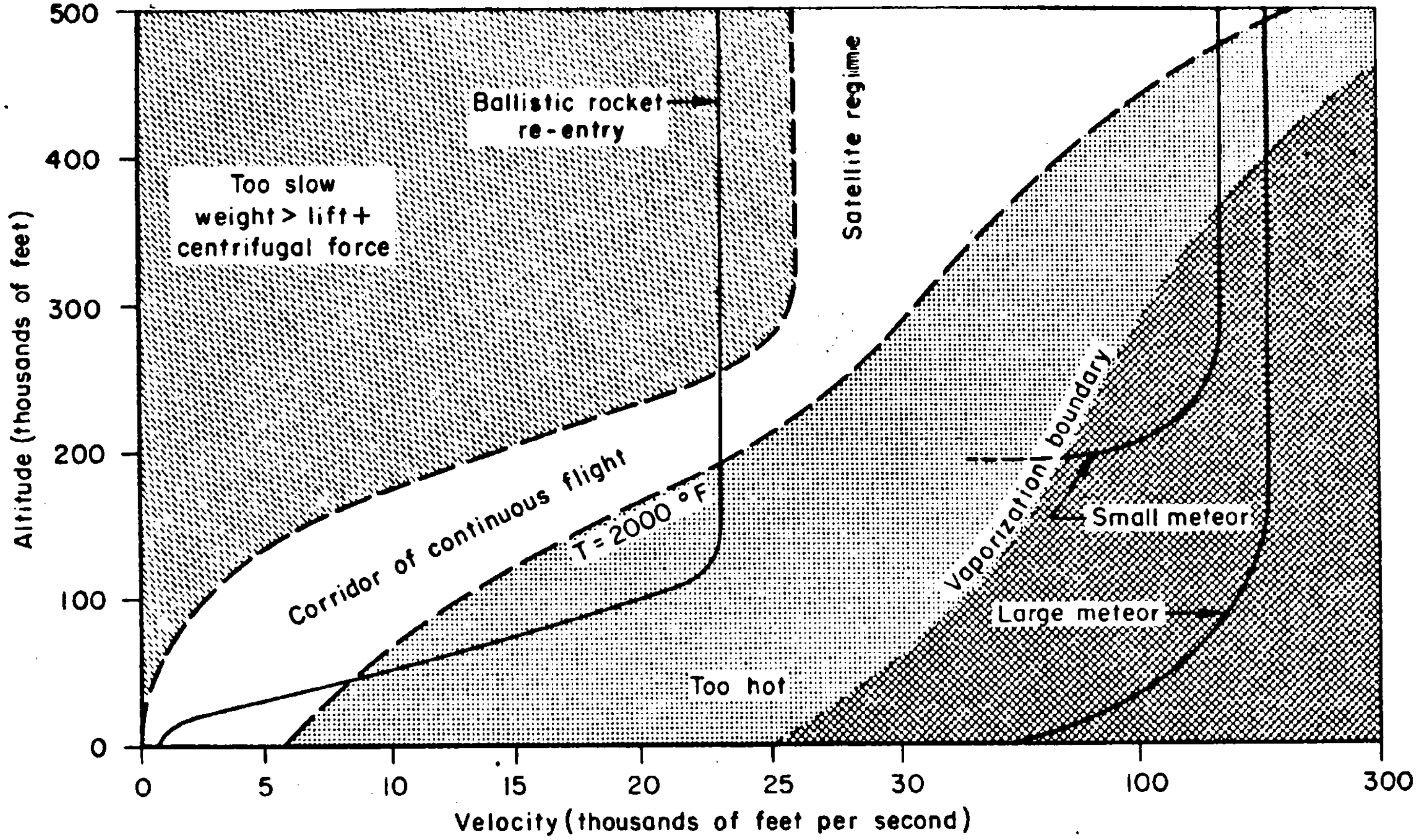


Fig. 9-8 —— Flight spectrum-extended

is a gradual process. The layman may like to consider hypersonic flow as starting at speeds of, say, about 5000 fps or Mach 5. To the aerodynamicist, the existence of hypersonic flow depends not only upon the speed, but also upon the thickness or bluntness of the body. However for most typical hypersonic vehicles, the dividing line still falls close to Mach 5, so we shall accept this rather than to go into aerodynamic details. In hypersonic flow the shock wave lies close to the surface of the body and frequently results in a nasty boundary layer - shock wave interaction problem, whereas in supersonic flow the nose shock wave is far enough from the body to avoid complications with the boundary layer, as indicated by Fig. 9-9.

The characteristic non-linearity of hypersonic flow is illustrated by the fact that the pressure (P) or lift varies with the square of the surface angle (δ) in hypersonic flow, whereas it varies linearly with angle in the supersonic regime.

Despite the complications of hypersonic flow, the extremely simple concept of Newtonian flow gives surprisingly good estimates of surface pressures. In Newtonian flow it is assumed that the gas stream consists of inelastic particles which maintain their speed and direction unchanged until they strike a solid surface, whereupon the component of momentum normal to the surface is lost and the particles move along the surface with the tangential component of momentum unchanged (Fig. 9-10). The shock wave is assumed to lie on, or follow, the surface of the body. For a flat plate inclined at an angle to the flow, the Newtonian pressure coefficient on the surface is

$$C_p = 2 \sin^2 \delta$$

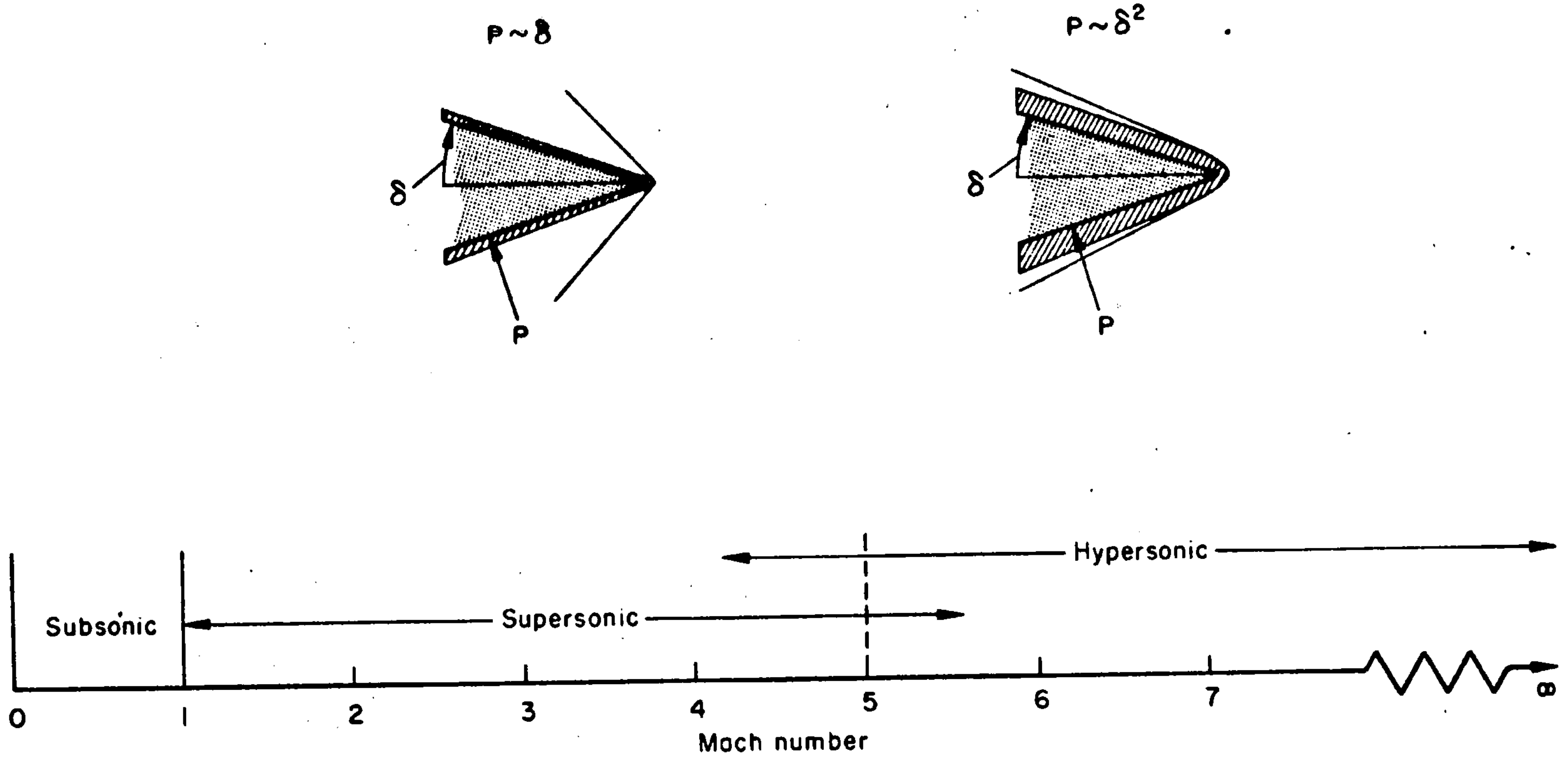
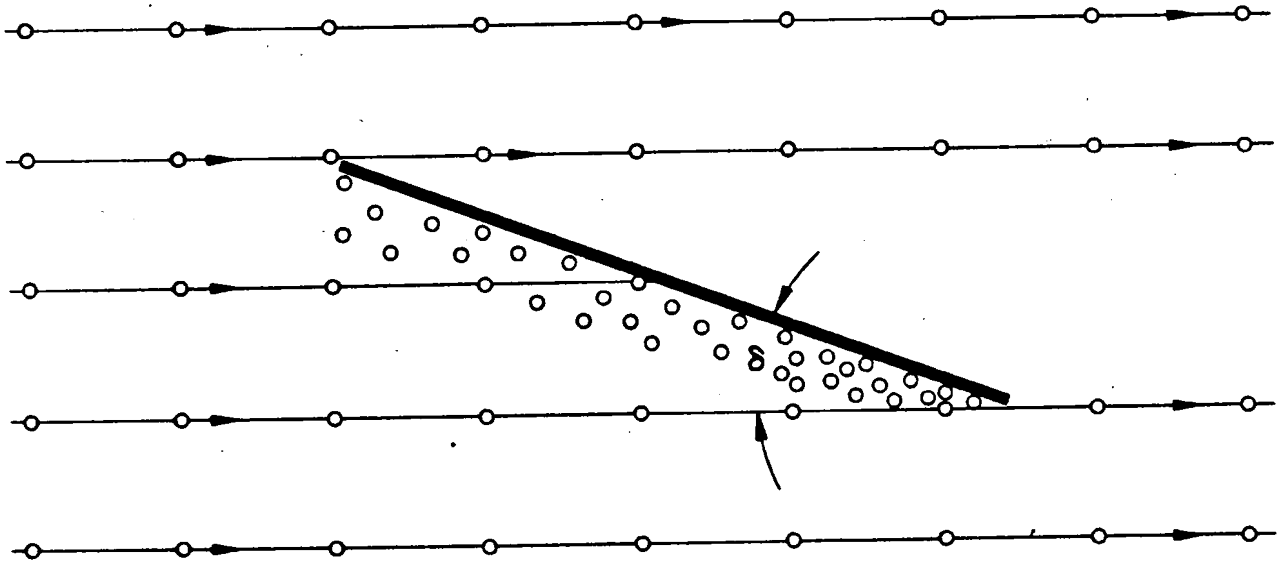


Fig.9-9— Aerodynamic regimes



$C_p = 2 \sin^2 \delta$

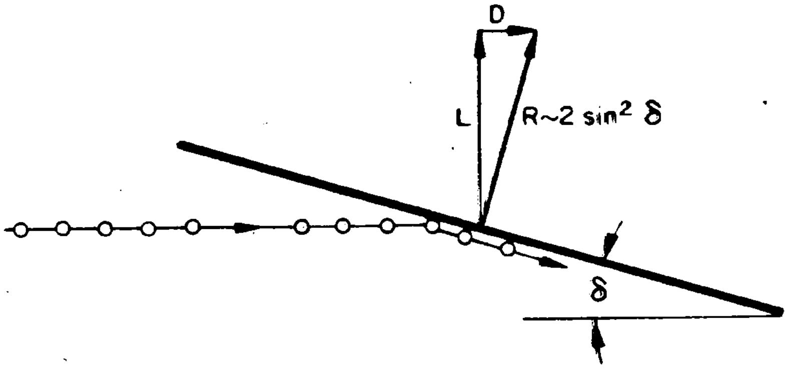
Fig. 9-10 —Newtonian flow

The concept of Newtonian flow can also be approached from the exact two-dimensional gas-dynamic equations by letting $M \rightarrow \infty$ and $\gamma \rightarrow 1$. Indeed the Newtonian flow concept applies rigorously only for these conditions. Fortunately, however, aerodynamic pressure coefficients approach their ultimate value asymptotically as Mach number is increased, so the simple Newtonian value finds wide practical application throughout the hypersonic regime.(1)(3)

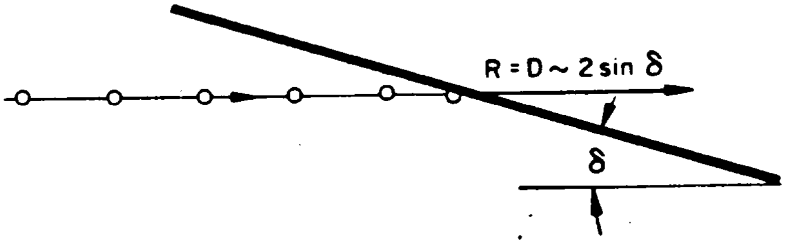
HYPERSONIC FLOW IN RAREFIED GASES - FREE MOLECULE FLOW

At altitudes above 100 mi (outside the effective atmosphere on the ballistic trajectory chart of Fig. 9-1), the atmospheric gas becomes so rarefied the continuum assumptions no longer apply. A slight modification of the Newtonian flow assumptions is required. The gas stream is again assumed to consist of inelastic particles which maintain their speed and direction unchanged until striking a solid surface. Upon impact, however, the gas particles lose their entire momentum to the surface, not just the normal component of momentum as in Newtonian flow. This produces a resultant force in the drag direction and no lift, whereas down in the continuum regime the resultant force is normal to the surface and has a lift component (Fig. 9-11). The fact of zero lift in a hypersonic, rarefied gas is sometimes overlooked. At lower velocities where the kinetic speed of the air particles becomes appreciable compared with the vehicle velocity, there is a small lift component in free molecule flow due to diffuse re-emission.

All aerodynamic forces in a rarefied gas are, of course, relatively small because of the low dynamic pressure, $1/2\ \rho U^2$.



Continuum



Free molecule flow

Fig. 9-11 —Resultant hypersonic forces

SURFACE HEATING IN HYPERSONIC FLIGHT

In the flight of a vehicle through the atmosphere, the body's kinetic energy is continuously converted to thermal energy in the air, and some of this thermal energy is transferred to the body (Fig. 9-12). The rate of conversion of kinetic energy to thermal energy and the rate of heat transfer to the vehicle surface increase approximately directly with air density and with the cube of the vehicle's velocity. Surface heating rates are thus most severe when high velocities occur at low altitudes; and they are much more severe than any heating rates experienced in current heat-transfer technology.

Below 20,000 ft/sec convective aerodynamic heating dominates, but at higher speeds the air temperatures and emission coefficients become large enough so that surface heating by thermal radiation from hot gas becomes appreciable.

The portion of the vehicle's kinetic-energy loss which is transferred to the surface as heat depends upon the body shape and the altitude (Fig. 9-13). It can be shown that a maximum fraction of one-half of the body's kinetic-energy loss may reach the body as heat. This occurs in flow situations where there is no shock wave, i.e., when the thermal energy appears in the air very close to the body. Shock-free flow occurs: (1) at very high altitudes in the free-molecular flow regime where molecules impinge directly on the surface and liberate heat energy; and (2) for very slender bodies at lower altitudes, in which case most of the thermal energy appears in the viscous boundary layer adjacent to the body surface. For blunter bodies in the lower atmosphere, the shock wave preceding the body heats a greater mass of air - but most of it does not get close enough to the body

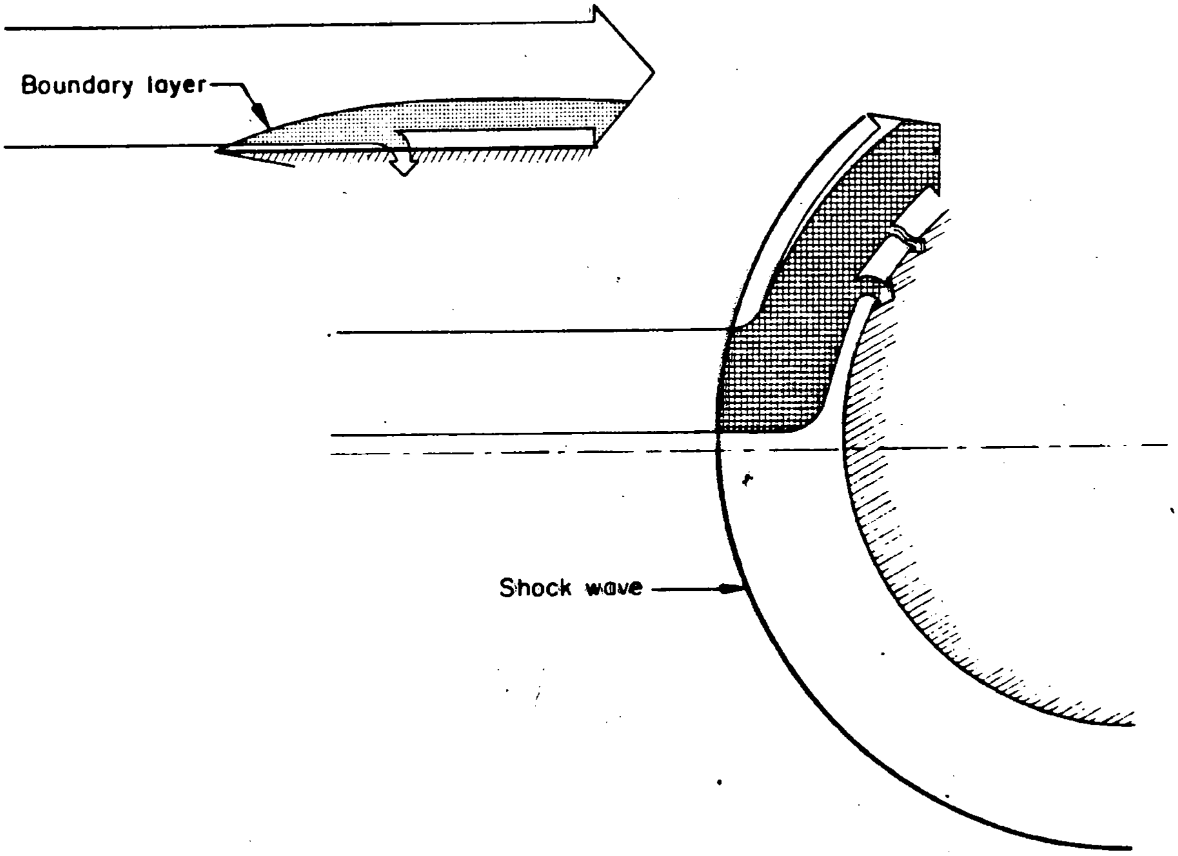


Fig. 9-12 —Kinetic to thermal energy conversion

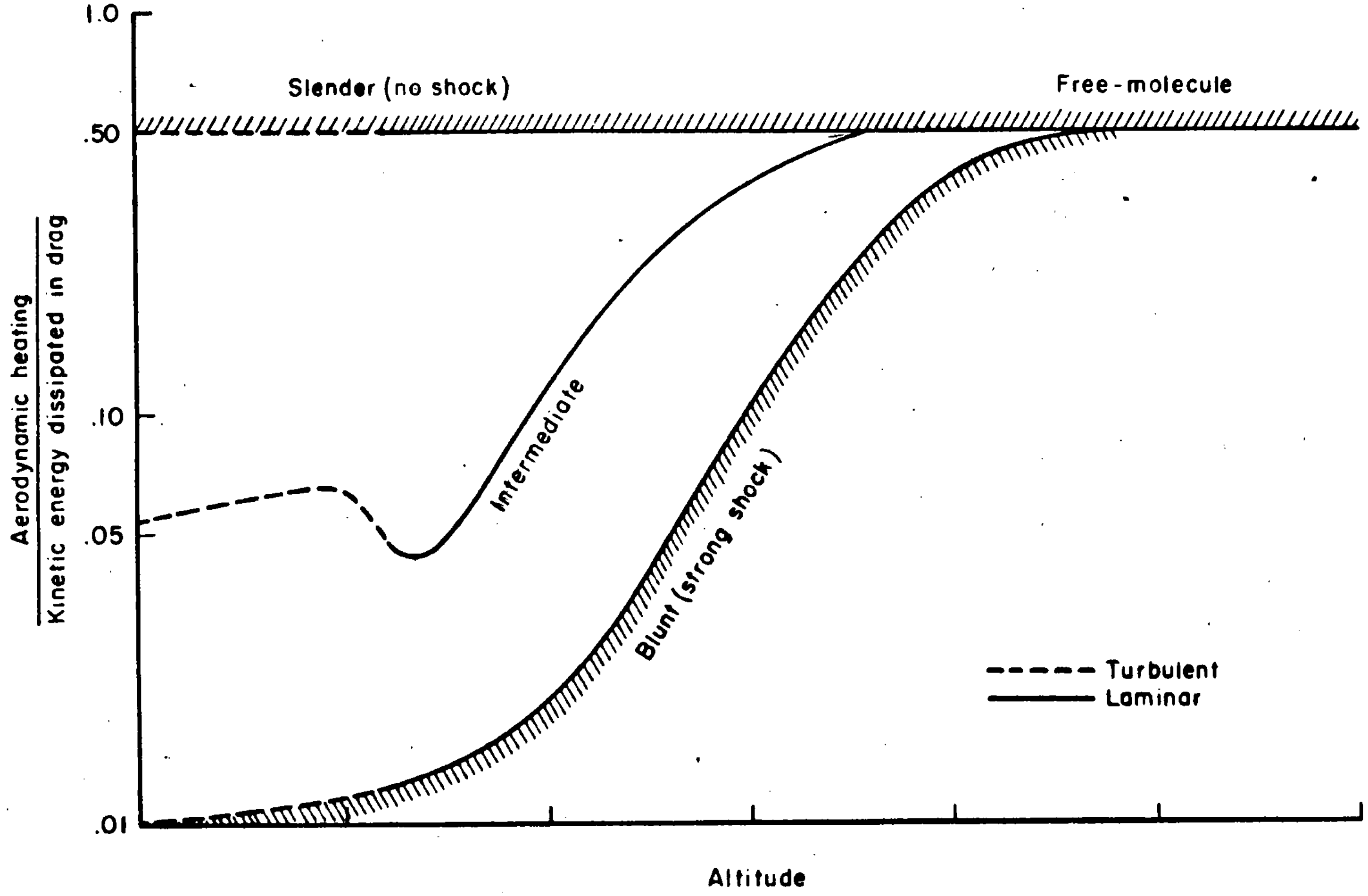


Fig. 9-13—Factors affecting surface heating "efficiency"

to transfer heat to the surface. In this case, the amount of heat transfer depends also upon the character of the flow in the boundary layer - whether laminar or turbulent. The turbulent boundary layer, occurring in the lower atmosphere, allows a much higher rate of heat transfer to the surface.

There are several ways of keeping the surface heating rates at tolerable levels:(4)

- Distribute the body's weight and energy over a large area to reduce the heating per unit area as well as to provide a large radiating surface.
- Use a blunt body to minimize the fraction of kinetic-energy loss transferred to the body.
- Arrange heating to occur in 'depths' of laminar region to minimize conversion 'efficiency.'
- Reduce the rate of Kinetic energy change, and hence the heating rate, by slow deceleration, e.g., glide rocket.

This subject is discussed at greater length in the following lecture.

CHEMICAL EFFECTS

Because the air is no longer a simple fluid, hypersonic aerodynamics is much more complex than lower-speed aerodynamics. Unusual chemical and physical phenomena occur in the violently heated air adjacent to a hypersonic vehicle. The high air temperatures cause excited states, radiation, chemical reactions, ionization, etc.

The left half of Fig. 9-14 illustrates this for the blunt body. Incoming molecular air may be dissociated in the high-temperature region behind the strong shock caused by the blunt body. Upon moving into the

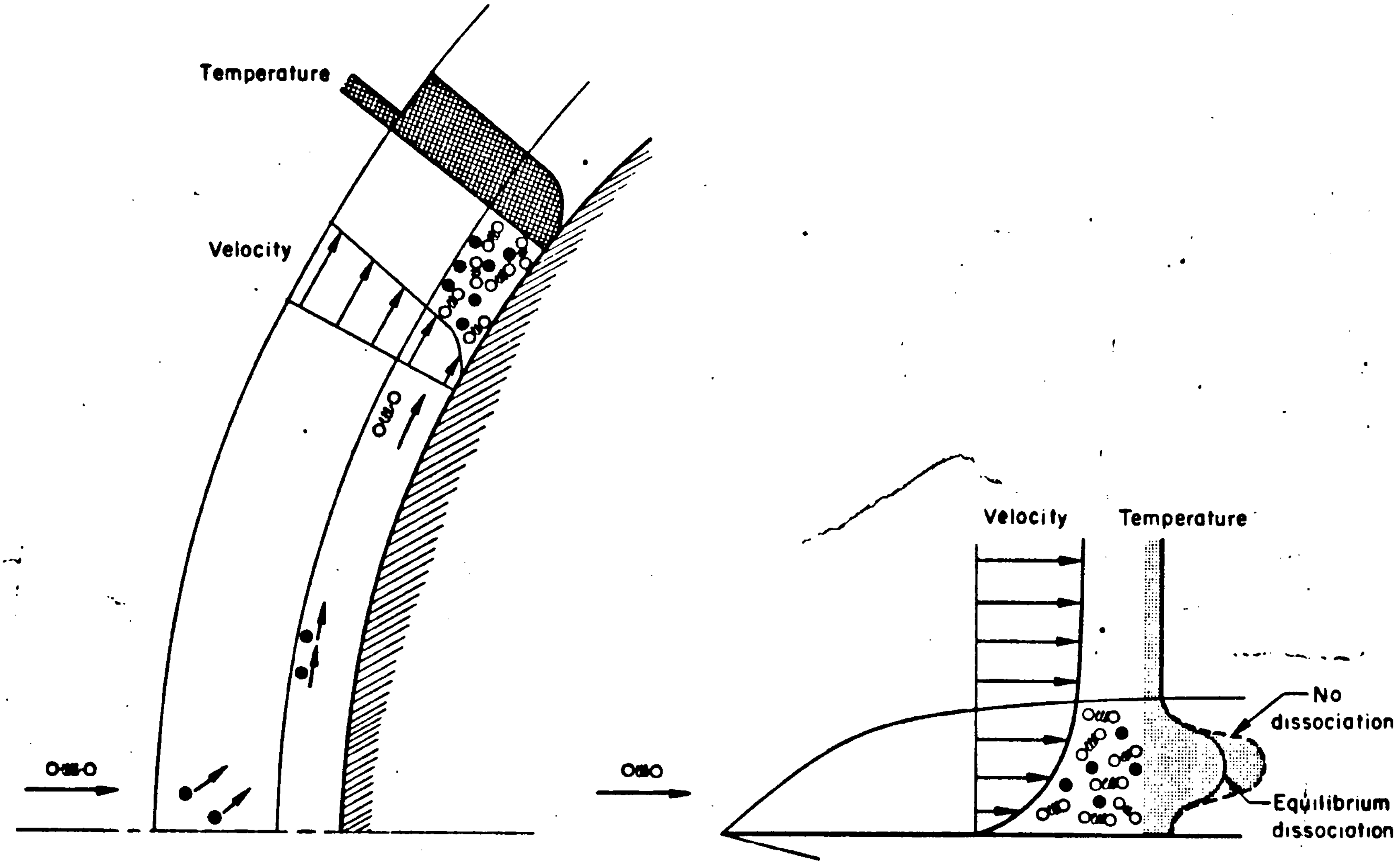


Fig. 9-14 —Chemical effects

boundary layer and close to the relatively cool wall, some of these atomic air particles may recombine, thus releasing energy as heat and complicating the over-all heat-transfer problem. The velocity and temperature profiles are indicated.

The right side of Fig. 9-14 shows the corresponding case for the slender body or flat plate. Here there is no shock wave but the temperature rise in the boundary layer may be great enough to cause some dissociation. Temperature profiles in the boundary layer are indicated for both equilibrium dissociation and no dissociation. Equilibrium dissociation reduces the peak temperature in the boundary layer with little change in the wall temperature for typical glide rocket vehicles.

Enough ionization may occur in a gas passing through a strong shock at speeds above 20,000 ft/sec to complicate radio transmission and heat transfer. Also a slight amount of ionization in the wake of a ballistic missile may make for easier detection and discrimination. Some surface protection materials become quite luminous on re-entry. For example, the Jupiter nose cone was reported to have been visible 90 mi away during re-entry.

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