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THERMOPHYSICAL ASPECTS AND FEASIBILITY OF A JUPITER ATMOSPHERIC ENTRY

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Report No. S-4

THERMOPHYSICAL ASPECTS AND FEASIBILITY OF A JUPITER ATMOSPHERIC ENTRY

by

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SUMMARY

Much of the information needed to understand the internal structure and development of the outer planets cannot be obtained unambiguously using current remote techniques. Spectroscopic and occultation measurements from flybys and orbiters, and ground-based observations can yield information which is pertinent mainly to the atmospheres above the clouds. And, unfortunately, those remote sensing techniques which do involve deep atmospheric penetration do not give composition data. An atmospheric probe offers the distinct advantage of acquiring not only composition, structure, and other data correlated spatially and temporally, but also information which cannot be obtained remotely.

The principal difficulty in successfully penetrating the upper atmospheres of the outer planets can be traced to the characteristically high entry velocities, to the difficulties in estimating vehicle performance, and to the major uncertainties and lack of information about such entries. At Jupiter, for example, the entry velocity would be in the range 48-60 km/sec. These velocities, which are several times larger than typical Earth entry velocities, imply at least a factor of ten increase in heat transfer magnitudes over those currently manageable in Earth and inner planet entries.

The objectives here are to determine on a preliminary basis the thermodynamic feasibility of outer planet entries, especially into Jupiter's atmosphere, and to delineate the major technical problem areas associated with them. The study concludes that a surviving entry into Jupiter's lower atmosphere is feasible and can be best accomplished using a grazing trajectory, but it also points out that there are many major assumptions inherent in this judgment. The approach consisted of first obtaining empirical expressions for the instantaneous vehicle heat absorption rates, and, secondly, estimating the total heat absorption over the trajectory together with the resulting mass loss. An IBM 7094 Fortran II computer program was employed to calculate instantaneous total heat absorption rates at the stagnation point. (It was assumed that such rates would be greater than the rates averaged over the whole vehicle.) The instantaneous rates were integrated over the entry trajectory, and mass loss estimates were derived from them using an assumed, constant heat of ablation (2500 cal/grams). A fractional ablated mass loss was then computed by comparing the mass lost by ablation with the original vehicle mass, assuming also a constant ballistic coefficient during entry.

In the process of obtaining heat transfer prediction schemes, several major technological problem areas, which must be developed in support of detailed outer planet entry studies, were elicited. These are:

Planetary atmospheric composition and structure, most especially the helium abundance

Theoretical and experimental helium and hydrogen radiative data and laboratory helium and hydrogen thermodynamic and transport data

Comprehensive hypersonic heat transfer prediction schemes (for radiation-dominated flow fields)

Ablator materials performance, particularly in a hydrogen environment, and as a function of initial shape.

Some of the more important problems specific to this study include:

Ablation induced changes in the ballistic coefficient

Influence of ablation products on heat transfer

Helium-hydrogen reactions

Ablator and ablation product radiative properties

Boundary layer gas injection benefits

Helium convective heating

Definition of free molecule and transition regimes in hypersonic flow

High 'g' structures and mechanical design

Upstream radiative heating

In order to assess the feasibility of individual entry cases, a concept of successful atmospheric penetration has been defined in terms of "survival criteria"; viz., that, at entry into the cloud tops, an entry probe retain at least 10 percent of its initial mass and that its velocity be no more than

1 km/sec. Within these criteria only grazing entry trajectories are clearly feasible. However, because of the conservatism used in the heat absorption estimates, the more objective conclusion is that in the context of these "survival criteria" grazing entries are always superior to angle or direct entries.

In the following figure are shown, for a Jupiter entry, the ablated mass loss compared to original vehicle mass, F_m, and the "terminal" (cloud top entry) velocity, V_t, versus the entry vehicle ballistic coefficient, B. The values of F_m greater than 1.0 are, of course, unreal. From these data it is evident that direct entries are non-surviving - either because of excessive mass loss at low B values or because of excessive terminal velocities at higher B values. Reflecting the strong influence of the high rotational speed of the planet, the grazing entries survive over a rather wide range of ballistic coefficients.

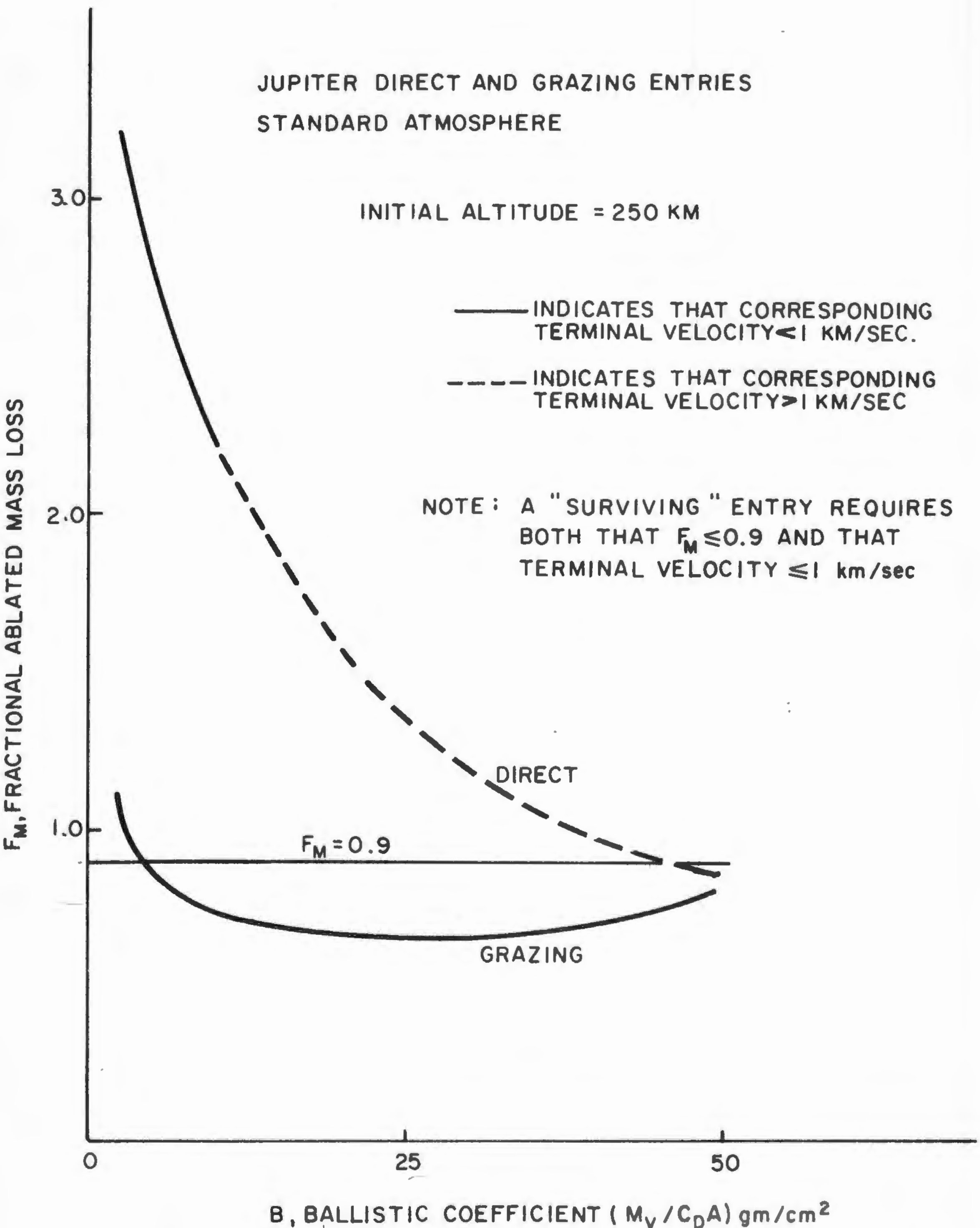

FIGURE S1. SURVIVAL RESULTS - FRACTIONAL MASS LOSS DUE TO ABLATION VS. BALLISTIC COEFFICIENT OF ENTRY VEHICLE.

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THERMOPHYSICAL ASPECTS AND FEASIBILITY OF A JUPITER ATMOSPHERIC ENTRY

1. INTRODUCTION

The objectives of this report are to obtain a preliminary assessment of the feasibility of outer planet atmospheric probes, and to identify major technical problem areas. Primary attention is given to Jupiter atmospheric entries. In the performance of this study many assumptions were made which profoundly affect the determination of feasibility of Jupiter atmospheric entry. It was recognized that it is of equal, if not greater, importance to point out the technological weaknesses necessitating these assumptions.

The interest in entering the atmospheres of the outer planets with probe vehicles derives in large part from the limitations of ground-based and other remote techniques to answer questions about the structure and composition of the planetary bodies and their atmospheres below the clouds. Conventional astronomy has identified conclusively several upper atmosphere constituents and has given rough quantitative estimates of their abundances. Prevailing evidence strongly suggests that Jupiter's atmosphere also contains elements and compounds which cannot be detected - at least in the current state-of-the-art - by conventional astronomical techniques.

Flyby and orbiter vehicles, which would have the effect and advantage of improving spatial resolution and of removing the absorption and scatter contributed by the matter between Jupiter and an Earth-based observer, offer little improvement, because the basic difficulty is that of planetary atmospheric extinction and thus limited penetration. Some measurements (e.g., most isotopic abundances) must be made in-situ.

An atmospheric probe can measure atmospheric properties either directly or indirectly, but its unique value is its ability to gather data continuously and simultaneously, so that the structure of the atmosphere can be determined. Outer planet probes also have the advantage that they penetrate the lower atmosphere, a region inaccessible to remote spectroscopic techniques.

All these considerations offer compelling reasons to determine whether deep penetration probes are feasible. This report treats the question of whether probes can survive the gasdynamic heating associated with Jupiter entries, thus restricting the question to one of thermodynamic feasibility. In this limited sense, feasibility is determined by the fraction of the initial vehicle mass which survives entry heating. Many important non-thermodynamic considerations, such as communications, terminal guidance, payload science, etc., are recognized but have been specifically excluded from this study.

The scope of this study has been limited to Jupiter entries, because Jupiter is the nearest and the largest of the outer planets, with the highest escape velocity of all the planets. Among the outer planets Jupiter is of primary interest. It is also a worst case on the basis of entry velocity. Furthermore, the conclusions reached regarding the feasibility of a Jupiter atmospheric entry should be qualitatively applicable to entries into the other outer planets.

In Section 2 the planetary data used in this study are summarized, with emphasis on Jupiter. Of particular importance are the planetary escape and rotational velocities, and the properties of the upper atmospheres (i.e., the atmospheres above the cloud tops). We discuss the general aspects of heat transfer in Section 3, and the problem of estimating hypersonic heat absorption. Also in Section 3, a scheme referred to as survival criteria is derived which forms the basis for determining the thermodynamic feasibility of deep penetration probes. Section 4 details the development of applicable hypersonic heat transfer prediction schemes, the synthesis of a heat transfer model, and the method of estimating mass loss. The results and a discussion of them, in Section 5, are presented in terms of peak heating, total integrated heat absorption and the estimated resulting mass loss. Finally, our conclusions and recommendations are given in Sections 6 and 7. These relate not only basic feasibility results but also point out important areas for future research activities.

2. PLANET CHARACTERISTICS AND DESCRIPTIONS

The planets Jupiter, Saturn, Uranus, Neptune, and Pluto are commonly called the outer or Jovian planets. Table 1 lists for each of these planets some of their physical and astronomical characteristics and the effects of these on the velocities of approaching spacecraft.

The ballistics and thermodynamics of planetary entry are sensitive functions of gasdynamic velocity and atmospheric density. In this section are indicated the important planetary characteristics which influence these parameters. The total inertial velocity, V_H, for example, is basic; it depends upon escape velocity, V_{esc} (measured at atmosphere entry), and VHP, the asymptotic velocity of approach to the planet, determined by launch date, launch energy, and trajectory. It is expressed by the relation

$$V_H^2 = \overline{VHP}^2 + V_{esc}^2, \quad (1)$$

in which

$$V_{esc}^2 = 2K/r \quad (2)$$

and,

K = Gravitational constant (km^3/sec^2).

r = Radial distance from planet center to vehicle (km).

The gasdynamic velocity, V_E*, however, is the velocity of

*In the remainder of this report the subscript is dropped, and it is understood that the symbol V (= V_E) means gasdynamic velocity.

Table 1

FACTORS AFFECTING PLANETARY ENTRY VELOCITY

Planet	Perihelion Distance (AU)*	Optical Radius r_{pl}* (km)	Surface Rotational Velocity V_{rp}* (km/sec)	Surface Escape Velocity V_{esc}* (km/sec)	Typical Hyperbolic Approach Velocity VHP** (km/sec)	Total Entry Velocity V_H (km/sec)	Initial Gasdynamic Entry Velocity V_E: Direct, $-\gamma_I = 90°$ (km/sec)	Initial Gasdynamic Entry Velocity V_E: Grazing, $-\gamma_I \approx 0°$ (km/sec)
Jupiter	4.95	71,350	12.653	59.60	7.0	59.90	61.33	47.25
Saturn	9.0	60,400	10.300	35.435	7.5	36.27	37.58	25.97
Uranus	18.23	23,800	3.840	22.083	12.0	25.13	25.44	21.3
Neptune	29.80	22,200	2.583	25.145	12.0	27.85	27.98	25.3
Pluto	29.69	~3,000	~0.03	3.8-5.0	15.0	-	-	-
Earth	1.00	6,378	0.465	11.2	0-6***	11.2-12.7	11.2-12.9	10.7-12.2

*Allen (1955).

**Based on flight times: 800 days to Jupiter; 1,300 days to Saturn; 2,200 days to Uranus; 5,000 days to Neptune; and 16,000 days to Pluto (Narin and Pierce 1964).

***For comparison, typical of lunar return.

interest because it determines ballistic and thermodynamic performance. Its initial (drag-free) magnitude depends only upon V_H, the atmospheric rotation rate, and the flight path angle, and is computed from the expression:

$$V^2 = V_E^{\ 2} = V_H^{\ 2} + V_{rp}^{\ 2} - 2V_H V_{rp} \cos \gamma_I \ , \qquad (3)$$

in which

V_{rp} = Equatorial atmospheric rotation velocity

= $r_{P\ell} \cdot \Omega_{P\ell}$, (km/sec)

$\Omega_{P\ell}$ = Equatorial planet rotation rate (rad/sec).

γ_I = Inertial flight path angle (deg).

The vector relationships between these quantities will be explained more fully in Section 3. Characteristic velocities and typical VHP values are given for each of the outer planets in Table 1. V_H has been calculated using Equation 3 for direct ($-\gamma_I = 90°$) entries and for grazing ($-\gamma_I \approx 0°$) entries. The strong influence of planet rotation rate on gasdynamic entry velocity is very noticeable. The range of gasdynamic entry velocities, in Jupiter's case, for example, is actually 59.90 $\pm$ 12.65 km/sec; if the vehicle enters directly in the direction of planet rotation (along the equator), it is 47.25 km/sec; and in the retrograde direction, 72.55 km/sec. Hence, the nominal range of Jupiter entry velocity is, for practical purposes, 48-60 km/sec.

The structure of a planetary atmosphere (its composition, density, and temperature versus altitude) strongly influences the ballistic behavior of a vehicle and the entry heat generation. Both the gasdynamic drag and heat generation depend upon local atmospheric density, vehicle velocity, local atmospheric composition, and vehicle characteristics.

A gross measure of the structure of an atmosphere is the scale height, β^{-1}, which is the vertical height in which the density changes by a factor of e, and is defined by the expression

$$\beta = \frac{\overline{M}g}{RT} \tag{4}$$

The quantity $\overline{M}$ is the average molecular weight of the atmospheric constituents; g, the acceleration of gravity; R, the universal gas constant; and T, the absolute temperature. For an isothermal atmosphere with constant composition, the density, ρ, at any altitude, h, is then

$$\rho = \rho_o e^{-\beta h} \tag{5}$$

In Equation 5, ρ_o is a "sea level" or reference density.

Jupiter's atmosphere may be thought of in terms of an upper atmosphere and of a lower atmosphere, with the visible clouds defining the interface. Structure information about the upper atmosphere is uncertain and incomplete. Only temperature data exist for its lower atmosphere and are difficult to associate with a specific distance below the cloud tops. The elemental composition data in Table 2 represent a synthesis of the data of several investigators (Rank et al. 1966, Kuiper 1952,

Table 2

ATMOSPHERIC COMPOSITION AND STRUCTURE DATA

Planet	Elemental Abundances (km-atm)* H_2	He	CH_4	NH_3	Isothermal Temperature T_I (°K)	Blackbody Temperature T_B (°K)	$\frac{\overline{M}g}{RT_I}$ (= β) (km^{-1})	Scale Height β^{-1} (km)
Jupiter	200	36	0.200	0.040	88	173	0.087	11.3
Saturn	355	64	0.35	**	68	127	0.051	19.7
Uranus	135	373	3.5	**	47	90	0.093	10.8
Neptune	230	640	6.0	**	38	72	0.115	8.70
Pluto	-	-	-		60	63		

*1 km-atm = 2.687×10^{24} molecules/cm^3

**Undetected (i.e., $<10^{-4}$ km/atm)

Owen and Greenspan 1967, Owen 1967); they are current estimates of the composition of the upper atmospheres of the outer planets. The data in Table 2 are not necessarily precise; because of the nature of the measurement techniques, errors of ± 100 percent are not uncommon. Hence, we urge caution in adopting these data for additional calculations. They have been presented mainly to indicate typical values for these quantities (Baum and Code 1953, Spinrad and Trafton 1963).

In Table 2, the Jupiter ammonia (NH_3) data are from Kuiper (1952). NH_3 has not been detected on any of the other planets, even though its threshold for measurement is 10^{-4} km-atm. Also in Table 2 is the isothermal temperature, T_I*, which is the temperature of the stratosphere; the value for Jupiter is from Taylor (1965), and those for the other planets, from Kuiper (1965). The temperature of a blackbody receiver located at the planet's distance from the Sun is the blackbody temperature, T_B (Allen 1955); it has been shown for comparison. Finally, in Table 2 we list the calculated scale heights using Equation 4.

Figure 1 illustrates the "Jupiter Standard Atmosphere," a model atmosphere we have adopted for Jupiter. It is by no means certain that this model is valid, although it seems to be a logical construction from available information. Temperature, composition, and other data indicate that the clouds surrounding Jupiter are condensed ammonia crystals.

*The temperature of the stratosphere, the atmosphere above the altitude at which the lapse rate, dT/dh, becomes negligible.

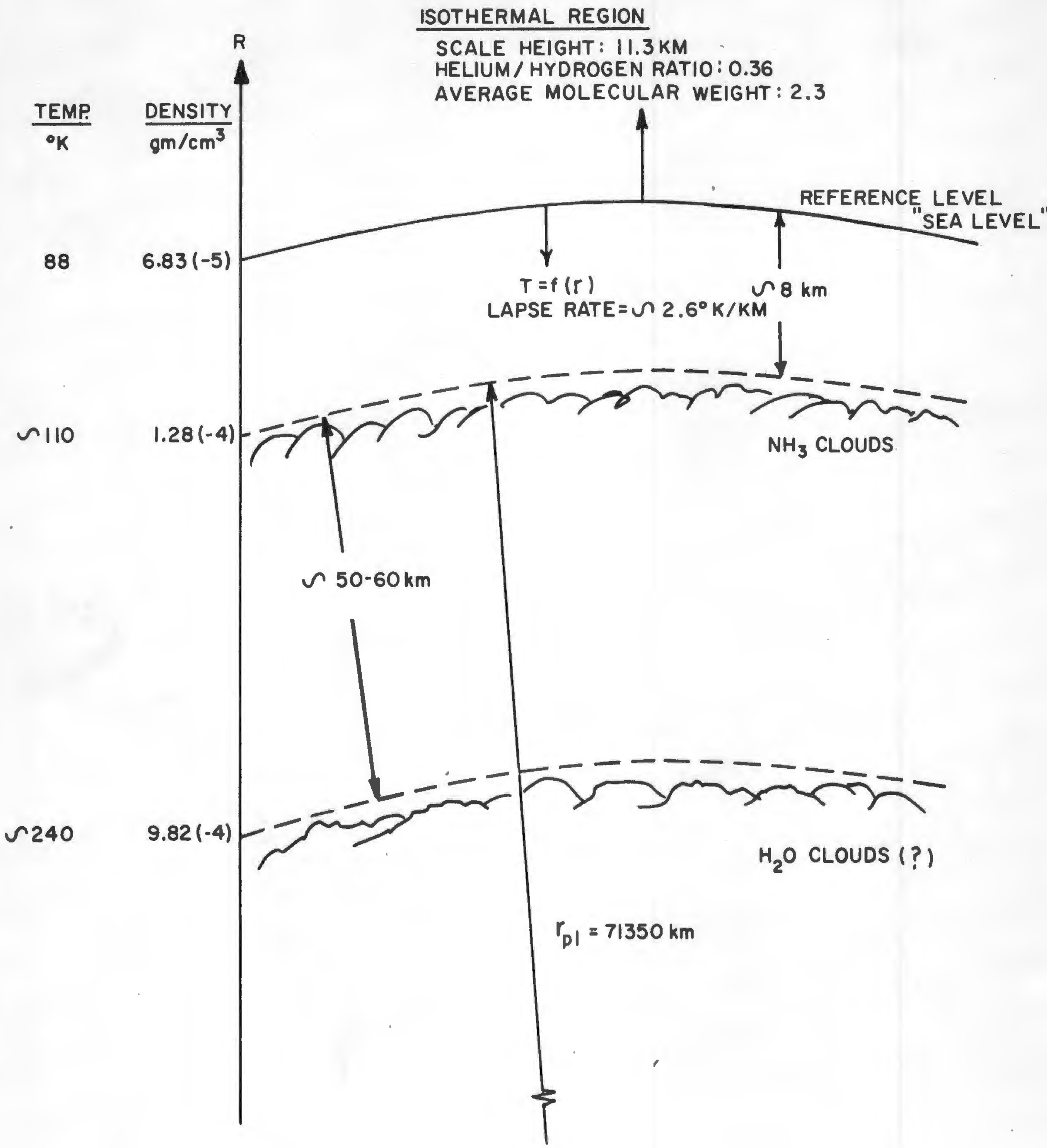

FIGURE 1. JUPITER STANDARD ATMOSPHERE

Since the thermodynamic properties of ammonia are known, intelligent estimates can be made of the temperature and pressure conditions at the cloud tops. Analogous treatments of other data yield the remainder of the information contained in Figure 1. The model presents a reasonable picture of Jupiter's atmospheric structure in light of existing information. This model, while pertinent specifically to Jupiter, should apply qualitatively to other planets. Table 2, it must be remembered, refers to the atmosphere <u>above</u> the clouds. The atmosphere below the clouds remains virtually unknown.

- We emphasize the need for better upper atmosphere data for the outer planets.

3. GENERAL HEAT TRANSFER AND BALLISTIC CONSIDERATIONS

Basically there are three regimes of hypersonic flow: free molecular, transition, and continuum. The character of a vehicle's ballistic and thermodynamic responses in each are quite distinct.

The general expression for heat transfer rate is

$$q = C_H \left(\frac{1}{2} \rho_\infty V^3\right) = C_H \cdot q_\infty , \qquad (6)$$

in which

q = Total heat transfer rate to vehicle, cal/cm^2-sec

$C_H = C_C + C_R$

C_C = Convective heat transfer coefficient

C_R = Radiative heat transfer coefficient

ρ_∞ = Ambient atmospheric density, gm/cm^3

V = Gasdynamic velocity, cm/sec

$q_{\infty} = (\frac{1}{2}\rho_{\infty} V^3)$ = free stream enthalpy flux, cal/cm^2-sec.

The free stream enthalpy flux is the total rate of flow of kinetic energy in the flow stream. The factor, C_H, the heat transfer coefficient, ranges from nearly unity in free molecular flow to the order of 10^{-3} to 10^{-5} in the continuum regime.

In this section we will discuss hypersonic heat transfer in general and indicate the various processes comprising it. The more detailed development of a heat transfer model will be given in the next section. Consistent with the stated objectives, we will identify the principal problems attendant to the hypersonic ballistics and thermodynamics of Jupiter entries.

3.1 Free Molecular Heating

In the free molecular flow regime the heat transferred to the vehicle can be a substantial fraction ($C_H \sim 0.1$-0.8) of the total kinetic energy of the free stream. It would be important here if free molecular heating (e.g., at velocities up to 60 km/sec) persists for long times. A large amount of heat then would be generated in the vehicle with little compensating velocity reduction. Ideally the vehicle should spend a minimum of time in this regime.

Free molecular interactions occur when a molecule striking a surface is reflected and does not re-encounter that surface before reaching equilibrium. The molecules colliding with a surface interact with it independently of one another.

The situation is not qualitatively different when the surface also is moving. The energy and momenta transfer will depend upon relative velocities; and as long as each molecule interacts individually with the surface, the energy exchange will be a large fraction of the total kinetic energy of the surface and the molecule. The surface will experience an increase in temperature as a result. The thermal energy absorbed in free molecular flow can be estimated with much greater certainty than can the limits in which free molecular flow exists.

Throughout this report we refer to free stream enthalpy rate, q_{∞}, free molecular heating rate, q_{FM}, and maximum (effective) free stream heating rate, q_F. To avoid confusion, we define q_{∞} as the total enthalpy rate in the free stream ($\frac{1}{2} \rho_{\infty} V^3$). We define q_{FM} as $C_H \cdot q_{\infty}$ within the regime of free molecular heating. We arbitrarily assume that the maximum fraction of the free stream enthalpy rate which can be transferred to the vehicle in any flow regime is 0.5. Thus q_F is 0.5 q_{∞}, but in this case represents an upper bound on the heat transfer rate. To distinguish, note that q_{FM} is the estimated actual heat transfer rate in free molecular flow, while q_F acts as an upper bound to heat transfer estimates in all regimes of flow.

3.2 Transition Regime Heating

Estimating heat transfer in the transition flow regime has always been a particularly difficult problem because the shock layer changes very rapidly in geometry and thermodynamic structure. Nonetheless, we are faced with the necessity of estimating the heating contribution in the transition regime. The heat transfer coefficient C_H varies in this regime from about 0.5 initially to somewhere in the region of 10^{-4} at the inception of continuum flow.

We require some idea of the importance of this regime in terms of heat transfer rates. The velocity of a Jupiter entry spacecraft is of the order of 48-60 km/sec. The thermal velocity of Maxwellian molecules with a molecular weight of 2.0 at Jovian upper atmosphere temperatures ($\sim$88°K) is 0.85 km/sec. The extremely high ratio of vehicle velocity to average ambient molecular velocity implies effective capture of all molecules encountered in the flight path. Until the density of these "captured" molecules is such that the oncoming flow stream interacts principally with the "captured" shock layer, rather than with the vehicle body, the flow will be in the transition regime.

We can estimate the length of time the vehicle will spend in this regime by calculating the time required in vertical descent to generate a weak shock layer. This will be the time it takes to sweep out enough molecules in the vehicle's path such that their accumulated density will result in a mean free path roughly the same as the vehicle's radius. For a radius of 0.5 meter and a shock layer thickness of 10 cm this density would be 5×10^{-12} gm/cm^3. The vehicle will sweep out a number of molecules equivalent to this density when it has descended to an altitude at which the ambient density is of this order, assuming no molecules escape.

It can be shown that the altitude change in which the accumulated density of molecules reaches 5×10^{-12} gm/cm^3 is very much less than the scale height, β^{-1}, and in general, the altitude change, Δh, corresponding to this swept out density is such that $\Delta h \ll \beta^{-1}$. This reasoning suggests that the shock layer develops in a time $\ll \beta^{-1}/V$ once significant ambient densities are reached. For Jupiter's standard atmosphere $\beta^{-1} \approx 11$ km, so that for $V = 60$ km/sec, the shock layer is developed in a time < 0.25 sec. This is a small fraction of the total entry time and because the shock layer is developed at very low densities, an even smaller fraction of the total entry heat absorption is involved.

In a somewhat analogous manner, the same qualitative result may be obtained for grazing entries. The difference is that the time to descend a scale-height in altitude is usually at least an order of magnitude longer than in direct entry. But since the "effective capture" of enough molecules to form a shock wave depends on ambient density, the portion of the trajectory in which free molecular and transition regime heating will be important is almost negligible compared to total entry time. This conclusion results from the fact that shocks will form at very low densities ($\sim 10^{-13}$ gm/cm^3) and thus at relatively high altitudes. The maximum transition time, and the altitude at which a shock layer is evidently formed, suggest that both free molecular and transition heating will be negligible. Our succeeding discussions will not consider them further.

The important question is: What are the actual density and velocity criteria or conditions for the onset of a shock layer (the end of free molecular flow), and when is the shock layer fully developed?

3.3 Continuum Heating

In the continuum regime the molecules of the oncoming flow stream interact with the vehicle's shock layer rather than with the vehicle. Continuum heating thus refers to the total heat exchange between the shock layer and the vehicle. Ordinarily, convective laminar heating would be the dominant heat transfer process. But in the range 48-60 km/sec, many other processes come into play. Thermal radiation from the shock layer will be a principal heat transfer process (i.e., 20-80 percent total heat transfer). Diffusion of chemical species through the boundary layer, ion recombination at the vehicle's surface, ablation product radiation, chemical and physical reactions liberating radiant energy, laminar and turbulent convection, non-equilibrium radiation, and many other processes contribute to the total heat transfer to the vehicle.

The heat transfer predictions in this study nevertheless include only thermal radiation from the bow shock and laminar convective heating in the stagnation region. With the intent to generate only a "first look" at the overall Jupiter entry problem, we have not sought detailed descriptions of any of the above processes. More than one species of atmospheric gases and more than one ablator component immeasurably complicate these descriptions.

We assume from previous considerations that the shock layer in the continuum regime is fully developed. There are, however, many other necessary assumptions to be made; and it is very important to emphasize those which arise from deficiencies in the state-of-the-art of hypersonic heat transfer and to distinguish them from those made simply to facilitate calculations. These assumptions are stated and discussed in Appendix A. In discussing them we have noted the probable effect of each on the heat transfer estimate. Most assumptions tend to be conservative; that is, the effect of the assumption should be an over-prediction of the heat transfer rate. A summary of the assumptions is given in Table 3.

3.4 Survival Criteria

Whether a vehicle can physically survive the total entry environment is only part of the question of feasibility. In addition, we recognize several other criteria for determining feasibility. The survival criteria in their simplest form reduce to the requirements that the vehicle velocity at entry into the cloud tops be less than 1 km/sec and that the surviving mass fraction be at least 0.1. Without these or similar criteria, mission feasibility judgments would be meaningless.

Table 3

SUMMARY OF IMPORTANT HYPERSONIC HEAT TRANSFER ASSUMPTIONS

Assumptions of Necessity

A. Optically thick shock layer

B. Uncoupled heat transfer processes

C. Chemically inert ablation products

D. Negligible ablation product heat transfer

E. Chemically inert atmospheric constituents

F. Negligible surface ion-electron recombination

G. Constant ballistic coefficient

H. Constant composition of atmosphere and negligible heat transfer effect of minor constituents

Assumptions of Convenience

I. Typicality of stagnation point heating

J. Negligible vehicle re-radiation

K. Negligible vehicle heat capacity

L. Negligible vehicle wall enthalpy.

The latter criterion is completely arbitrary. The criterion setting an upper limit to the vehicle velocity at entry into the cloud tops (chosen at 1 km/sec) is in appreciation of the possibility of severe erosion by cloud crystals, and to be certain that ionization effects will not disrupt probe experiments in the lower atmosphere. Since a most important phase of the probe mission is its descent through the lower atmosphere, it further seems logical to maximize the time the vehicle will take to traverse it. Therefore, the less the "terminal velocity" (velocity at entry into the clouds), the longer are the effective measurement and communications times. At velocities greater than 1 km/sec the probe may not have emerged from the communications blackout, and the ionization sheath also may interfere with the payload measurements. Also, since there is literally no information regarding the structure of Jupiter's lower atmosphere, a rational design of a probe specifically taking account of the lower atmosphere is virtually impossible.

3.5 Entry Ballistics

An IBM Fortran II digital computer program was used to solve the equations of motion of a vehicle in a planetary atmosphere; the program assumes a spherical planet and takes into account the planet's rotation. The parameters include VHP, the hyperbolic excess velocity; γ_I, the inertial flight path angle, which is defined at h_o, the initial altitude; h_p, the altitude (vacuum miss distance) at perijove; ρ_o, the reference ("sea level") density, here taken at the visible cloud tops (see Fig. 1); β^{-1}, the atmospheric scale height; and B, the ballistic coefficient. Planet constants, heating expressions, and related values are treated as constants of the program. The program produces as output instantaneous values of velocity, acceleration, ambient density, altitude, and heat absorption.

The terms "grazing" entry, "angle" entry, and "direct" entry which occur quite frequently in subsequent discussions all refer to entry in the equatorial plane and have the following meanings: Grazing refers to a ballistic trajectory whose distance of closest approach is in the planet's sensible atmosphere, and would otherwise miss the planet, were it not for eventual capture due to atmospheric drag. Angle entries ($0 < -\gamma_I \leqslant 90°$) are ballistic entry trajectories which pass through the planet and thus would result in impact. Direct entries are special cases of angle entries in which the vehicle follows a radius vector (i.e., $-\gamma_I = 90°$). It should be noted that the flight path angle in grazing entries $-\gamma_I = 0°$, is not an unambiguous quantity. The equivalent grazing entry parameter is the periapsis altitude, h_p, which must be specified before a unique value of $-\gamma_I$ can be calculated. These general relationships are depicted in Figure 2.

The equations of motion in an inertial frame of reference and with fixed planet coordinates are:

$$\dot{V}_r = \omega^2 r - Kr^{-2} + a_r, \text{ and}$$

$$\dot{\omega} = r^{-1} (a_t - 2V_r)$$

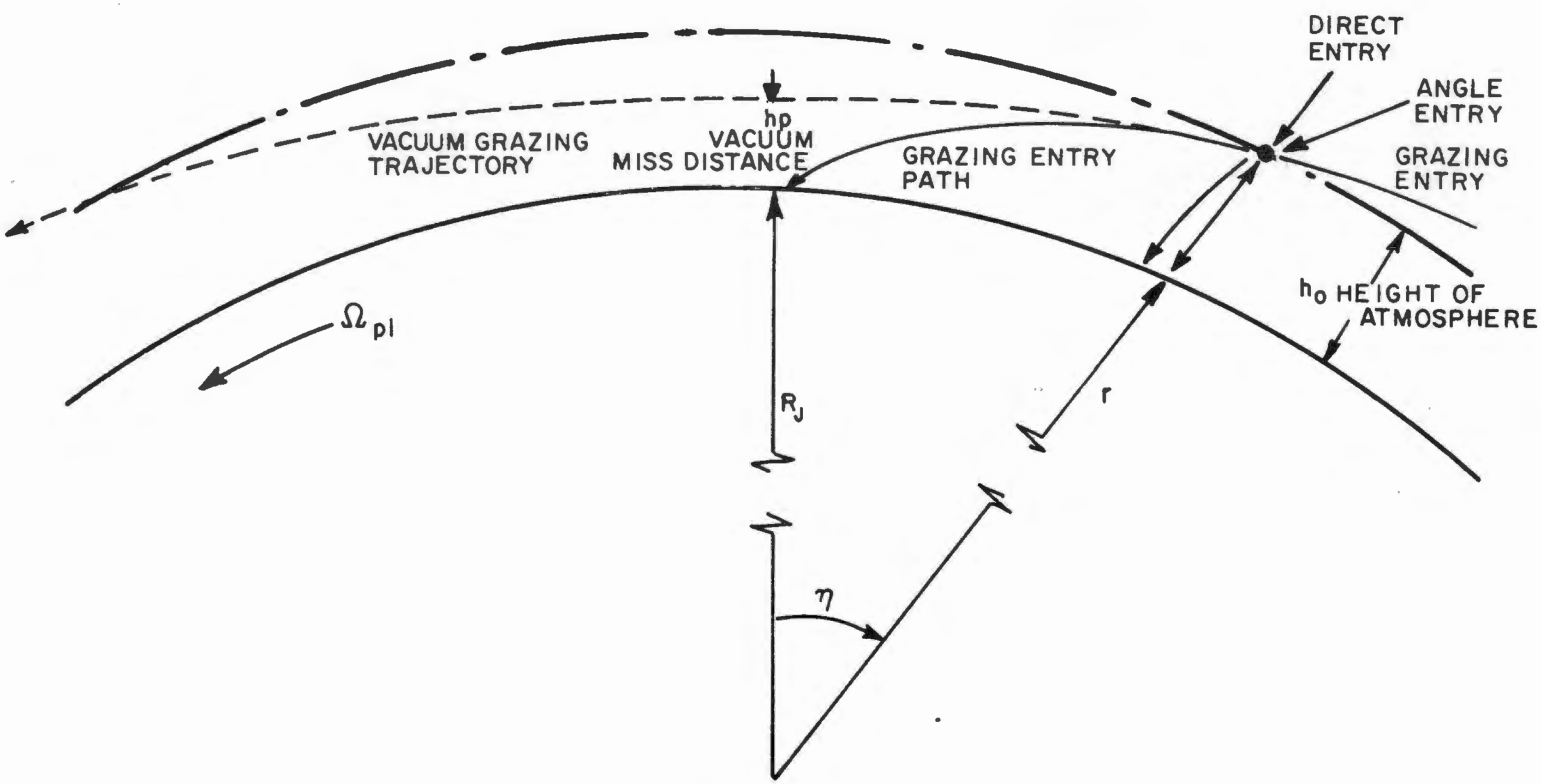

FIGURE 2. GENERAL PLANETARY ENTRY TRAJECTORIES

in which

$\dot{V}_r$ = Vehicle acceleration resolved in radial direction

ω = Inertial rotation rate of vehicle with respect to fixed planet

$\dot{\omega}$ = Vehicle acceleration resolved in tangential direction

r = Radial distance from planet center to vehicle

K = Planet gravitational constant

a_r = Radial component of gasdynamic acceleration

a_t = Tangential component of gasdynamic acceleration.

For a planet with a rapidly rotating atmosphere the above equations of motion must be supplemented by those describing the effective gasdynamic velocity. These are

$$V = \tan^{-1} V_r/(V_t - r \cdot \Omega_{P\ell}), \text{ and} \tag{7}$$

$$V = V_r/\sin \gamma_E \ , \tag{8}$$

where

γ_E = Gasdynamic flight path angle

V_r = Component of inertial velocity in radial direction

V_t = Component of inertial velocity in tangential direction

$\Omega_{P\ell}$ = Equatorial planet rotation rate

V = Gasdynamic velocity of vehicle.

The vector relationships of these quantities are diagrammed in Figure 3.

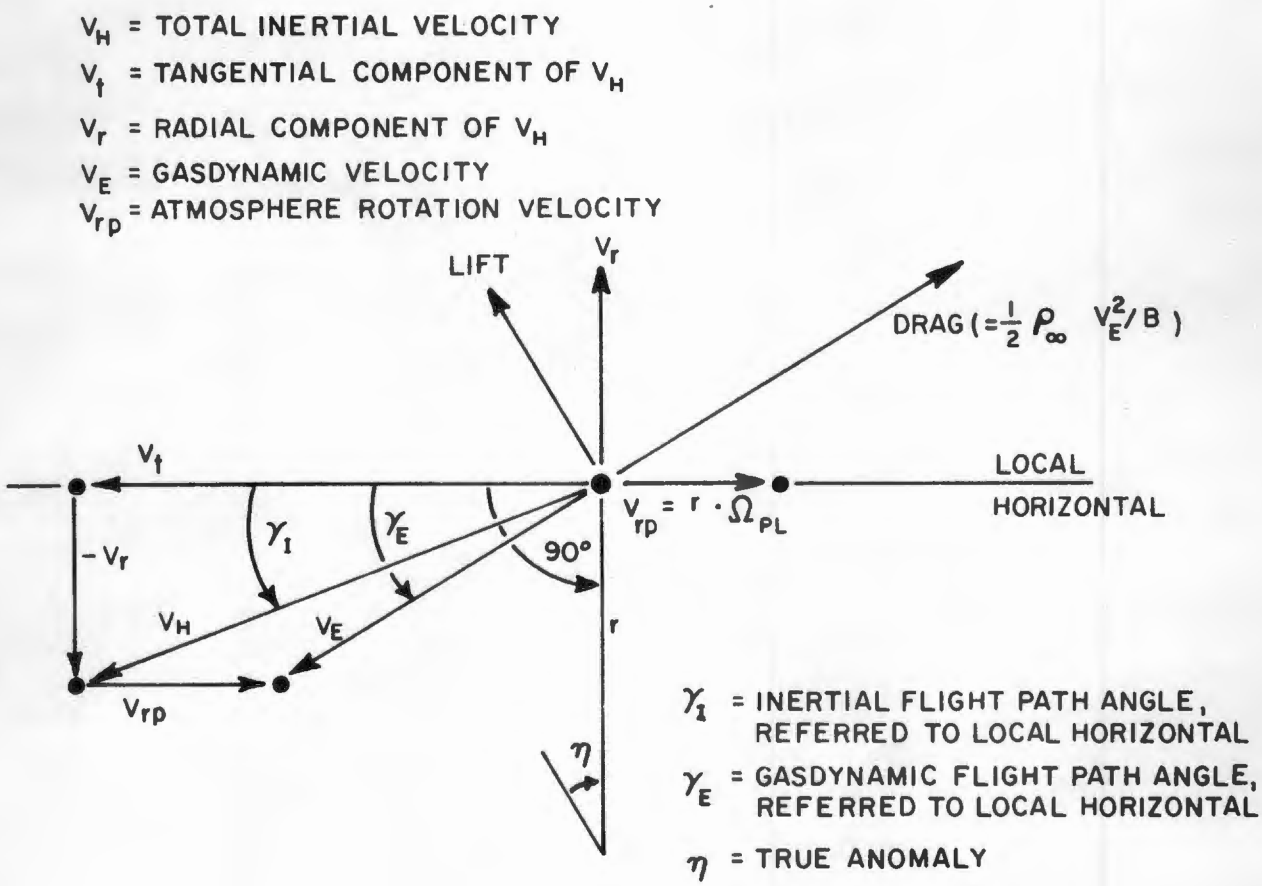

FIGURE 3. ENTRY VELOCITY RELATIONSHIPS FOR ROTATING ATMOSPHERES

Because of the high radial rotation rate of Jupiter, the gasdynamic velocity can differ substantially from the inertial velocity, depending upon flight angle. The two must be distinguished because the inertial velocity is governed by inertial forces, whereas the vehicle's interaction with the atmosphere is determined solely by gasdynamic considerations.

In the computer program a grazing entry trajectory not resulting in planetary capture is detected by calculating the orbital elements when the vehicle re-attains the initial entry altitude (300 km), after passing the (vacuum) perijove, h_p. If the eccentricity is 1.0 or greater, the vehicle is on an escape trajectory. An eccentricity of less than 1.0 indicates a multiple pass entry, and the program calculates the new orbital elements; if the orbital period is 10^7 sec or less, it calculates the location of the next entry point into the atmosphere and the flight parameters at that point. The program calculates the ballistic and thermodynamic quantities whenever the vehicle altitude is below 300 km. Thus each pass of the multiple pass entries is described, until the vehicle reaches zero altitude (the planet cloud tops). The actual number of passes a vehicle makes before achieving an impact trajectory is recorded in the program.

4. HEAT TRANSFER PREDICTIONS

In this section we will separately formulate and discuss the convective and radiative heat transfer expressions used in the computer programs, expressions which would be consistent with our assumptions and of the form:

$$q = C_1 \cdot \rho_\infty{}^a V^b . \qquad (9)$$

We prefer this form because ρ_∞ and V are natural parameters. A major goal of this section is to identify key problem areas in the development of heat transfer models and to give them perspective.

4.1 Literature Searching - Entry Technology

Entry into the atmospheres of Earth and the planets (see Bibliography) has been discussed at great length by many authors. A report by D. R. Chapman (1959) is the only one, however, which seriously considers a Jupiter entry.

Chapman performed a parametric study of lifting and non-lifting entries into Earth, Mars, Venus, Jupiter, and Mercury. He considered mainly manned entries, and therefore the entry trajectories were constrained in allowable deceleration 'g' limits. The majority of his analyses pertained to entry from circular orbits, and did not consider the total entry heating problem.

4.2 The Jupiter Hypersonic Heat Transfer Problem

Entry into Jupiter's atmosphere involves initial gasdynamic velocities from 48 to 60 km/sec. At present only educated guesses can be made of the heat transfer at these velocities; pertinent experimental data do not exist. The conversion of the gasdynamic velocity into thermal energy causes complete dissociation, and nearly complete ionization of the atmospheric gases. The resultant heat transfer rate to the vehicle is so high that ablation is the only effective mechanism available to dissipate it.

The gross radiative properties of the ablation products, which depend on their concentration and temperature, strongly influence the heat transfer. The heat absorption in the vehicle will depend critically upon how ablation product radiative properties will affect absorbed radiant energy. The vehicle will absorb (at least by assumption) all the radiation reaching it, but it will be partially shielded by the ablation products. The ablation products entering the boundary layer will be further heated, dissociated, and ionized, and may effectively absorb heat which would have reached the vehicle. This discussion raises these important points:

- The probability that the ablation products will opacify the boundary layer is quite high; consequently, ablation product radiation could strongly influence the heat transfer rate. The effects of a high ablation rate on the thermodynamics of a shock layer are not known.

The effect of shock radiation can have an important bearing on the assumptions about the free stream enthalpy flux. Moreover, depending upon the radiant intensity and the magnitude of the mean free path upstream, changes in the upstream composition may occur through dissociation and ionization. In this study we treat this effect as negligible because of the absence of pertinent data. But, in line with our objectives, we point out that this is a problem area.

- The shock layer radiation can affect the upstream conditions by "heating" the otherwise undisturbed gas ahead of the vehicle.

Theoretical estimates at least must be made of the high temperature radiative properties of each of the planetary atmospheric constituents. The spectral absorption constants as a function of temperature and pressure are necessary in order to compute Planck and Rosseland mean free paths and thus to obtain detailed radiative heat transfer estimates. More accurate thermodynamic and transport properties are needed, especially enthalpy and composition (species, fractional dissociation, and ionization levels) vs. temperature and pressure. These data are necessary for any reasonable approach to predicting heat transfer in fully dissociated, and highly ionized flow streams. Assumptions about many of these quantities may lead to order of magnitude uncertainties in heat transfer predictions when dealing with velocities in the 30-60 km/sec range. The key point is:

- Hypersonic heat transfer predictions hinge on the availability and accuracy of high temperature thermophysical properties data.

In constructing the general entry heating problem, we excluded lifting vehicle concepts, electromagnetic braking, boundary layer gas injection (Gross et al. 1961), hypersonic drogues, and other devices or techniques for reducing the deceleration and heating severities. While we do not discount their individual potential values, the further uncertainties introduced could hardly be justified in a "first look" study.

4.3 The Convective Heating Model

A great number of theoretical and experimental relationships exist for undissociated flow in many gases and gas mixtures (see Bibliography), but relatively few for dissociated flow, and even less for ionized flow. Prediction schemes for heat transfer in the flow regimes in which ionization and radiation processes may even dominate very often are either mostly theoretical (e.g., Ahyte 1965) or highly specific (e.g., Allen and James 1964).

No single convective prediction scheme could be found which could be applied over the whole range of velocity as the spacecraft slows down from about 60 km/sec. The suitability of available convective heating models is discussed in Appendix B.

We have adopted the Fay-Moffatt-Probstein (1964) method for determining the convective heat transfer rate (q_1 for hydrogen, q_2 for helium) for velocities between 60 km/sec and 30 km/sec. For velocities below 30 km/sec a Marvin-Deiwert (1965) correlation has been used for the hydrogen convective heat transfer rate (q_3). These heating rates are presented for hydrogen in Figures 4 and 5 for typical direct entry and grazing entry profiles for Jupiter. The heating rates for helium have not been included because they are less well understood.

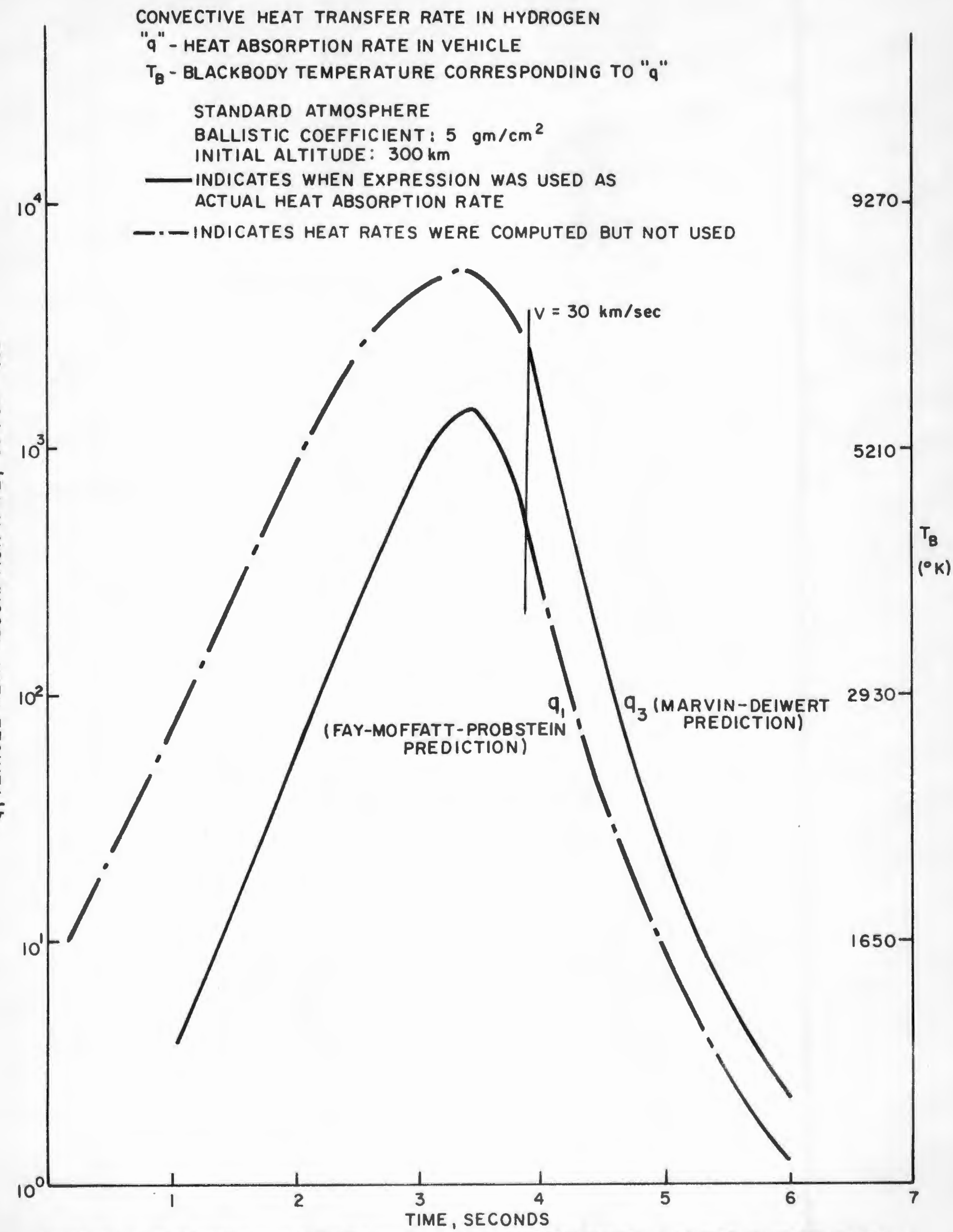

FIGURE 4. ESTIMATED <u>CONVECTIVE</u> HEAT ABSORPTION RATE - <u>JUPITER DIRECT ENTRY</u>

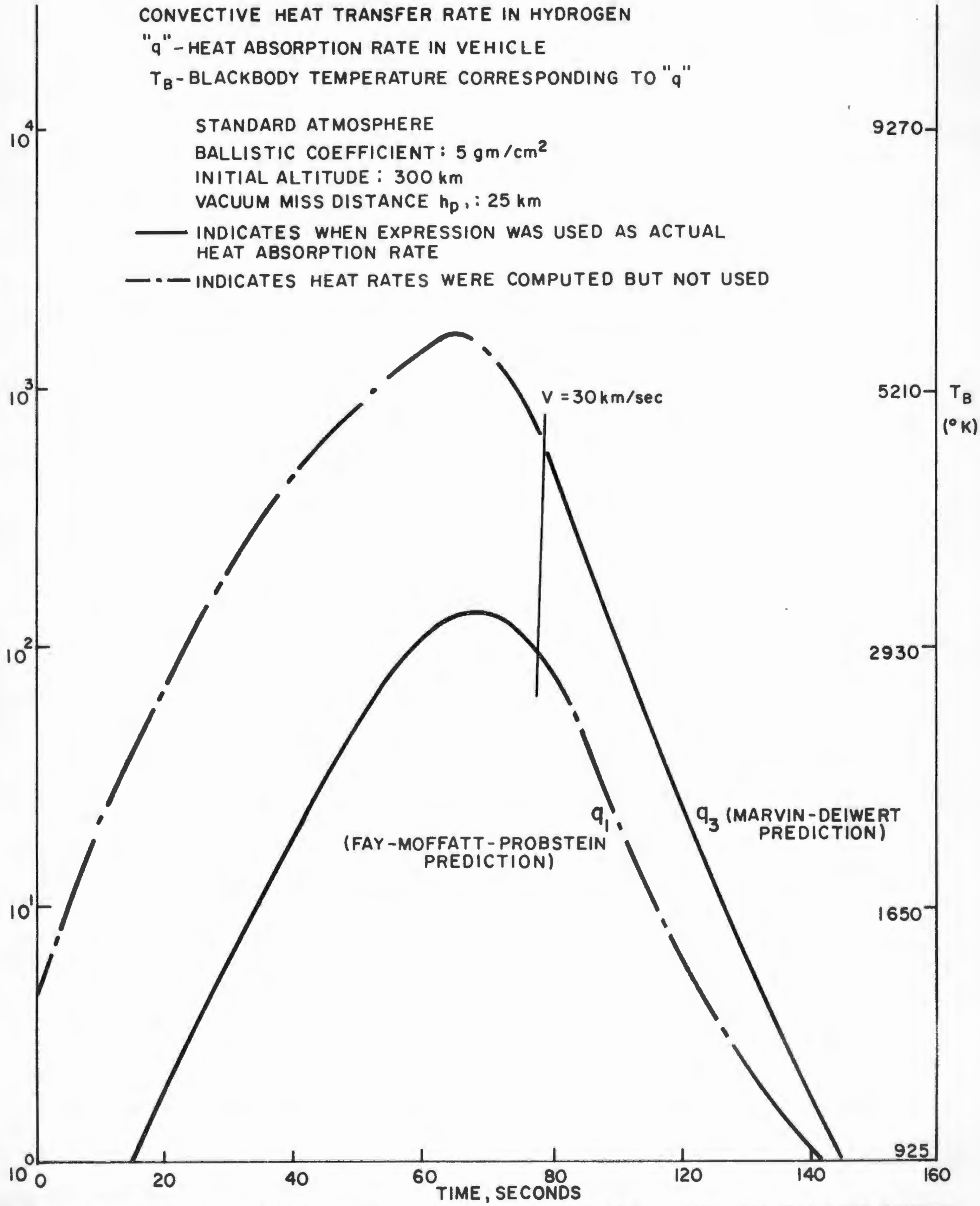

FIGURE 5. ESTIMATED CONVECTIVE HEAT ABSORPTION RATE-JUPITER GRAZING ENTRY

4.4 The Radiative Heating Model

The radiative and convective heat transfer rates are not independent but by assuming them to be independent we introduce a margin of conservatism. It is assumed that the net radiation transfer to the vehicle depends only upon the shock temperature, pressure and structure. A radiative heat transfer model based on calculated gross radiative properties is derived and discussed in Appendix C.

The radiative heat transfer rate, q_4 for hydrogen is shown in Figures 6 and 7 for typical direct entry and grazing entry profiles for Jupiter. Also shown are the heat transfer rates, assuming the hydrogen radiates as a blackbody (q_5), and the free stream profile (q_F), which approximates the maximum possible heating rate. It must be emphasized that no credible radiative data were found for helium and thus a useful model could not be developed.

4.5 Overall Heat Transfer and Mass Loss Model

Though previous sections have somewhat anticipated the intent of this section, we will bring together here the various prediction schemes and indicate how total vehicle heat absorption and resultant mass loss are estimated. Table 4 lists each expression and the gasdynamic velocity range in which it is considered valid. In general, the validity of these expressions is independent of free stream density.

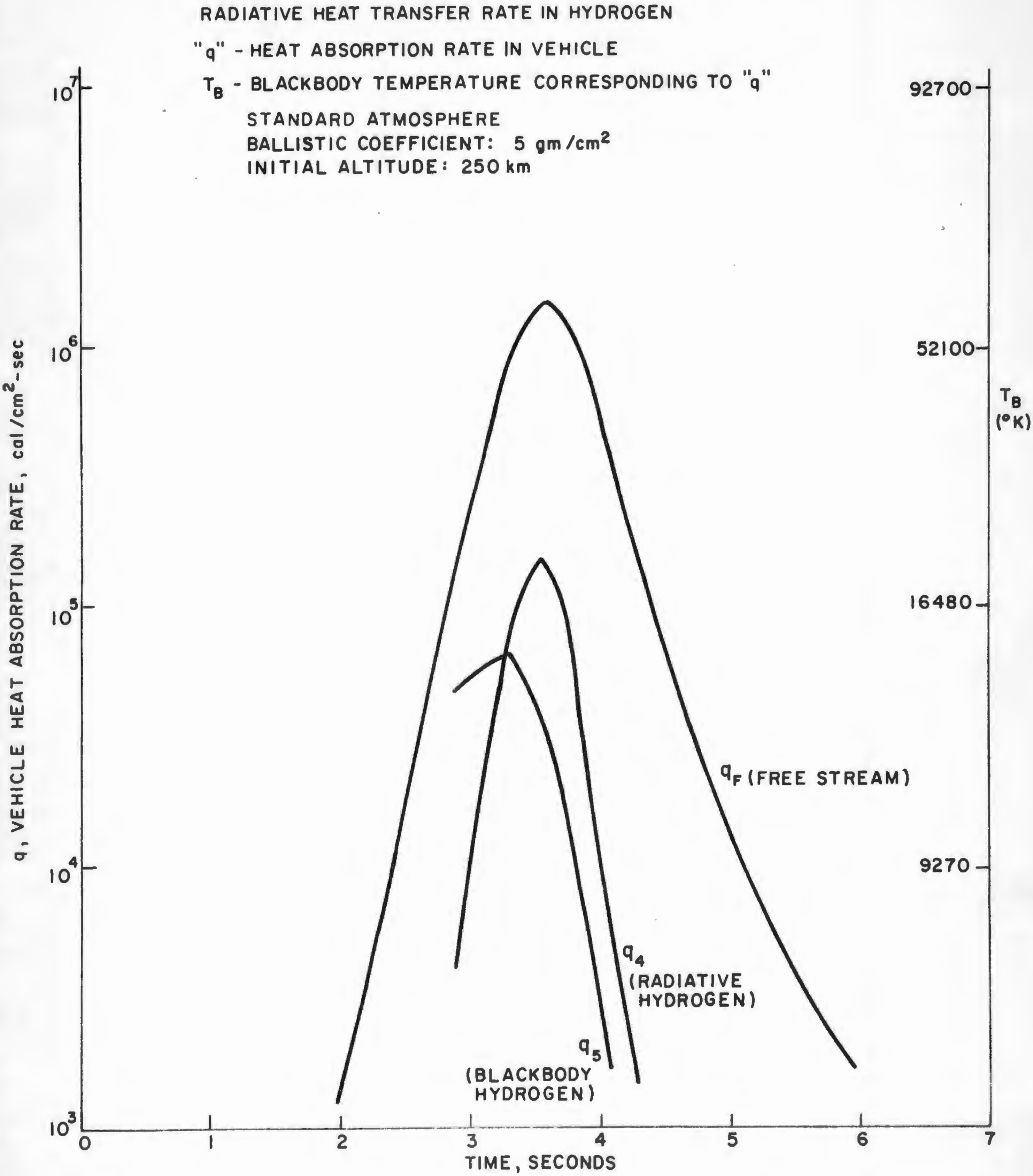

FIGURE 6. ESTIMATED RADIATIVE HEAT ABSORPTION RATES- JUPITER DIRECT ENTRY

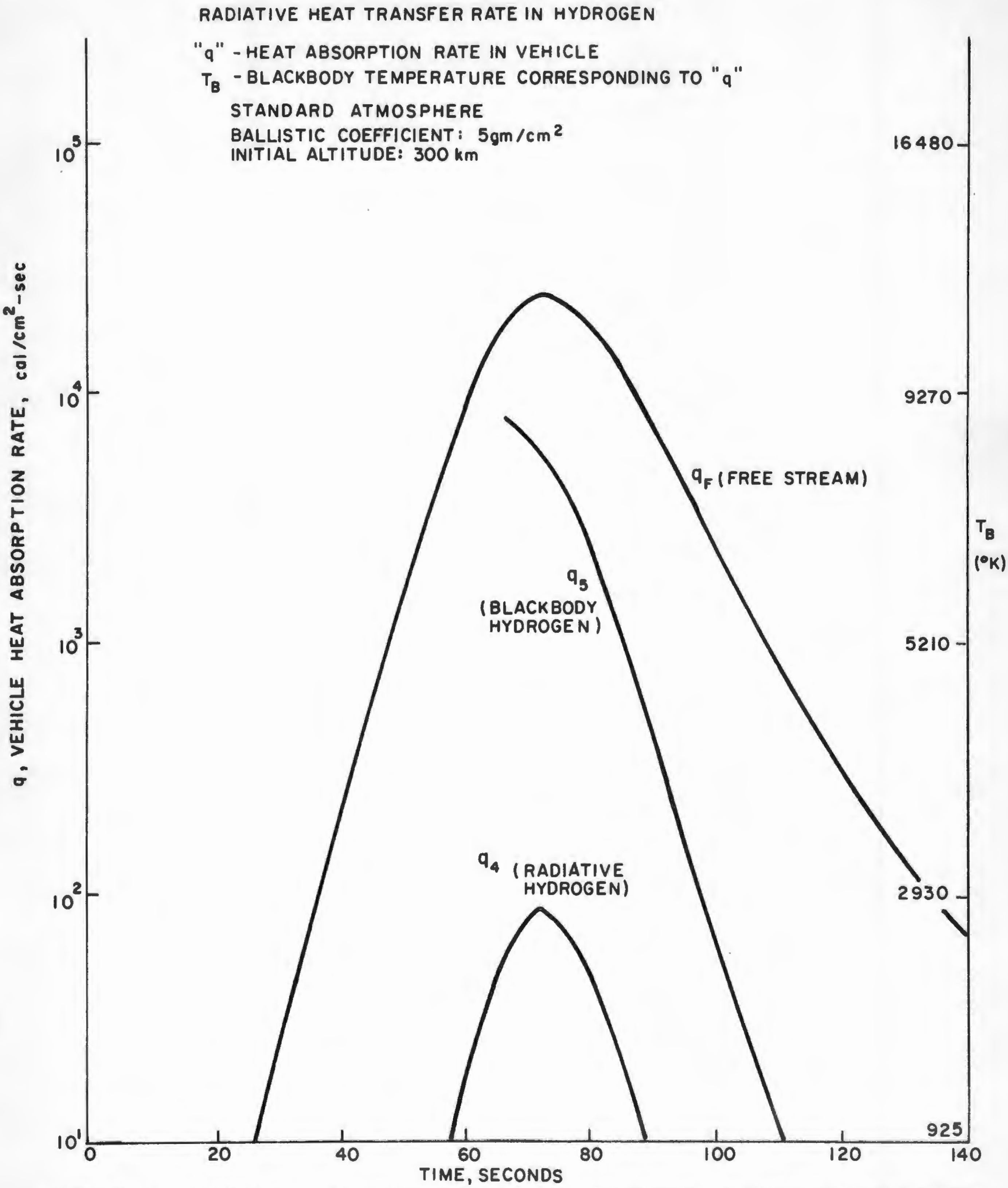

FIGURE 7. ESTIMATED RADIATIVE HEAT ABSORPTION RATES-JUPITER GRAZING ENTRY

Table 4

SUMMARY OF HEAT TRANSFER EXPRESSIONS

	Range of Validity V (km/sec)
Free Stream	
$q_F = 1.194 \times 10^{-8} \rho V^3$	60-0
Convective, q_C	
$q_1 = 1.81 \times 10^{-12} \rho^{0.5} V^{2.65}$ (H_2)	60-30
$q_2 = 1 \times 10^{-16} \rho^{0.625} V^{3.5}$ (He)	60-36
$q_3 = 1.94 \times 10^{-15} \rho^{0.5} V^{3.24}$ (H_2)	30-0
Radiative, q_R	
$q_4 = 1.8125 \times 19^{-25} \rho^{1.8} V^6$ (H_2)	60-0
$q_5 = 4.607 \times 10^{-19} \rho^{0.28} V^{3.68}$ (H_2 black-body)	60-0

The overall model, or system, we develop here follows the assumptions mentioned earlier, we merely add the convective and radiative terms in a consistent manner.

The convective and radiative expressions used in computing heat absorption and mass loss are for hydrogen heating; they derive from the same thermodynamic data so that the heat transfer results will be consistent. This latter point deserves emphasis because, in applying the model, it is very important that the trends be qualitatively correct. Even though the heating estimates may be subject to large uncertainties they must be consistent in order to compare with one another.

The nature of the assumptions and the conservatism in developing the individual expressions, however, make it necessary to have a check on the results of each heat transfer expression in order to discriminate against unrealistic values. Specifically, the free stream flux, q_F, is an absolute upper heating rate limit; and, any heat transfer rate which exceeds q_F is, of course, impossible. Likewise, in practice, the radiative heat transfer estimate cannot be greater than the blackbody flux, e.g., q_4 cannot exceed q_5.

The total heat absorption (H_T) estimate is obtained by adding the convective (H_C) and radiative (H_R) contributions within valid velocity limits:

$$H_T = H_C + H_R . \qquad (10)$$

The total convective contribution, H_C, is the time integral of q_1 (the FMP expression for H_2 convection) over that part of the trajectory in which $V \gg 30$ km/sec added to the time integral of q_2 (the extended Marvin-Deiwert empirical H_2 correlation) over the remaining trajectory, i.e.,

$$H_C = \int_{t_o}^{t_{30}} q_1 \, dt + \int_{t_{30}}^{t_f} q_2 \, dt \qquad (11)$$

where

H_C = Total integrated convective heat absorption,

t_o = Time at beginning of trajectory

t_{30}= Time along trajectory at which V = 30 km/sec

t_f = Time at terminus of trajectory.

The radiative contribution, H_R, consists of the time integral of q_4 up to the time at which it equals q_5 (blackbody flux limit), and the time integral of q_5 over the remainder of the trajectory, thus

$$H_R = \int_{0}^{t_1} q_4 \, dt + \int_{t_1}^{t_f} q_5 \, dt, \qquad (12)$$

where

t_1 = Time along trajectory at which $q_4 = q_5$

t_f = Time at terminus of trajectory.

This latter is a reasonable procedure because whenever q_4 exceeds q_5, it almost always remains greater over the remainder of the trajectory.

The curves of heat transfer rate vs. time along an entry trajectory show that no more than one percent (and generally less than 0.1 percent) of the total heat absorption is absorbed at a heat flux of one cal/cm^2-sec or less, compared to several thousand cal/cm^2-sec at peak heating. Consequently, ablation is expected to be the only effective heat dissipation mechanism; and the mass loss follows by dividing the total heat absorption, H_T, by the heat of ablation, q_A*.

Since we are calculating total heat absorption per unit area at the stagnation point, we obtain a specific ablated mass loss, m_A, which is the quotient of H_T over q_A*, that is

$$m_A = H_T/q_A* \quad . \tag{13}$$

The fractional ablated mass loss, F_m, is the specific mass loss divided by the overall projected (frontal) vehicle density (i.e., m_V/A); or

$$F_m = \frac{m_A}{m_V/A} \quad . \tag{14}$$

By definition, the ballistic coefficient is

$$B = \frac{m_V}{C_D A} \quad ,$$

and, since we can and have arbitrarily set $C_D = 1.0$, we can write

$$F_m = \frac{m_A}{B} = \frac{H_T/q_A*}{B} \quad . \tag{15}$$

This latter definition is the one used in the computations; its validity depends upon the vehicle and ablator densities being equal. The magnitudes of the F_m values, however, suggest that equating these densities is more a reality than an assumption. The advantage of Equation 15 is that masses, projected areas, and densities of vehicles can be expressed as one parameter, the ballistic coefficient B.

Perhaps of at least equal interest are the factors which were not calculated in the entry heating programs. From studying the Jupiter entry heating estimates, one can quickly surmise that many processes routinely neglected in existing programs may have to be accounted for. The effect of mass on ballistic coefficient certainly will be a prime consideration. The rocket (impulse) effect of the ablation products entering the shock layer, the radiation pressure of the shock wave, upstream heating, and magnetofluid-dynamic effects, all exert forces in addition to the gasdynamic braking. We mention these effects because, collectively, they may be of importance.

4.6 Ablative Materials Considerations

Up to this point the discussions have dwelt mainly on prediction of heat transfer. In the previous section, nevertheless, ablated mass loss was related to total heat absorption through the quantity q_A*, the heat of ablation. Here we discuss the materials aspects of ablation, particularly considerations arising from the limited empirical, and even more limited theoretical, knowledge of ablation heat transfer.

A successful entry, as we have noted, implies a tolerable mass loss. For Jupiter entries, materials which have large heats of vaporization or sublimation must be selected. In such entries the effective heat of ablation will be very high, because of the very great dynamic pressures. Since vaporization requires more energy than fusion the ablative material should vaporize, and preferably sublime, but should not melt. It should not enter into exothermic reactions with the hot gas stream. Ideally it would vaporize at temperatures sufficiently low that, even if the sublimation products are highly absorptive of the shock layer radiation and are opaque to their own radiations, the net heat transfer to the vehicle will not be increased. In addition to the thermal environment, very high g forces, shock pressures, and pressure and shock gradients, add to the problem of obtaining an effective ablator system.

The materials which satisfy all of the above considerations are few, if any. Graphite, quartz, and silicon carbide are obvious ablator candidate materials at first glance, but their reactions with hydrogen are highly exothermic. Nylon phenolics, fiberglass reinforced plastics, teflon, and similar organic heat shield materials contain sufficient carbon and oxygen to raise serious doubts about their performances. It may be that certain ceramic materials such as the borides and silicides, may be suitable. We can summarize these remarks by noting that:

- Obtaining high strength ablative materials which change phase with large activation energies yet do not react chemically with hydrogen at high temperatures may be a serious developmental problem.

Another very important aspect of the ablator problem is the question of optimum nose cone shape. We have not adopted the usual practice of choosing nose cone shapes to minimize the total convective and radiative contributions. Such a trade-off is not currently practical, mainly because the manner in which the shape will change due to ablation is not known; yet because large mass losses and consequent shape changes are certainly indicated, the shape change question will be a critical one.

The magnitude of the heat transfer rates during entry suggests that if they are not uniform over the nose cone, lateral thermal stresses will be induced which may lead to local mechanical failures (spalling) in the heat shield and eventually to its premature destruction, particularly if the ablation shaping tends to intensify the lateral gradients. The initial shape therefore may be even more critical inasmuch as the instantaneous heat transfer distribution and how it varies are critical. The ablator, in order that its thermal protection will be effective, must also have sufficient mechanical integrity to survive forces of Jupiter entry magnitudes; and this integrity will also be strongly dependent upon initial shape.

In this report a specific ablative material has not been selected but one has been assumed which meets the general requirements outlined above. Further, an effective heat of ablation of 2500 cal/gram is used, which for convenience sake, is assumed not to be appreciably affected by pressure and temperature. Admittedly, such systems currently are beyond the state-of-the-art, but ablators with q_A* values of this magnitude are clearly demanded.

We have intentionally treated the overall ablator materials problem generally and quite conservatively. There can be little doubt that ablation effects will be important irrespective of vehicle design. The difficulty in estimating heat transfer in ablating systems has been long recognized; it is known, for example, that the effectiveness of an ablator depends, in ways as yet poorly understood, not only upon the shape and size of the nose cone but also quite strongly upon the composition of the ambient gas. Summarizing:

- The calculation and estimation of ablative heat transfer remains as one of the most difficult and complex aspects of hypersonic heat transfer. A choice of materials or even a class of materials to consider is by no means obvious.

4.7 Summary of Major Technical Problem Areas

The first of many major problem areas is that due to the unknown composition and structure of the atmospheres of the outer planets. In particular, ignorance of the helium abundances represents an impediment of major significance, because the gasdynamics and especially the thermodynamics of entry depend critically upon it. If composition is unknown, the thermodynamics likewise are unknown. If complete composition data were available, the thermophysical properties of the components and appropriate mixtures could be studied. These data then could be used to estimate the effects on heat transfer estimates of uncertainties which might exist in the composition data.

The high temperature radiative properties of helium are not available in the literature in an engineering form. The radiative and thermodynamic properties of high temperature mixtures of helium and hydrogen likewise do not exist in engineering form although it is evident that astrophysicists have had to predict the radiative properties of H-He mixtures in order to study solar and stellar radiation processes.

Accurate estimates of the heat transfer to entry vehicles and of their thermal performance would become possible only through a comprehensive scheme which couples the radiative, convective, and diffusive modes of heat transfer and takes account of the strong interaction of the ablation process with these modes. Finally, the questions surrounding the choice of an ablator material for outer planet entries will inevitably engender considerable development effort, primarily to find hydrogen-compatible materials and optimum initial shapes. The multitude of possible heat transfer suppression techniques and devices aggravates the ablator development problem because none have been proven in simulated outer planet environments or at the velocities of interest here. These problem areas have been listed in Table 5.

5. DISCUSSION OF RESULTS

Basically, the results obtained in the study are ballistic and thermodynamic profiles as a function of initial entry parameters for Jupiter. These data include trajectory parameters (velocity, altitude, flight path angle, etc.), heat transfer rates, and integrated heat absorption into the spacecraft. Table 6 lists the parameters varied or used to generate these data. While not all of the possible cases implied in Table 6 were run, a sufficient number were computed to establish the more important parameters.

The purpose of this section is to interpret the ballistic and thermodynamic data in terms of feasibility. Let us recall briefly the survival criteria, viz., that at entry into the cloud tops (zero altitude) we require that the terminal velocity, V_T, be less than 1 km/sec and that the fractional ablated mass loss, F_m, be less than 0.9. These are the key elements in the assumed survival scheme.

Before going into the survival results, however, we would like to call attention to several representative heat transfer profiles. In Figure 8 are plotted the time profiles of the estimated total (convective and radiative) heat absorption rates for a vehicle on a direct entry trajectory; in

Table 5

MAJOR TECHNICAL PROBLEM AREAS

Planet Considerations

1. Elemental abundances (He, H_2, CH_4, NH_3, Ar ...)
2. Scale height ($RT/\overline{M}g$) vs. altitude
3. "Sea level" density or pressure

Heat Transfer Considerations

1. Basic Gas Properties

   Radiative properties of helium to 60,000°K

   - Engineering form
   - Analytical approximations
   - Experimental validity

   Thermodynamic and radiative properties of hydrogen to 25,000°K

   - Experimental validity

   Chemistry, physics, and engineering properties of gas mixtures (transport properties, recombination, gas interactions)

   - Engineering form
   - Analytical approximations
   - Experimental validity

2. Gasdynamics and Heat Transfer

   Shock structure (in geometry and time)

   - Shock onset conditions and transition flow
   - Stagnation point conditions (temperature, pressure, density, shock thickness)
   - Enthalpy distribution

Table 5 (Cont'd)

Heat and mass transfer effects on thermodynamics of shock layer

- Radiation from shock layer(s)
- Ablation effects
- Chemistry effects
- Upstream effects (radiation heating)

Comprehensive heat transfer models

- Coupling of convective, diffusive, and radiative heat transfer modes

Ablative materials considerations

- Hydrogen compatibility
- Initial shape
- Ablation shaping
- Thermochemistry and high pressure effects
- Thermal stress
- Mechanical stability

Table 6

INPUT PARAMETERS FOR JUPITER ENTRY PROGRAM

Symbol	Parameter	Value/Range of Values	Units
$B\ (= \frac{m_V}{C_D A})$	Ballistic coefficient	2.5,5.0,7.5,10,0,12.5,20,25, 30,32.5,45,50	g/cm^2*
$\beta = (\overline{M}g/RT)$	Inverse scale height	0.05,0.089,0.11,0.15	km^{-1}
ρ_o	Reference density	6.83×10^{-5}, 2.54×10^{-4}	g/cm^3
γ_I	Inertial flight path angle	-90,-60,-45,-20,-15,-10,-5,-0	deg
h_p	Altitude at periapse (vacuum)	0,25,50,75,100,125,150,175, 200,225,250	km
DV	Retro velocity change	0, -6.0	km/sec
VHP	Hyperbolic approach velocity	0, 7.0, 14.9	km/sec
h_o	Initial entry altitude	250, 300	km
C_D	Gasdynamic drag coefficient	1.0	-
A	Vehicle projected frontal area	1.0	cm^2

*A value of B (= m_V/C_DA) equal to 1 g/cm^2 is equivalent to a W_V/C_DA of 5.1 lb/ft^2 or to a m_V/C_DA of 0.16 $slug/ft^2$.

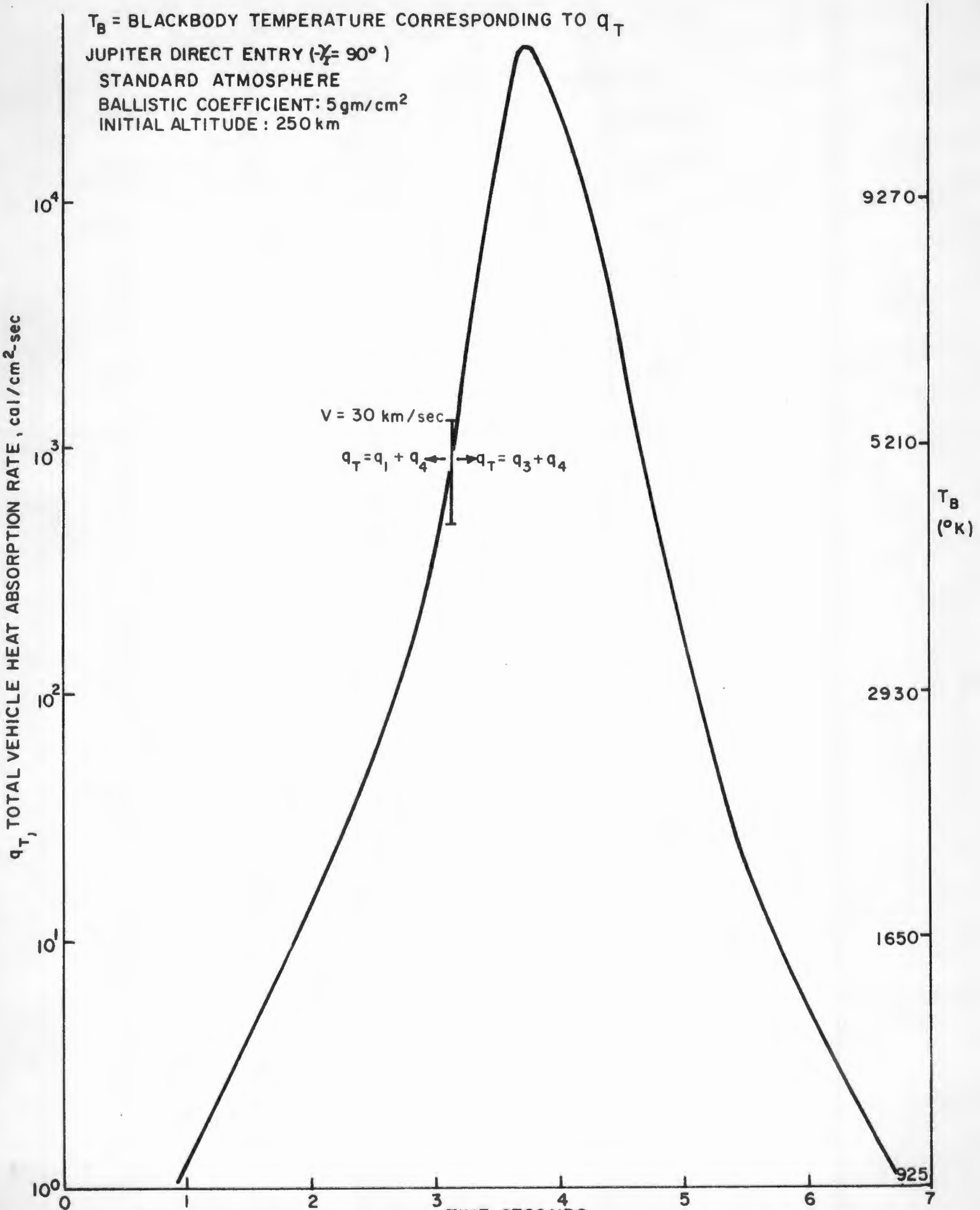

FIGURE 8. ESTIMATED TOTAL HEAT ABSORPTION RATE VS. TIME - JUPITER DIRECT ENTRY

Figure 9, for a grazing entry. The important point is that over a major part of the trajectory, the heat transfer rate greatly exceeds 1 cal/cm^2-sec. And in general, it is found that the integrated heat absorption at fluxes less than 1 cal/cm^2-sec is negligibly small compared to the heat absorption integrated over the entire trajectory. These results justify our assumption that all heat absorbed causes ablation.

An interesting and potentially important deduction can be made by noting the magnitudes of the heat transfer and thermodynamic quantities characterizing a vertical Jupiter entry. One can see that the rate of ablation is easily high enough to cause a quasi-rocket effect in which the ablation thrust, to first order, augments the gasdynamic drag. The effects of radiation pressure, of ablation shaping, and of numerous other factors also may be significant. It would seem that they should be accounted for and, taken advantage of, in reducing entry heating magnitudes. In short, the heat absorption and dissipation mechanisms accompanying very high speed hypersonic entries might well be put to advantage in reducing net total heat absorption and mass loss.

5.1 Heat Transfer Results

Most of the heat transfer data follow predictable trends so that there is little point in displaying other than summary graphs. Aside from the very high heat fluxes, it is of interest and benefit to observe the dependence of q_{max} (the maxima of the various profiles) upon B, the ballistic coefficient, upon

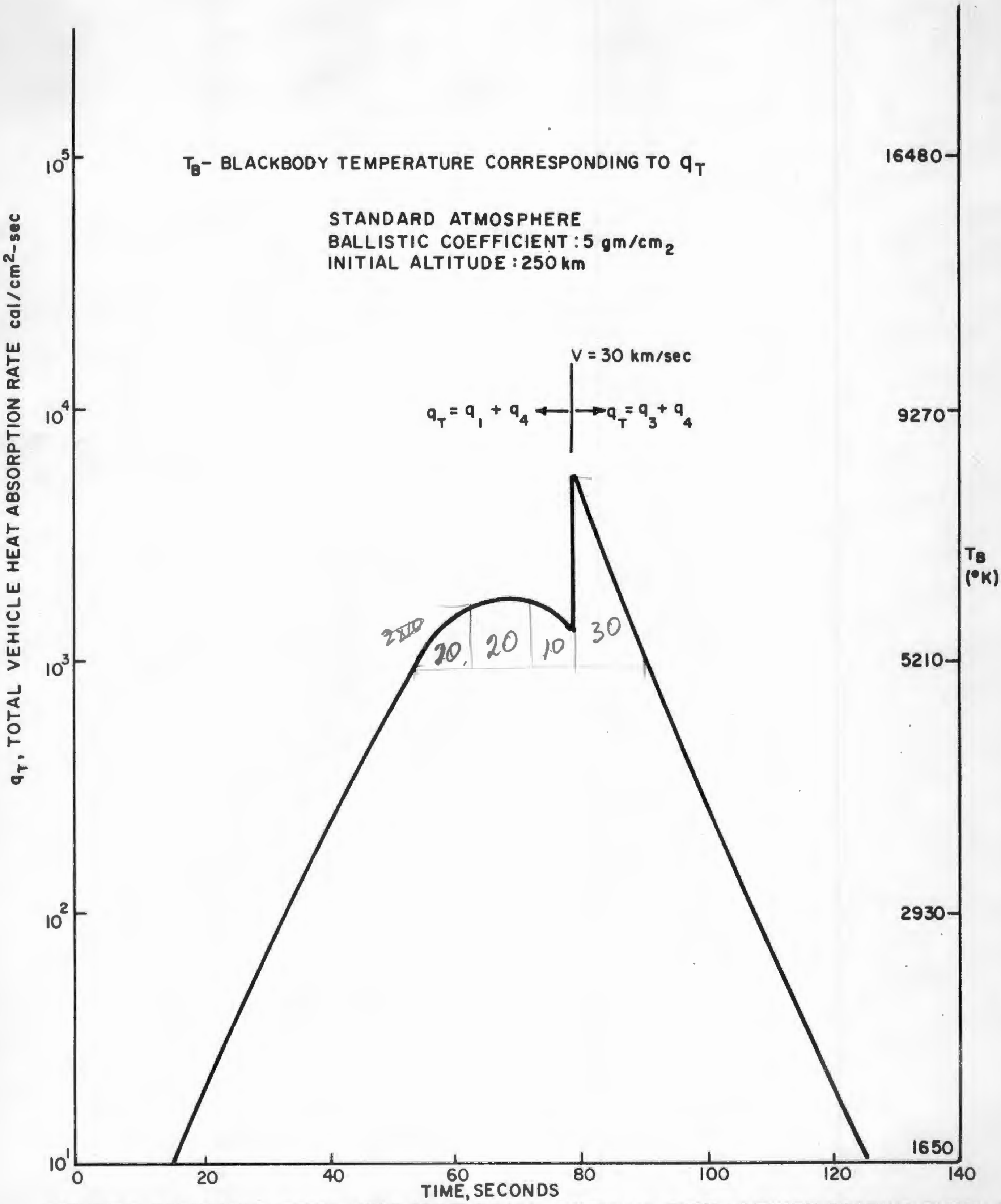

FIGURE 9. ESTIMATED TOTAL HEAT ABSORPTION RATES VS. TIME - JUPITER GRAZING ENTRY

β^{-1}, the inverse scale height, and upon $-\gamma_I$, the inertial flight path angle. These relationships are shown in Figures 10, 11, and 12, respectively. From these relationships and from the fact that the total entry heat absorption, H_T, is proportional to q_{max}, it will be easier to understand the survival results and to scale them to the true atmospheric parameters.

In comparing the q_{max} and H_T for each scheme over the range of entry conditions, it became apparent that an unusual effect occurs (compared to entries into the Earth's atmosphere): grazing entries result in both a lesser peak heating rate and a lesser total heat absorption. This is the effect of a very high atmospheric rotation rate. From a thermodynamics point of view grazing entry trajectories are clearly preferred.

Lastly, in terms of heat absorption,the parameters VHP, DV, and h_p have comparatively insignificant effects. VHP's ranging from 0 to 14.9 km/sec produced less than a 2 percent increase in q_{max}. Via retro-maneuvers, the entry velocity was reduced in certain direct entry cases by 6 km/sec; the resultant reduction in q_{max} and H_T were not large enough to be worthwhile, because a retro DV of -6 km/sec implies a mass loss (due to the expenditure of fuel and propulsion structure) of roughly 90 percent of the initial vehicle mass. The value of such a maneuver to reduce the heating effect is evidently negligible. In grazing entry cases, the vacuum miss distance, h_p, over a range of 300 km is found to affect q_{max} less than 10 percent.

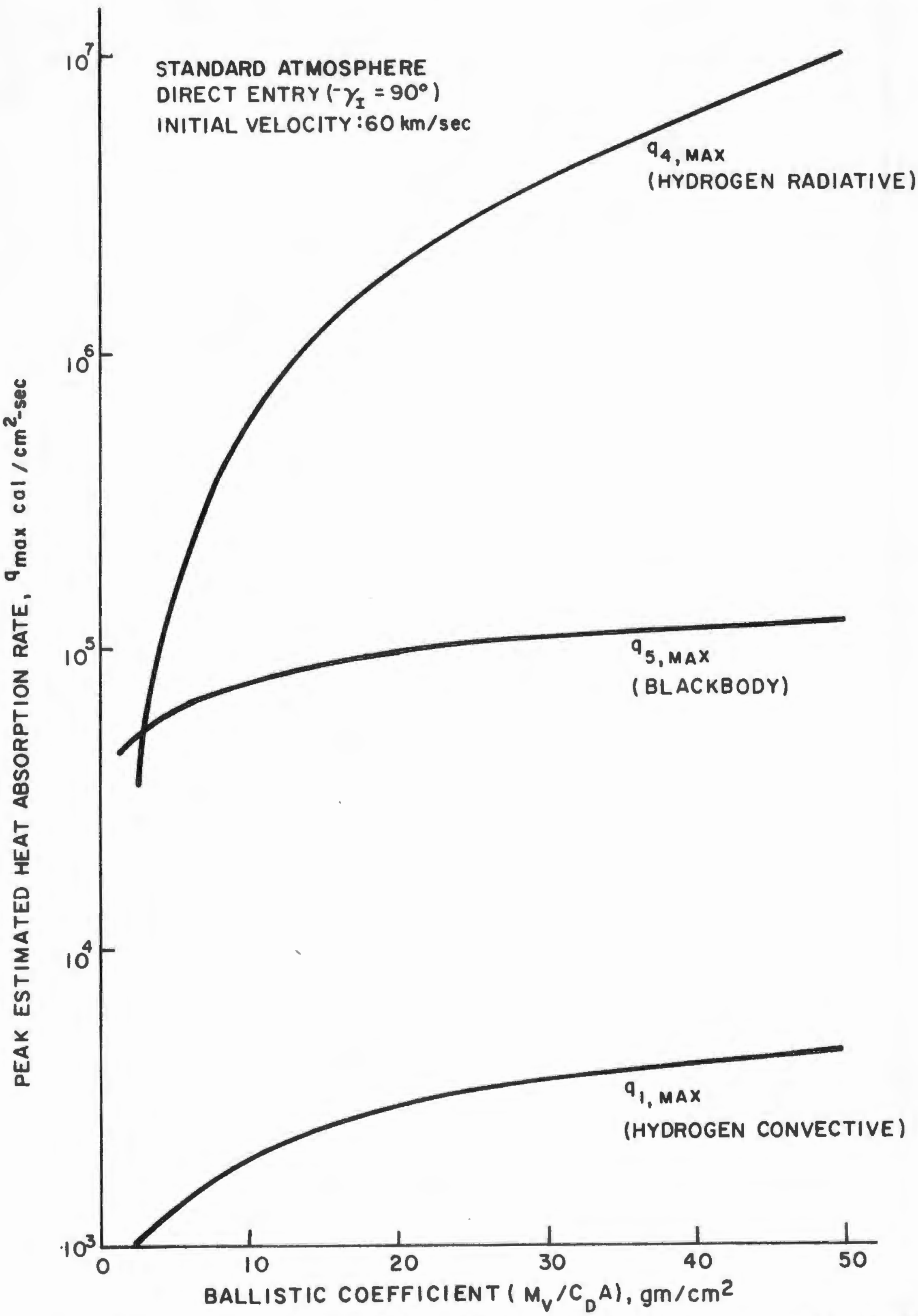

FIGURE 10. ENTRY HEAT ABSORPTION RATE MAXIMA VS. BALLISTIC COEFFICIENT

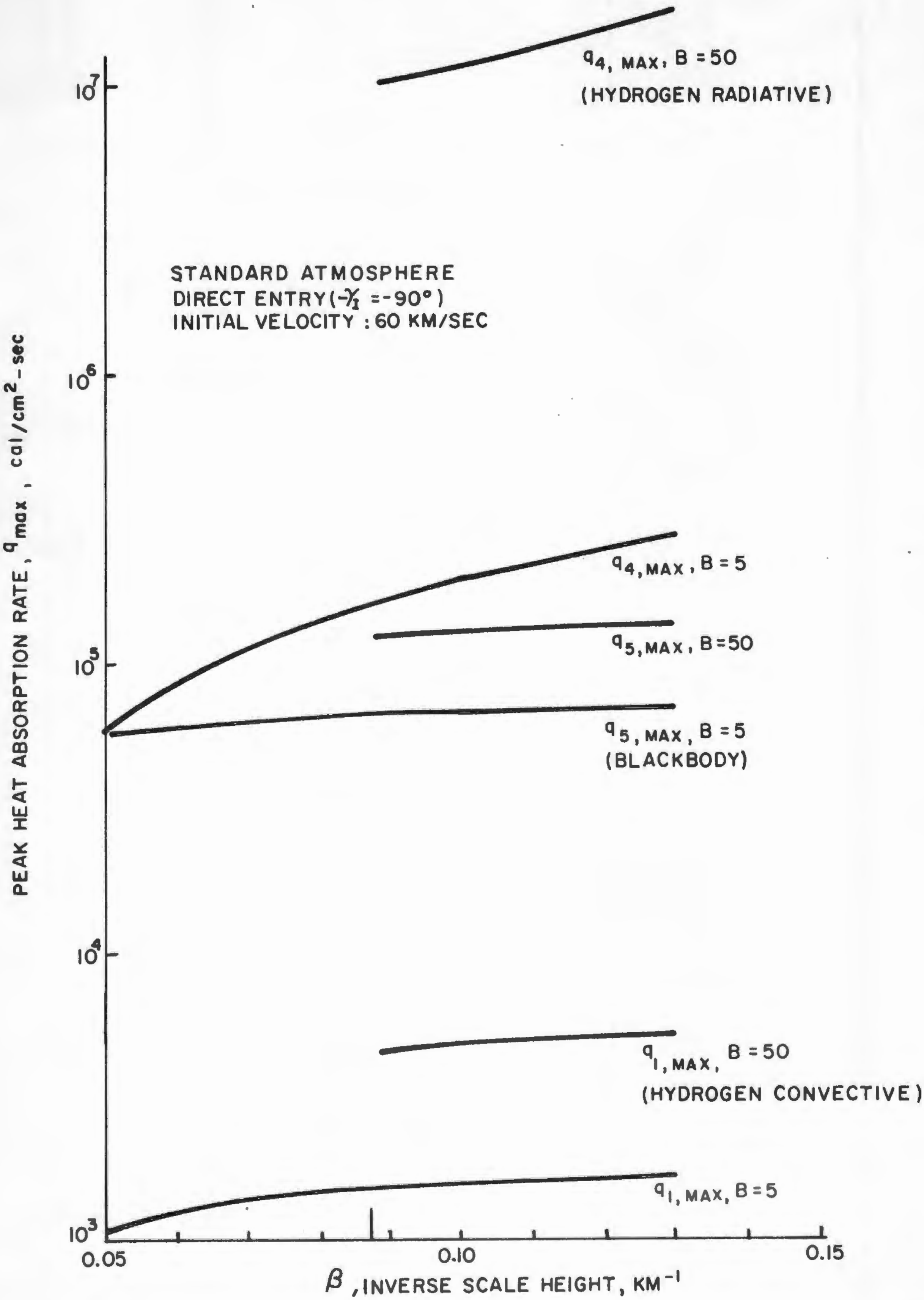

FIGURE 11. ENTRY HEAT ABSORPTION RATE MAXIMA VS. INVERSE SCALE HEIGHT

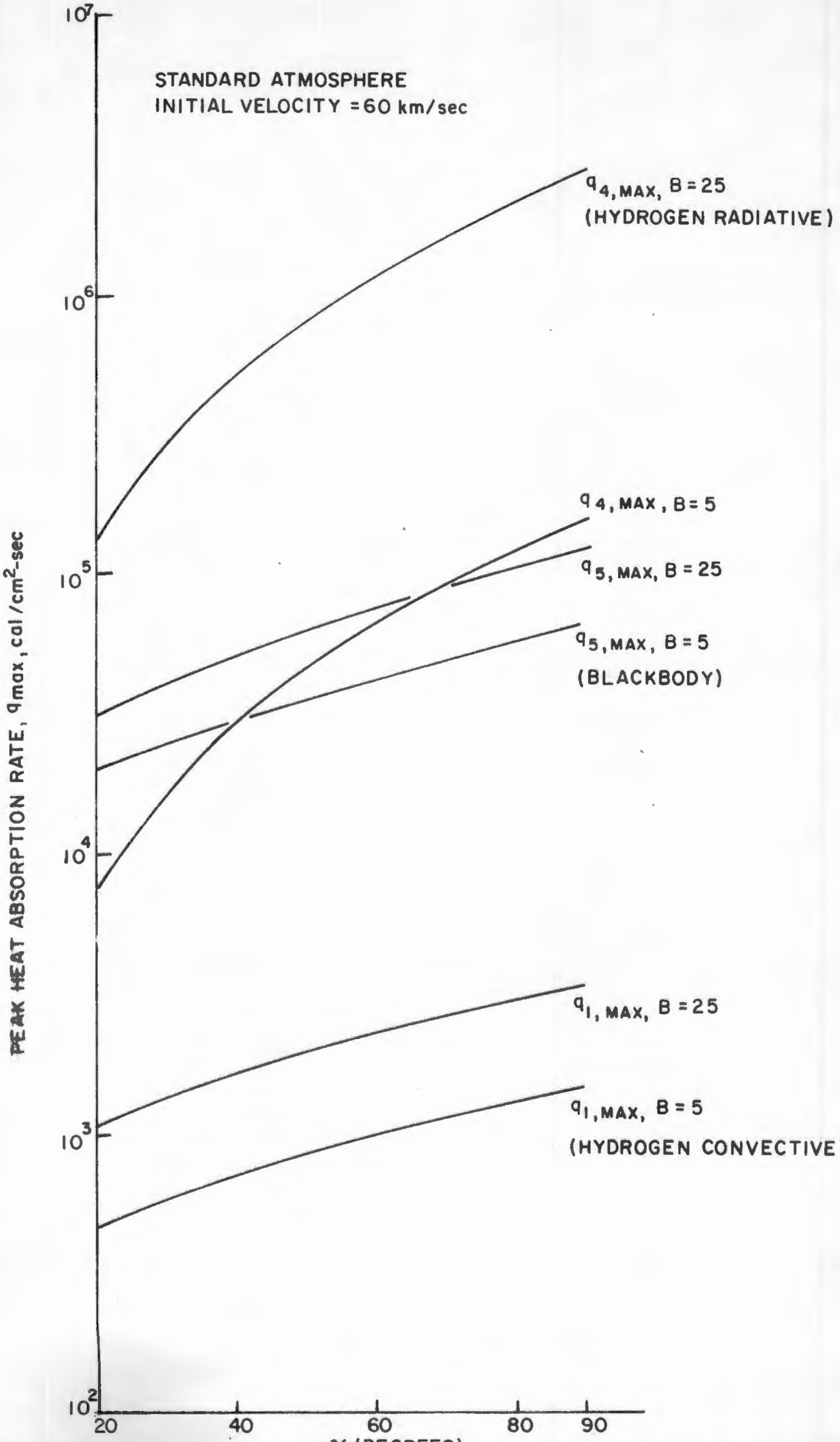

FIGURE 12. ENTRY HEAT ABSORPTION RATE MAXIMA VS. INITIAL FLIGHT PATH ANGLE

5.2 Mass Loss Estimates

The reduction of the heat transfer data to obtain mass loss estimates in general followed the description given in Section 4.5. Tables 7 and 8 contain representative raw data and the survival results obtained in the cases of direct entry and grazing entry, respectively. For information, the peak accelerations experienced on the entry trajectory also are given.

A vital issue in the concept of survival is the manner in which the fractional ablated mass loss, F_m, is defined. For this reason we reiterate the bases inherent in its definition. The heat absorption estimate is on the basis of the total heat absorbed in one square centimeter at the stagnation point; (it should thus overestimate the heat absorption averaged over the entire shock layer). F_m is then the ablated mass per cm^2 divided by the initial mass of the vehicle per cm^2 of frontal area. There is, of course, in this simple definition the implicit assumption that the densities of the ablator and of the overall vehicle, on average, are equal.

5.3 Survival/Feasibility Results

Representative survival results for Jupiter entries are given in Figures 13a, b, and 14a, b. Figures 13a, b show F_m and terminal velocity, V_t, versus the ballistic coefficient, B, for two direct and two angle entry cases. It is evident from the survival criteria that direct entry probes do not survive. An F_m of 1.0 implies total mass loss, and higher values are,

Table 7

TYPICAL JUPITER DIRECT ENTRY SURVIVAL RESULTS - FRACTIONAL ABLATED MASS LOSS AND TERMINAL VELOCITY

Initial Velocity: 61.3 km/sec

Atmosphere: Standard (ρ_o = 6.83 x 10^{-5} g/cm^3, β^{-1} = 11.3 km)

Flight Path Angle: $-\gamma_I$ = 90°

Initial Altitude: 250 km

	Ballistic Coefficient (g/cm^2)						
	2.5	5.0	7.5	10	12.5	25	50
Total entry heat absorption, H_T (kcal/cm^2)	20.2	34.8	45.1	62.5	68.9	83.5	108
Specific ablated mass loss, Δm (g/cm^2)	8.08	13.90	18.0	25.0	27.6	33.4	43.2
Fractional ablated mass loss, F_m	3.23	2.78	2.40	2.50	2.20	1.33	0.864
Terminal velocity, V_t (km/sec)	0.134	0.201	0.415	1.185	3.45	13.27	28.6
Peak entry deceleration, $\dot{V}_{max}$ (Earth g's)				6350			

Table 8

TYPICAL JUPITER GRAZING ENTRY SURVIVAL RESULTS -
FRACTIONAL ABLATED MASS LOSS AND TERMINAL VELOCITY

Initial Velocity: 47.65 km/sec
Atmosphere: Standard ($\rho_o = 6.83 \times 10^{-5}$ g/cm^3, $\beta^{-1} = 11.3$ km)
Initial Altitude: 300 km

	Ballistic Coefficient (g/cm^2)							
	2.5	5	12.5	50	2.5	5	12.5	50
	h_p = 25 km				h_p = 50 km			
Total entry heat absorption, H_T (kcal/cm^2)	6.79	10.48	22.0	107.3	7.1	10.66	22.65	92.45
Specific ablated mass loss, Δm (g/cm^2)	2.72	4.19	8.81	42.9	2.84	4.26	9.16	37.0
Fractional ablated mass loss, F_m	1.09	0.84	0.71	0.85	1.13	0.85	0.73	0.74
Terminal velocity, V_t (km/sec)	0.13	0.19	0.33	0.803	0.132	0.19	0.32	0.764
Peak entry deceleration, $\dot{V}_{max}$ (Earth g's)	116.9	111.6	103.9	90.8	107.0	100.6	92.2	77.5

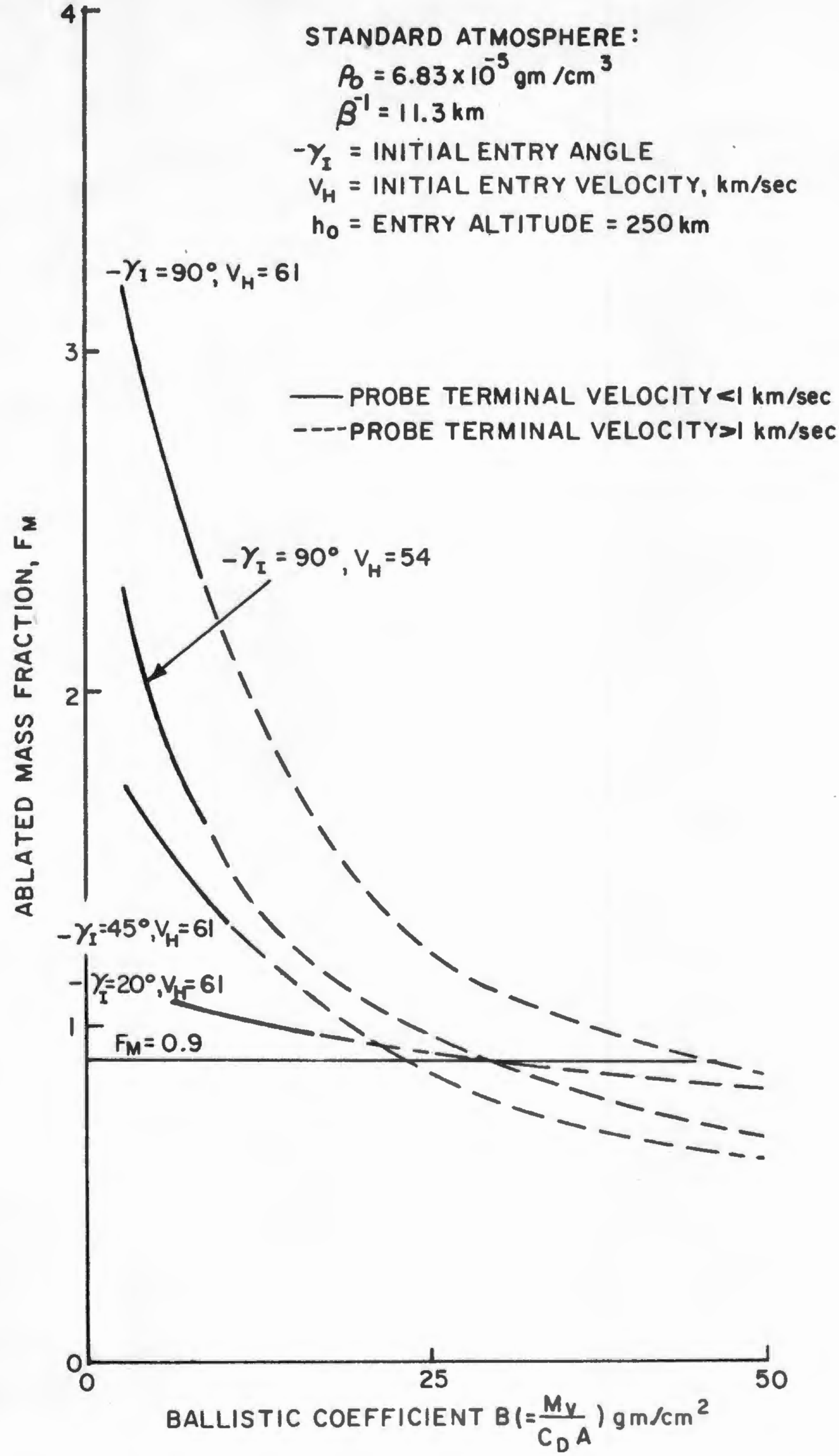

FIGURE 13a. SURVIVAL RESULTS: FRACTIONAL MASS LOSS VS. BALLISTIC COEFFICIENT <u>FOR ANGLE ENTRIES.</u>

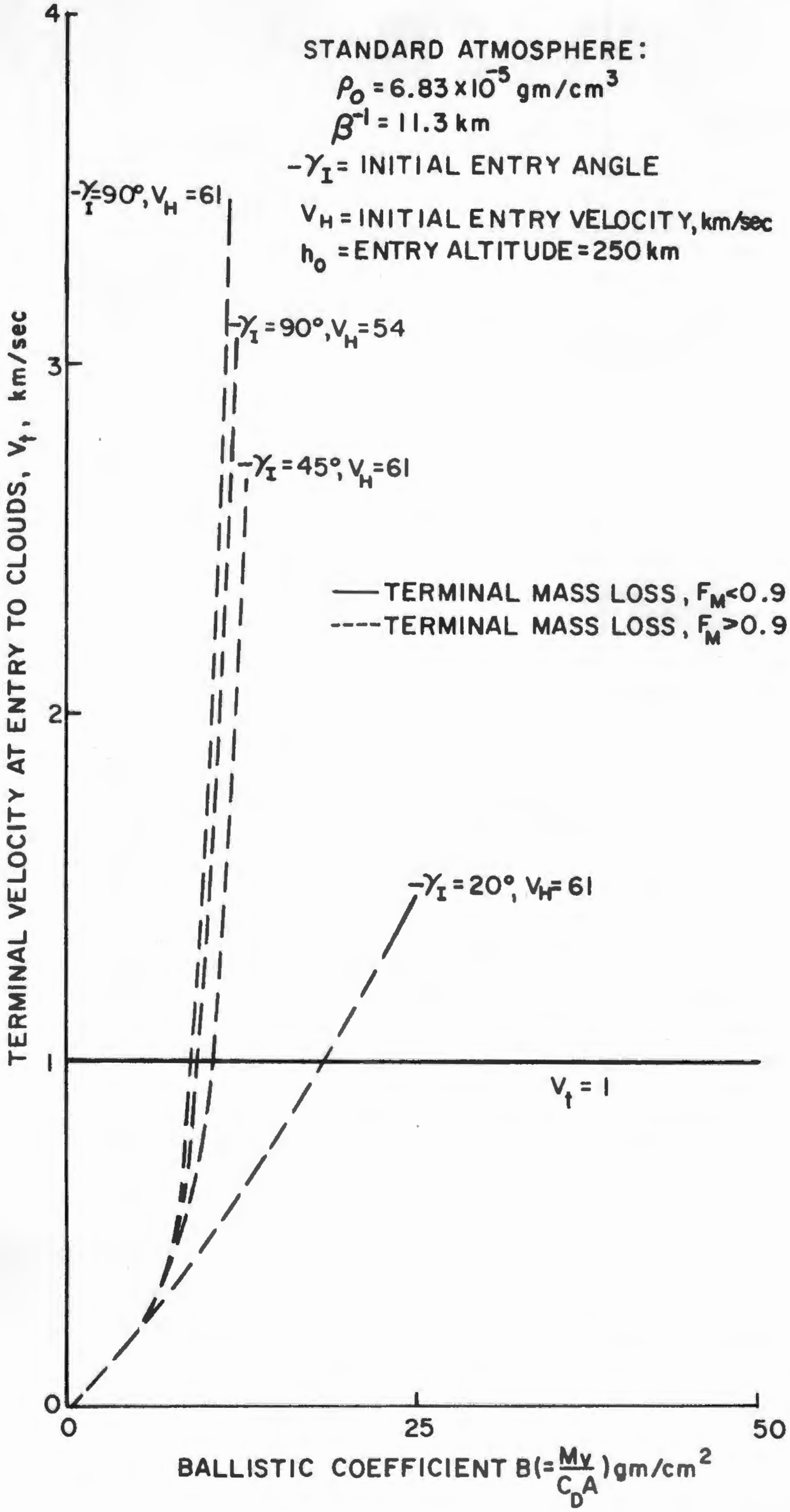

FIGURE 13b. SURVIVAL RESULTS: TERMINAL VELOCITY VS. BALLISTIC COEFFICIENT FOR ANGLE ENTRIES

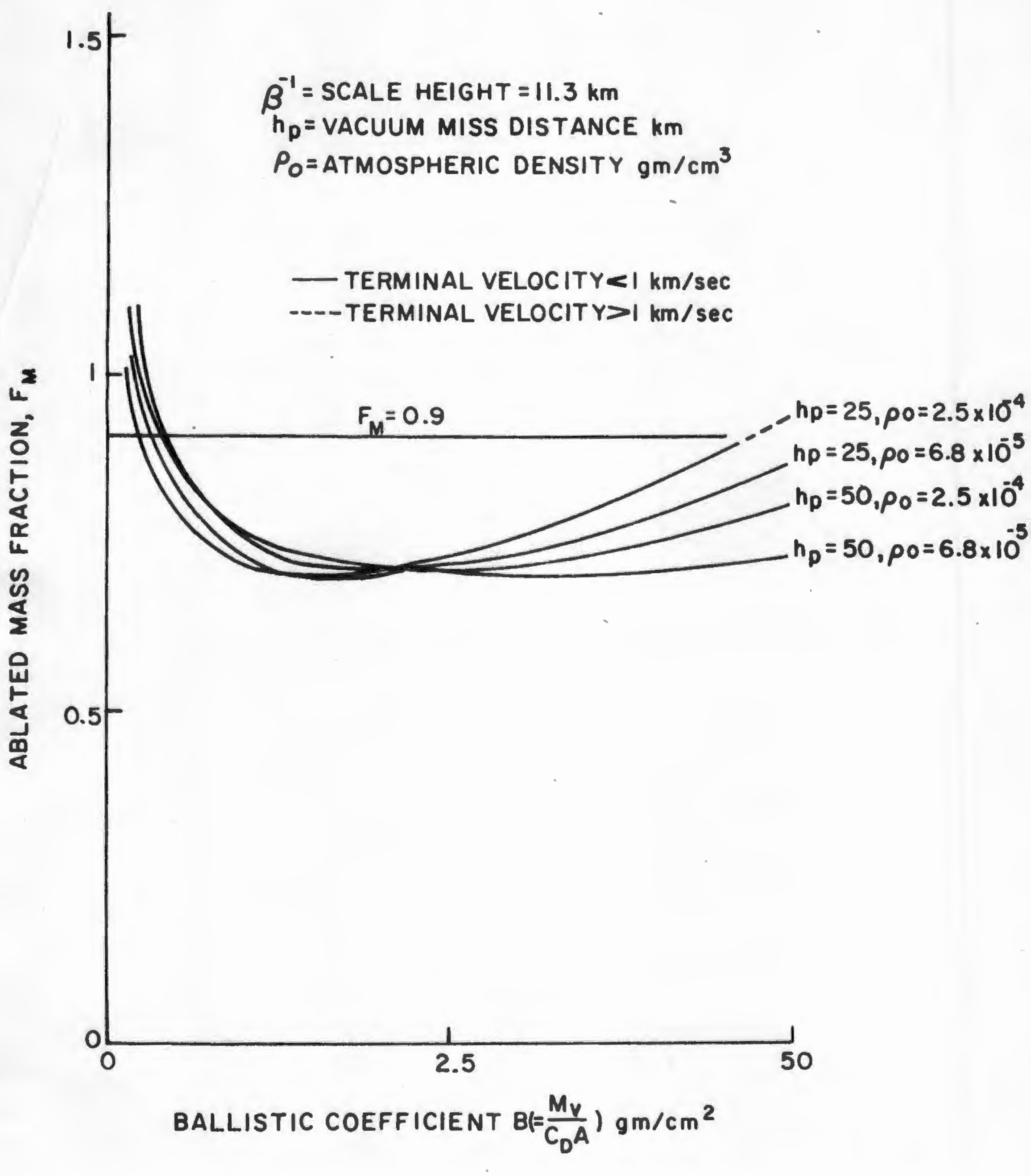

FIGURE 14a. SURVIVAL RESULTS: FRACTIONAL MASS LOSS VS. BALLISTIC COEFFICIENT FOR GRAZING ENTRIES

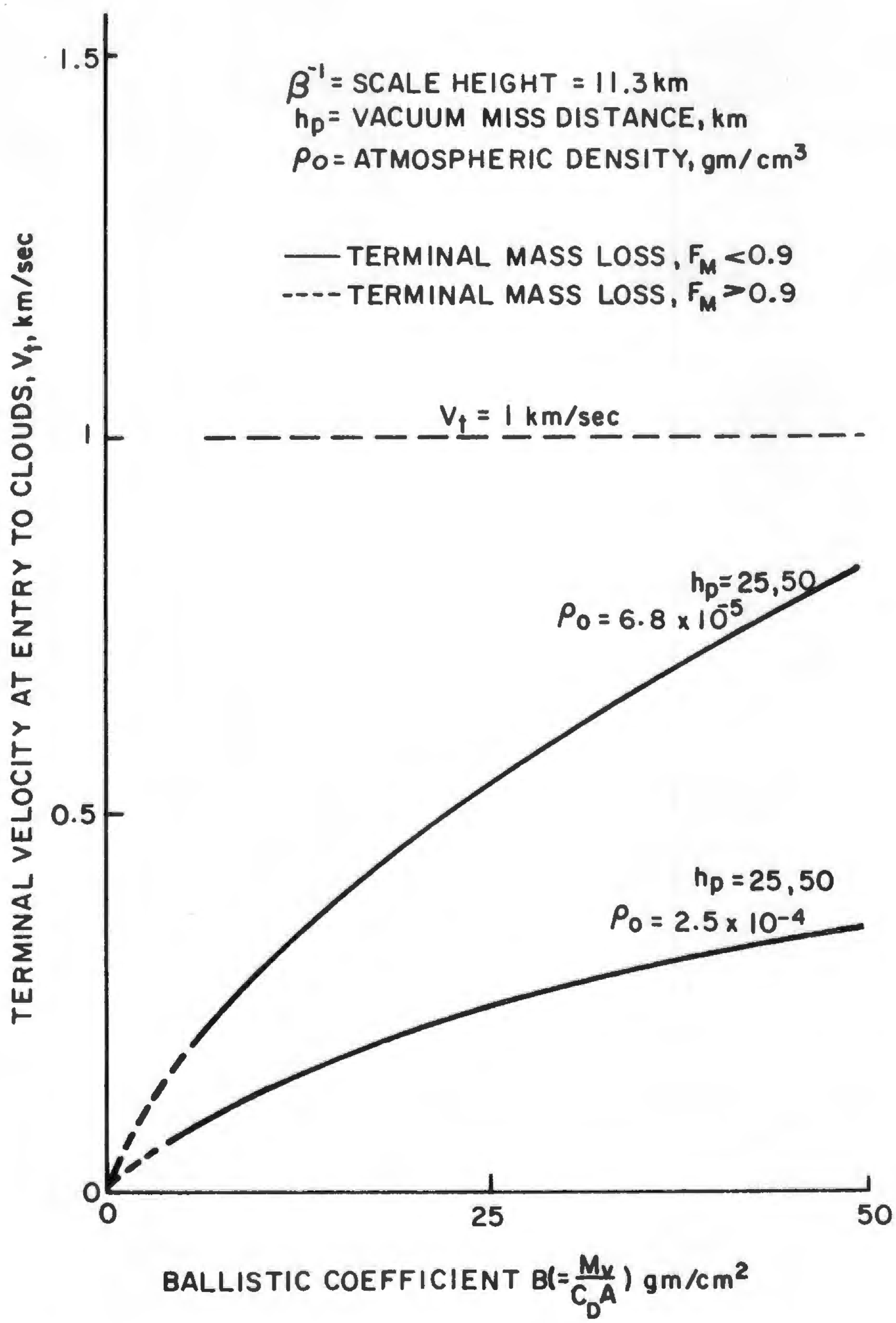

FIGURE 14b. SURVIVAL RESULTS: TERMINAL VELOCITY VS. BALLISTIC COEFFICIENT <u>FOR GRAZING ENTRIES</u>

of course, fictitious.

In the direct entry cases and also in angle entry cases the mass loss curves ostensibly indicate survival of heavy vehicles; the V_t curves, however, show that these vehicles will have terminal velocities in excess of 1 km/sec. The higher terminal velocities imply that the thermal histories are not complete; hence the corresponding fractional mass loss curves would be optimistic.

The importance of these data lies in the fact that grazing entry trajectories appear to be feasible while those of direct and angle entries do not.

In the case of Jupiter, direct and angle entries exhibit very few advantages except that their terminal guidance requirements are not acute.

Another important point to recognize is that the computer program does not correct for mass loss. Yet, the mass loss obviously is very large, and one would expect large changes in m_V/A and corresponding changes in B. If m_V decreases proportionately faster than A, the decreasing B would have the effect of slowing the vehicle at a rate faster than a vehicle with constant ballistic factor.

From Figures 13 and 14, it is obvious that mass losses are very substantial. In order to obtain a very quick and preliminary estimate of the mass loss effect, a separate program was written using approximations to the entry equations which are reliable only for direct entries. This program corrected the ballistic coefficient only for the mass change, not for changes in frontal area or drag coefficient; it used an improved heat transfer integration routine. The results are displayed in Figure 15. The F_m values for direct entries which have been plotted in Figure 15 will be slightly different from (and better than) those given in the previous graphs and tables. In two Jupiter direct entry cases, F_m was calculated as a function of initial B using in one case the mass loss as a correction to B, and in another case using a constant B. For an initial B of 7.5 g/cm^2, the mass loss case gives $F_m' = 0.372$, as opposed to $F_m = 2.17$ for the constant B case; the terminal velocities (V_t) were 0.485 and 6.521 km/sec, respectively. For an initial B of 37.5 g/cm^2, the results show that in the mass loss corrected case $F_m' = 0.178$, and $F_m = 0.961$ (the uncorrected case); in the mass loss case $V_t' = 16.98$ km/sec vs $V_t = 18.86$ km/sec (uncorrected). The differences between the corrected (F_m') and uncorrected (F_m) values are remarkable. Clearly the magnitude of the mass loss has a very profound effect upon the entry thermodynamics and upon ultimate survival.

Finally, we should remark on the connection between multiple pass entries and survival. The importance of multiple pass entries is that they greatly increase the maximum surviving B value. The greater range of surviving B values in grazing entries (Figs. 13, 14) results from the fact that the heavier vehicles take as many as three passes before being captured in an impact trajectory. This range would have been even larger

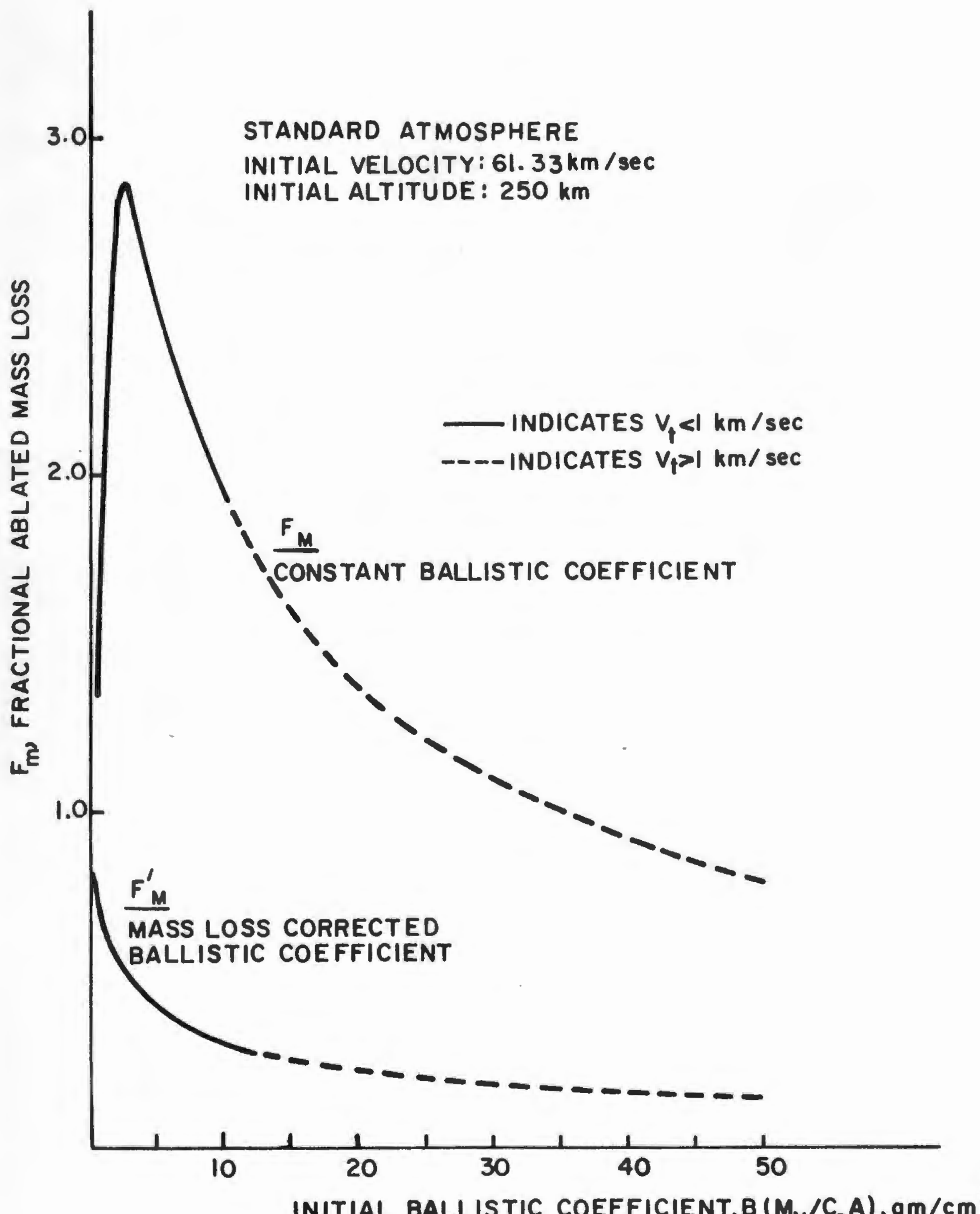

FIGURE 15. MASS LOSS CORRECTED SURVIVAL RESULTS - FRACTIONAL ALBATED MASS LOSS VS. INITIAL BALLISTIC COEFFICIENT JUPITER DIRECT ENTRY

if the maximum orbital period following the first pass had been set larger than 10^7 sec. The grazing entry trajectory data also reveal that:

As B increases, the maximum h_p for entry capture on the first pass decreases.

All vehicles regardless of B value will not enter on the first pass if $h_p > 100$ km.

All vehicles (irrespective of B) will escape (or enter very long period orbits) if $h_p > 125$ km.

Multiple entries do not substantially increase the total heat absorbed and from a survival viewpoint represent a rather good means of entering heavy vehicles successfully.

The above results are only very slightly affected by atmospheric parameters (i.e., "sea level" density and scale height).

Peak deceleration forces in grazing entries range from 50 to 200 g's, contrasting with direct entry g's of 6000 and greater.

5.4 Overall Results

As with most entry situations, the effect of entry angle is very strong, but in Jupiter's case grazing entry trajectories bear with them both a lesser peak heating rate, q_{max}, and a lesser total heat absorption, H_T. This, of course, is a result contrary to that usually found in inner planet entries, and is the effect of Jupiter's high atmospheric rotation rate. The manner in which the fractional ablated mass loss varies with the ballistic coefficient shows that direct entry vehicles with B > 7.5 g/cm^2 will not only experience increased q_{max}, but will not "survive" in the sense we have defined it. These deductions, however, result from the use of a constant ballistic factor and do not reflect the possible benefits of other phenomena which may operate to reduce the heating effect. In general, the results definitely favor grazing entry; the significant effects, heating, total heat absorption, and deceleration forces, all are substantially less than in the angle and direct entry cases. Grazing entries in general permit a rather wide range of B values to survive.

6. CONCLUSIONS

The conclusions fall into two basic categories: Feasibility Results and Major Technical Problem Areas; both are very important and not unrelated. The conclusions regarding feasibility are heavily dependent upon our assumptions (see Appendix A).

Under the stated assumptions and conditions, grazing entry trajectories appear to be thermodynamically feasible; angle and direct entries apparently are not. The more general conclusion, however, should be that grazing entries are always superior to other modes. Because of the conservatism in the heat transfer estimates, it is possible that direct entries in reality might survive, but these conditions also would affect the grazing entry survival results in a favorable manner.

The finding that planetary capture is assured for $h_p < 125$ km then leads to the result that the most feasible entries are grazing entries with corridors of $h_p < 125$ km. But such entries impose critical terminal guidance requirements.

Accounting for mass loss effects on ballistic coefficient, for ablation product specific impulse, for thermal radiation pressure and for possibly important magnetofluid-dynamic forces may result in large performance gains.

A retro maneuver in which as much as 6 km/sec would be removed from the entry velocity has an effect on survival, but the weight penalty greatly exceeds that which would have been lost by ablation in accomplishing the same velocity decrement; the case for using a DV to ease the entry heating problem cannot be justified on a mass loss basis.

We can speculate on the survival of entry probes for the outer planets by comparing planet characteristics and using the same survival criteria. Grazing entries into Saturn appear feasible, but the success of a direct entry vehicle should be considered. The feasibility of such entries, nevertheless, depends on the elemental constitution of these planets in their visibly accessible atmospheres, and upon the validity of the survival criteria for each.

Major uncertainties in the composition of the atmospheres of the outer planets, in the thermophysical properties of high temperature gases, in hypersonic heat transfer, and in the performance of ablator materials essentially comprise the major technical problem areas.

Our current knowledge about the composition and structure of the atmospheres of the outer planets is grossly inadequate for detailed entry studies. If helium is assumed to be present, then the key unknown is its abundance, because this one unknown introduces ultimately the largest uncertainty in the survival results. Therefore, the questions of whether and how much helium exists in the Jovian planets are the most urgent.

The ultra-high shock temperatures generated in outer planet entries make it imperative that the chemistry and physics of gases and gas mixtures (specifically H_2-He) at very high temperatures and pressures be theoretically understood and experimentally determined. The lack of engineering methods to calculate their high temperature thermophysical properties, especially radiative properties of gases and gas mixtures, and the lack of experimental data pose serious impediments to estimating even gross radiative properties.

Current heat transfer prediction schemes generally fail to treat adequately, if at all, the collective heating effect of the individual heat transfer processes, i.e., the total hypersonic heat transfer environment. Schemes which treat the radiation-dominant cases are too specialized to be of general use. The basic deficiency is the inability to describe and solve the coupling between modes of heat transfer and the gas-dynamic variables.

The physical survival of a Jupiter entry vehicle rests almost entirely upon the effectiveness of the ablator system. If the ablator fails, the vehicle fails. This deduction exposes a more basic problem - that of establishing criteria for selecting these materials. The response of an ablator system to a very high heat flux environment substantially modifies that environment, and the equilibrium reached in the process varies with local geometry; and all of these vary greatly with time. The point is that without reasonable specifications of the environment and of the materials, little hope exists for making reasonable estimates of ablator performance in outer planet entries by extrapolating current technology. The basic question of materials performance itself is not clear, but it seems certain to be related to hydrogen compatibility, ablation shaping and optimum initial shape, and to high pressure thermodynamics.

7. RECOMMENDATIONS

The helium abundance on the Jovian planet is a question which we regard as the primary area for further study. The most immediate question is, of course, that of a lack of data on Jupiter's helium abundance. For this reason, we strongly urge more ground-based observations (including Earth orbiting astronomy), and occultation experiments. These recommendations are not inconsistent with the probe's mission, since we must know *a priori* about the upper atmosphere, which the probe must penetrate in order to look at the lower atmosphere. Much closer bracketing of planetary composition and structure data will be needed before engineering design may be initiated.

In recommending ground-based spectroscopic observations we realize the extreme difficulty in detecting helium and measuring its abundance, and that orbiters and flybys can add little to improve this situation. Occultation experiments, however, can give scale height, if not composition information; and such data would be very useful in resolving the helium question. Improved techniques and more sophisticated approaches now being developed give some promise that reasonable ground-based estimates of composition will be available in the early 1970's. If not, consideration of sacrificial probes may become necessary.

Even though Jupiter helium abundance data do not yet exist, the thermophysical properties of helium are of general interest and should be studied. In Jovian entry design studies, the properties of pure helium (or pure hydrogen for that matter) will likely be of limited value. More properly are needed the physics and chemistry of a hydrogen-helium mixture representative of Jupiter's upper atmosphere. Our current information allows equally plausible models of hydrogen-rich or helium-rich atmospheres. Assuming that reasonably accurate helium abundance data are not soon forthcoming, we would recommend an exploratory study to examine the gross properties of two hydrogen-helium compositions, one 30 percent (hydrogen-rich) and the other 70 percent helium (helium-rich). Such a study should give a good feel for the types of, and difficulties in, the problems involved. Also, it would shed light on how the entry thermodynamics problems will vary with the individual outer planets, since the planetary helium abundance is expected to increase with increasing distance from the Sun.

The transfer of heat at very high velocities is tremendously complex, and requires much more understanding than apparently now exists. The thermal radiation transfer process, its effects on the flow field and enthalpy distribution, and its interaction with the ablation products and oncoming flow stream should be studied from a theoretical viewpoint as well as by experimentation. A comprehensive heat transfer prediction scheme is a necessity. Accounting for separable or distinguishable heat transfer processes individually will not be a valid approach when, as in the case of very high velocities, all these processes are strongly coupled and vary greatly with geometry and time. For outer planet entries such schemes must be developed early enough to be available in engineering form to vehicle designers.

The mechanisms of heat transfer by ions and electrons in collisions with the wall and the plasma-dynamic effects of the ions on the structure and thermochemistry of the flow field need to be understood more fundamentally. In short, the overall effects of intensely radiating shock layers on the heat transfer processes deserve much attention.

A materials system resistant to or inert to hydrogen is very much needed. The ablator material would ideally be characterized by high strength and optimum mechanical properties, a low temperature of but a very high heat of vaporization/sublimation, and by transparent ablation products. The important, if not the main, unknowns in ablator heat shields for Jupiter entries are the optimum initial shape and the manner in which the shape changes during ablation. The shape problem is of fundamental importance and should be given early attention.

We cannot recommend the early initiation of studies to devise techniques or processes to suppress entry heat transfer, although there are evidently many constructive and theoretically promising concepts. One possible exception in this respect is boundary layer gas injection, because it may drastically influence not only the overall heat transfer but the pattern of ablation shaping.

For heavy vehicles, grazing entries with multiple passes must be considered because of the survival conditions. There is much room for optimizing the entry trajectory in terms of survival criteria for such entries, particularly in the cases of vehicles with non-zero Lift/Drag coefficients.

In addition to devoting considerable effort to the development of the above technological problem areas, NASA should also give early attention to the development of scientific objectives of total Jupiter exploration, especially to those that suborbital missions could support.

Since the concept of survival we have devised has been based on somewhat arbitrary criteria, it would be appropriate to examine these criteria more closely in future endeavors.

In terms of specifics the above recommendations are these:

A. Research on the helium abundance and the composition and temperature profiles of the outer planets using theoretical and empirical models, ground-based observations, Earth satellite astronomy, multifrequency occultation and spectroscopy measurements on early flyby/orbiter, and stellar occultations when opportune.

B. Theoretical and experimental determinations of:

   1. The thermal radiative properties of helium to 60,000°K, of hydrogen to 25,000°K, and of the planetary minor constituents (CH_4, NH_3) to 25,000°K.

   2. The thermodynamic and transport properties of helium to 60,000°K, and of the planetary minor constituents to 25,000°K.

   3. The effects of high temperature hydrogen-helium chemistry on structure of the shock layer and flow field.

C. Fundamental and applied studies in hypersonic gas-dynamics to develop more comprehensive and more accurate heat transfer prediction schemes or to extend the range of validity of existing correlations; and to better understand the effects of gas injection, upstream heating, and of ablation and ablation products on hypersonic heat transfer.

D. Fundamental and applied research on low temperature, high enthalpy ablator materials resistant to hydrogen/helium mixtures, on the geometric shape changes induced by ablation, and on the ballistic and thermodynamic effects of these changes.

E. An experimental probe to Jupiter, which would either (1) enter Jupiter's upper atmosphere on a grazing trajectory, capture a sample of its atmosphere, and return to Earth for examination; (2) upon entering Jupiter's atmosphere in a non-surviving descent, provide a luminous wake for spectrographic analysis by an orbiting spacecraft, or (3) be an instrumented engineering dummy to determine the thermal environment, ablation rates, materials performance, and the associated thermodynamics.

Appendix A

HYPERSONIC HEAT TRANSFER ASSUMPTIONS FOR THE CONTINUUM REGIME

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HYPERSONIC HEAT TRANSFER ASSUMPTIONS FOR THE CONTINUUM REGIME

A.1 ASSUMPTIONS OF NECESSITY

A. The shock layer is optically thick, and its optical properties may be calculated from a knowledge of the Rosseland Mean Free Path.

The assumption of an optically thick shock layer corresponds to a gas emissivity approaching unity; hence it is conservative. The Rosseland Mean Free Path overpredicts emissivity except at high opacity, thus erring on the conservative side. The assumption becomes necessary (at least in this study) because the shock statistics - composition, thickness, radiative properties of constituents - are either unknown individually or their expressions are mathematically intractable.

B. Thermal radiation from the shock layer has a negligible effect on shock profile and on convective heat transfer.

Thermal radiation from the shock layer has the effect of reducing temperatures and temperature gradients, which in turn affect shock profile and convective heat transfer. The assumption is conservative but allows independent computation of convective and radiative heating. It is conservative because the total energy dissipation is not restrained by energy conservation requirements, and thus the thermal radiation is not assumed to deplete the energy available to other processes, and vice versa.

C. Ablation products do not react with atmospheric components to increase the heat transfer.

The ablation products might enter into chemical reactions with the atmospheric constituents, and may have a profound heat transfer effect. We cannot judge the effects of uncertainties in this assumption because the ablator material and its products in a Jovian atmosphere are unknown; nevertheless, an appropriate choice of materials would minimize such effects.

D. Ablation products do not affect the overall heat transfer.

The heat transfer processes produce a very high ablation rate. Unless a low temperature ablator is used, the ablation products will be very hot, will contribute to the radiative heating, and will affect the convective heating rate (Craig and Davey 1963). Nevertheless, the omission of their potential contributions to the total heat rate should not lead to large or unacceptable errors, because of compensating effects and also because the predicted heat rates approach closely to their theoretical limits.

E. Induced chemical reactions of the components of the atmosphere do not affect overall heat transfer.

The outer planet atmospheres consist mainly of hydrogen and helium. We do not expect that they will interact chemically with one another to the extent of having first order effects on the overall heat transfer. The minor constituents of methane (CH_4) and ammonia (NH_3) likewise are not expected to react significantly either with one another or with hydrogen and/or helium. These constituents in general would not be expected in other than trace concentrations above the cloud layers.

F. Recombination of electrons and ions at the vehicle's surface can be neglected.

This process increases the heat transfer to the vehicle because it involves considerably greater energy per collision than is transferred in convection (in which only kinetic energy is transferred). Without detailed calculations of the ion-electron distributions in the flow field, it is impossible to estimate what fraction of the total ion-electron concentrations will recombine at the vehicle's surface. A previous assumption - that of an optically thick shock layer - tends to reduce the error in this assumption, since the optically thick layer will radiate the energy before it can be released in surface recombination.

G. Over the major portion of the entry trajectory, the ballistic characteristics of the vehicle do not change.

In assuming constant ballistic properties we are actually asking the quantity m_V/C_DA to remain constant; this may not be unreasonable depending upon how rapidly vehicle mass, m_V, and projected (frontal) area, A, change due to ablation. However, if ablation causes gross shape changes, the drag coefficient, C_D, may also change. This assumption must be made because large mass losses are inevitable; the resulting changes in area and in drag coefficient, though perhaps dependent in part upon the ablator and its initial configuration, remain unknown. The assumption would be conservative if ablation reduces the ballistic factor; this is probably the more likely occurrence because area would change less rapidly than the mass.

H. The composition and temperature of the atmosphere do not change. Minor constituents are not present in sufficient quantity to register first order thermodynamic effects.

All the trajectories in this report have been calculated under the assumption of constant properties of the gas-dynamically sensible atmosphere. The first part of this assumption should hold in the case of Jupiter since we will require that all of the velocity loss occur in the stratosphere (the isothermal atmosphere). How well it would hold for the remainder of the outer planets we do not know.

The second part of this assumption removes the necessity to calculate the thermophysical properties of minor constituents. Lack of information and data concerning what elements are present, in what concentrations, and about their high temperature reactions and thermophysical properties necessitates this assumption. Planetary composition information becomes increasingly sparse going from the nearest to the furthest of the outer planets.

A.2 ASSUMPTIONS OF CONVENIENCE

The assumptions made largely to reduce the complexity or magnitude of the computational problem include:

I. Stagnation point heating predictions are conservative (pessimistic).

Peak heating usually occurs at the stagnation point. Thus stagnation point heat absorption rates generally over-predict the average heat transfer. The assumption is common practice and easily justified in gasdynamic heat transfer experiments (Hayes and Probstein 1959). With some configurations, however, peak heating may not occur at the stagnation point; but in such cases the excess over stagnation point heating is probably not greater than 25 percent, and the overall geometric average is probably still less than that at the stagnation point. Compared to other possible errors, this is a minor one.

J. Re-radiation from the vehicle is negligible, relative to the radiative intensities in the gas stream.

This is a conservative and realistic assumption, which removes the need to calculate vehicle wall temperatures and enthalpies.

K. All heat transferred to the vehicle causes ablation.

This neglects the relatively small storage and conductivity terms in the heat balance. It is easily justified, and somewhat conservative.

L. The enthalpies of the vehicle body and of the thermal boundary layer very near the wall are negligibly small compared to that of the shock layer.

This is a conservative assumption because it presumes a maximum enthalpy difference between the shock layer and the vehicle body. It also eliminates the need to calculate vehicle enthalpies and temperatures.

Appendix B

PREDICTION SCHEMES FOR CONVECTIVE HEATING

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PREDICTION SCHEMES FOR CONVECTIVE HEATING

Ideally, we want a comprehensive prediction scheme or correlation (a prediction scheme with experimental validity) which will give total heat transfer rates at velocities up to 60 km/sec in a combined hydrogen-helium atmosphere. In fact, however, there are no convective correlations for heat transfer in either hydrogen or helium at velocities greater than 10 km/sec. Convective heat transfer correlations usually break down when ionization influences the heat transfer process. Since each gas has its peculiar density and temperature conditions at which ionization becomes significant, the present task becomes one of finding the upper useful limit of a correlation, and using a theoretical scheme at velocities in excess of this limit.

After reviewing several prediction schemes an expression due to Fay, Moffatt, and Probstein (referred to hereafter as FMP) was selected (Fay et al. 1964). This method estimates the stagnation point convective heat transfer coefficient* in

*All of the expressions for heat transfer in this report are for stagnation point heating and all assume a vehicle nose radius of 0.5 meter.

highly ionized flow fields about blunt spherical bodies. The FMP method is quite general and should be reasonably valid for velocities up to 60 km/sec.

The FMP expression is:

$$\xi \, (= C_H) = 0.64 \left\{ \frac{\epsilon_1 \, K_s}{\sqrt{\epsilon} \, R_V \, V \rho_\infty \, C_{p_s}} \right\}^{1/2} \frac{C_{p_s} \, T_s}{V^2/2} \qquad \text{(B1)}$$

in which

$\epsilon = \rho_\infty / \rho_s = (\gamma-1)/(\gamma+1)$ (for $M_\infty \gg 1$)

ρ_∞ = Free stream (ambient) density

ρ_s = Stagnation point density

γ = Ratio of specific heats, c_p/c_v

M_∞ = Free stream mach number

R_V = Radius of nose cone, 0.5 meter

V = Gasdynamic velocity

C_{p_s} = Effective ionic heat capacity = $\frac{5}{2} \frac{k}{m_i} (1 + Z_e)$

k = Boltzmann's constant

m_i = Ionic mass

Z_e = Effective electronic charge

T_s = Temperature in stagnation region.

The subscripts e and i refer to electrons and ions, respectively; the subscript s refers to conditions in the shock at the stagnation point. The term $\epsilon_1 \, K_s$ comes from Spitzer (1956) and is essentially the thermal conductivity in the gas stream at the stagnation point, assuming a zero potential gradient. Spitzer gives the conductivity of an ideal (Lorentz) gas as

$$K_s = 4.67 \times 10^{-12} \frac{\delta_T \, T^{5/2}}{Z_e \ln \Upsilon} \tag{B2}$$

where

$$\ln \Upsilon = 9.43 + 0.5 \ln (T^3/n_e),$$

and

$$n_e = \text{electron number density.}$$

The quantities ϵ_1, δ_T, and Υ, defined by Spitzer (1956) account for thermoelectric, real gas, and electron shielding effects, respectively.

In the computations and throughout this report, the heat transfer rates are expressed in units of cal/cm^2-sec; all other quantities are in cgs units unless otherwise noted. For comparison:

$$\begin{aligned} 1 \text{ cal/cm}^2\text{-sec} &= 3.60 \text{ BTU/ft}^2\text{-sec} \\ &= 4.184 \times 10^7 \text{ erg/cm}^2\text{-sec} \\ &= 4.184 \text{ joule/cm}^2\text{-sec} \end{aligned}$$

To obtain the FMP expression in the form of Eq. 9, i.e., velocity, V, and ambient density, ρ_∞, as variables, Equation B1 was solved for various values of V and ρ_∞. Table B-1 lists representative data resulting from such solutions for both hydrogen and helium. The logarithms of heat transfer rates obtained were then cross-plotted vs. log V (at constant ρ) and vs. log ρ (at constant V) to obtain the best fits to the prescribed form. The process which Table B-1 reflects is the

Table B-1

THERMODYNAMICS AND CONVECTIVE HEAT TRANSFER RATES* OF HYDROGEN (H_2) AND HELIUM (He)

Gasdynamic Velocity, V (km/sec)	Stagnation Enthalpy, h_s (kcal/gram)	Ambient Density, ρ_∞ (g/cm^3)	Stagnation Pressure, p_s (atm)	Stagnation Temperature, T_s (°K x 10^{-3}) H_2	He	Electron Number Density, n_e (e^-/cm^3)** H_2	He	Fractional Ionization*** H_2	He	FMP Heat Transfer Rate (cal/cm^2-sec) $H_2(q_1)$	$He(q_2)$
60	430	10^{-9}	0.04	14.0	38.4	1.37(14)	1.15(15)	3.68	2.54	6.1	85
		10^{-8}	0.4	17.6	43.2	1.41(15)	1.02(16)	3.79	2.50	30	400
		10^{-7}	4.0	19.5	49.0	1.25(16)	8.85(16)	3.50	2.44	147	1600
48	275	10^{-9}	0.03	11.5	34.4	9.00(12)	1.13(15)	2.90	2.13	3.4	58
		10^{-7}	3.0	15.5	42.4	8.1 (15)	8.98(16)	2.75	2.08	74	1050
42	210	10^{-9}	0.02	11.0	27.7	7.4 (13)	1.33(15)	2.66	2.00	2.9	34
		10^{-8}	0.24	12.4	28.4	6.22(14)	1.29(16)	2.57	1.99	13	125
		10^{-7}	2.4	14.5	30.2	6.3 (15)	1.20(17)	2.54	1.97	61	480
		10^{-6}	24	16.5	33.8	4.75(16)	1.05(18)	2.40	1.94	280	2250
36	154	10^{-9}	0.02		18.8		1.73(15)		1.80		14
		10^{-8}	0.17		21.2		1.49(16)		1.76		61
		10^{-7}	1.7		24.3		1.27(17)		1.73		205
		10^{-6}	17		28.1		1.06(18)		1.69		1400
30	107	10^{-8}	0.11	9.4	19.5	1.09(14)	1.30(16)	2.07	1.50	5.3	45
		10^{-7}	1.1	10.3	22.2	4.08(15)	1.07(17)	2.05	1.48	24	210
		10^{-6}	11	11.0	25.4	4.60(15)	8.84(17)	2.03	1.44	88	950
24	68.8	10^{-8}	0.07	4.3		3.53(10)	9.06(15)	1.98	1.29	0.6	33
		10^{-7}	0.71	4.7		3.15(10)		1.95		2.7	
		10^{-6}	7.1	5.4	23.1	1.22(13)	6.17(17)	1.88	1.24	13	700

*Based on stagnation point conditions according to method of Fay-Moffatt-Probstein (1964).
**1.37(14) is read 1.37 x 10^{14}.
***Expressed as moles of electrons per original mole of undissociated, nonionized gas.

following: Given ρ_∞ and V, the dynamic pressure, p_s, and the enthalpy, h_s, at the stagnation point could be calculated from the expressions:

$$p_s^* = 1/2\ \rho_\infty\ V^2 \ ,$$

and

$$h_s = V^2/2 \ .$$

Once h_s and p_s are known, T_s may be found in thermodynamic tables (for H_2, Kubin and Presley 1964, Krascella 1963), (and for He, Lick and Emmons 1962), in which also we can find the degrees of dissociation and the ion and electron fractions. These data are then used to evaluate the FMP convective heat transfer coefficients and heat transfer rates. All q values refer to heat absorption in the vehicle.

The FMP heat transfer expression for hydrogen, q_1, is very well represented in the velocity range $V > 30$ km/sec by:

$$q_1 = 1.81 \times 10^{-12}\ \rho_\infty^{\ 0.5}\ V^{2.65} \ . \qquad \text{(B3)}$$

Similarly, the helium convective heat transfer expression, for $V > 36$ km/sec, is

$$q_2 = 1 \times 10^{-16}\ \rho_\infty^{\ 0.625}\ V^{3.5} \ . \qquad \text{(B4)}$$

Plots of log q_1 and log q_2 vs. log V however, show distinct changes in slope (i.e., the exponent of V) at 30 and 36 km/sec for hydrogen and helium, respectively. At velocities

---

*The dynamic pressure p_s is actually $p_s = p_o + 1/2\ \rho_\infty V^2$, but the ambient pressure, p_o, is usually very small compared to $1/2\ \rho_\infty\ V^2$.

below these "limits" the exponent of V approaches values more commonly found in (experimental) correlations. In any case we have regarded these "limits" as the lower limits of validity for the FMP expression for predicting heat transfer in ionized flow and also as the upper limit to an extrapolation of a correlation. The basis for this arrangement follows from the fact that at velocities less than 30 km/sec (for hydrogen) the electron/ion density is less than 1 percent of the total number density.

A correlation for stagnation point heating in hydrogen reported by Marvin and Deiwert (1965) suitable for our purposes is given in the form:

$$\frac{q_o \sqrt{R/P}}{1 - g_w} = \overline{C} \cdot \left(\frac{U_\infty}{10^4}\right)^N . \qquad \text{(B5)}$$

The Marvin-Deiwert heat transfer rate for H_2 (in which $\overline{C} = 23.9$ and $N = 2.24$) with $R = 0.5$ meter becomes:

$$q_3 = 1.94 \times 10^{-15} \rho_\infty^{0.5} V^{3.24} . \qquad \text{(B6)}$$

(Marvin and Deiwert did not work with helium.)

Equation B6 compares reasonably well with the FMP expression (Equation B1). In the case of the reformulated Marvin-Deiwert expression (Equation B6) calculations were made only for velocities below 30 km/sec. It is well to note that this represents a factor of three extrapolation and is thus bound to deviate significantly from the true situation. The thermodynamic data show that ionization does not become significant (heat-transfer wise) until this velocity is reached, and the evidence seems to indicate that the usual convective correlations break down seriously only when ionization is of the order of 1 percent and more.

Finally, in selecting the hydrogen convective heat transfer prediction scheme, we have adopted the Fay-Moffatt-Probstein (FMP) prediction method (q_1) for velocities between 60 and 30 km/sec and the Marvin-Deiwert (M-D) correlation (q_3) for velocities below 30 km/sec, because it has an empirical basis and is conservative. Table B-2 compares these predicted rates at several velocities and ambient densities.

Table B-2

COMPARISON OF PREDICTED CONVECTIVE HEAT TRANSFER RATES
(cal/cm^2-sec)

Velocity (km/sec)	Ambient Density 10^{-8} gm/cm^3		Ambient Density 10^{-6} gm/cm^3	
	q_1*	q_3**	q_1	q_3
24	14.6	91.1	146	911
30	27.0	192	270	1920
36	42.8	339	428	3390

*q_1, Fay-Moffatt-Probstein expression for convective heat transfer in hydrogen. (Fay, Moffatt and Probstein 1964).

**q_3, Marvin-Deiwert correlation for convective heat transfer in hydrogen (Marvin and Deiwert 1965).

Appendix C

THE RADIATIVE HEAT TRANSFER MODEL

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In an effort to remain conservative, we have assumed that the net radiation transfer to the vehicle depends only upon shock temperature, pressure, and structure. We expect the shock layer thickness in the free molecular regime to depend upon the mean free path both upstream and downstream of the shock front (Talbot 1962). Empirical measurements (Seiff 1962) of the shock wave thickness, δ_s, show that in the continuum regime it is of the order of 1/10th the radius of the body - the R/10 approximation. The transition from a shock layer determined by mean free path (in the free molecular and transition regimes) to one determined by vehicle geometry bears importantly on the radiative heat transfer estimate. The matter becomes even more complex in highly ionized flows. In any case, because it gives a far more conservative result, we use an empirical value. Nevertheless there remain these questions:

> How does the shock layer thickness and its development depend on ambient density and vehicle geometry; to what extent does the flow regime affect this determination; and what is the structure of a strongly ionized shock?

A search of the literature for the radiative properties of gases at high temperatures revealed that while some theoretical studies are available, relatively few detailed calculations except for air and other oxygen-nitrogen mixtures, have been made, and with the same exceptions none have been directly supported by experiment.

Our approach then is to construct the radiative heat transfer model based on calculated gross radiative properties. Krascella (1963) has tabulated both thermodynamic data and the Rosseland Mean Opacity (RMO) for hydrogen to 200,000° Rankine. The RMO can be combined with the shock thickness to obtain an approximate emissivity. The emissivity of a gas has the form

$$\epsilon_H = 1 - e^{-\delta_s/L_R} , \qquad \text{(C1)}$$

which in the optically thick case reduces to

$$\epsilon_H \cong \delta_s/L_R . \qquad \text{(C2)}$$

To first order we can now write the radiative heat transfer rate, q_4, of the shock layer radiation as

$$2q_{rad} = (\delta_s/L_R) \cdot \sigma T_s{}^4 , \qquad \text{(C3)}$$

where

q_{rad} = Shock radiation heat flux absorbed in vehicle,
δ_s = Shock thickness, cm
L_R = Rosseland mean free path (= 1/RMO), cm

σ = Stefan-Boltzmann constant, cal/cm^2-°K^4

T_s = Stagnation temperature, °K.

The hydrogen RMO data (Krascella 1963) and T_s^4 (from T_s data in Table B-1) were both fitted to a curve of the standard form (cf. Equation 9). Using in Equation C2 the RMO and T_s^4 data and a shock thickness of 0.13 R_V (Bronshten 1964), i.e., 6.5 cm for R = 0.5 meter, we finally have the result for the absorbed radiative heat transfer from a hydrogen shock:

$$2q_4 = 3.625 \times 10^{-25} \rho_\infty^{1.8} \cdot V^6 . \qquad \text{(C4)}$$

The radiative heat absorption rate in the vehicle is q_4; $2q_4$ is the estimated total radiative flux of the shock, where the factor 2 accounts for the fact that at least one half the radiation flux is directed away from the vehicle. Equation C4 predicts the values computed from Equation C3 to within 20 percent, but, in certain cases, exceeds the blackbody flux - in effect predicting that $\epsilon_H = L_R^{-1} \delta_s > 1$. Since the radiative flux cannot exceed the blackbody flux for any given temperature, the latter acts as an upper bound on the predicted radiative heat transfer rate. In the case of hydrogen the blackbody flux absorbed in the vehicle, at the stagnation temperature, is given by the expression

$$2q_5 = \sigma T_s^4 = 9.214 \times 10^{-19} \rho_\infty^{0.28} V^{3.68} . \qquad \text{(C5)}$$

For helium, the blackbody heat flux is:

$$2q_6 = 5.832 \times 10^{-30} \rho_\infty^{0.22} V^{5.60} . \qquad \text{(C6)}$$

High temperature radiative data for helium could not be found in a form useful for estimating heat transfer. It would be possible to obtain these data from theory, but this was outside the scope of the study. As Table C-1 shows, q_6 frequently exceeds the free stream enthalpy flux, q_F, and hence is an unrealistic prediction scheme. The time profiles of radiative rates q_4 and q_5 are compared in Figure C-1 for a direct entry trajectory, and in Figure C-2, for a grazing entry.

We must emphasize that no useful helium radiative data were found. Further, it should be realized that the radiative data for hydrogen (Krascella 1963) are theoretically computed data and have not been verified experimentally. Engineering data must be generated before probe vehicles can be intelligently designed.

In Table C-1 we have presented the heat transfer rates predicted by the radiative expressions and the free stream expression for selected velocities and densities. The magnitudes are very great and it is worth appreciating them in terms of ablation rates. For example, if we assume an ablator density of 1.0 gm/cm^3, a heat of ablation of 2500 cal/gram, and a heat transfer rate of 6250 cal/cm^2, we see that the surface recession rate is 2.5 cm/sec (at the stagnation point). Undoubtedly this rate cannot long be tolerated.

The above schemes have all been based on properties of the pure components, and it is worth asking to what extent the pure hydrogen results would represent or depart from those of

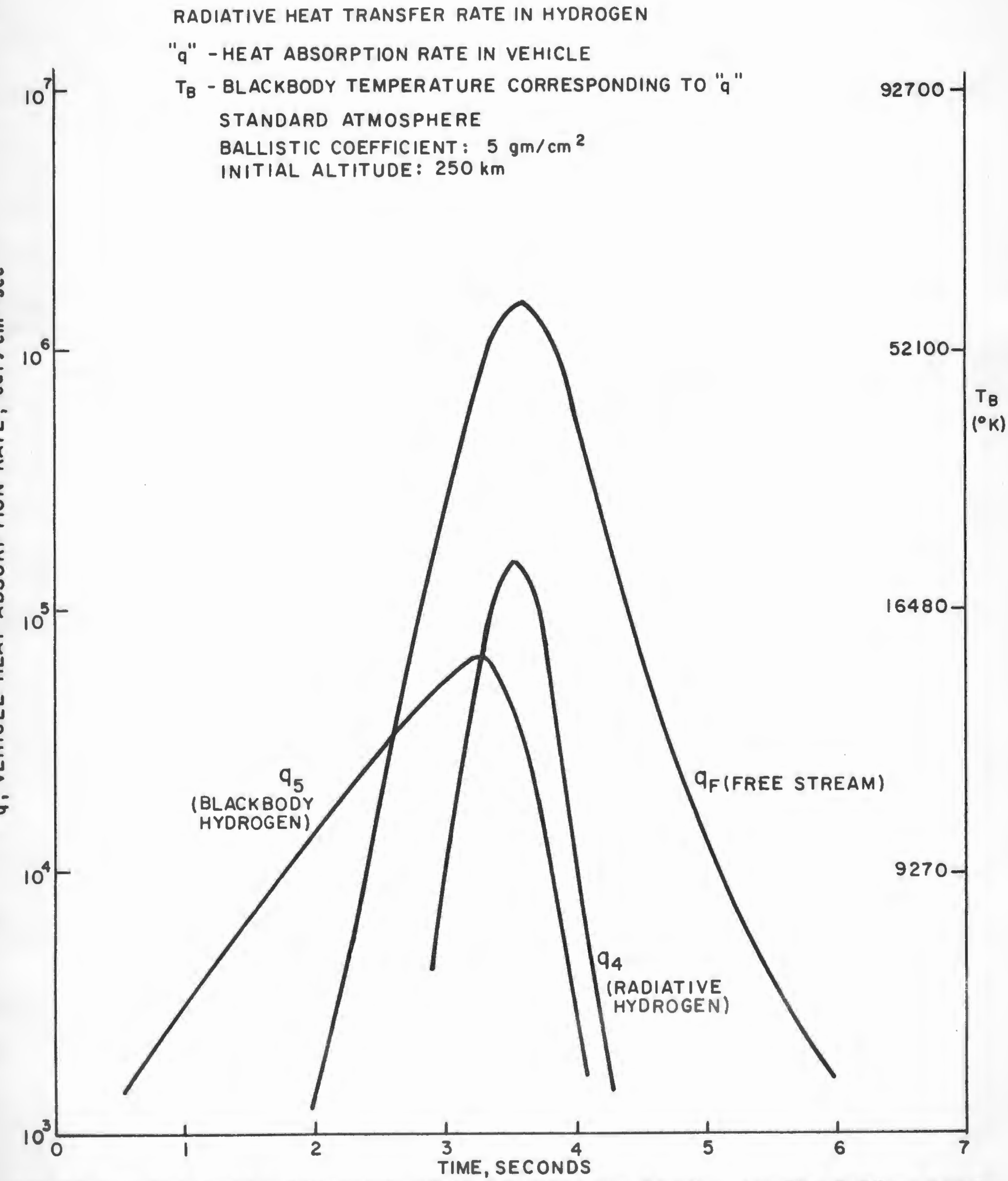

FIGURE C-1. ESTIMATED RADIATIVE HEAT ABSORPTION RATES- JUPITER DIRECT ENTRY

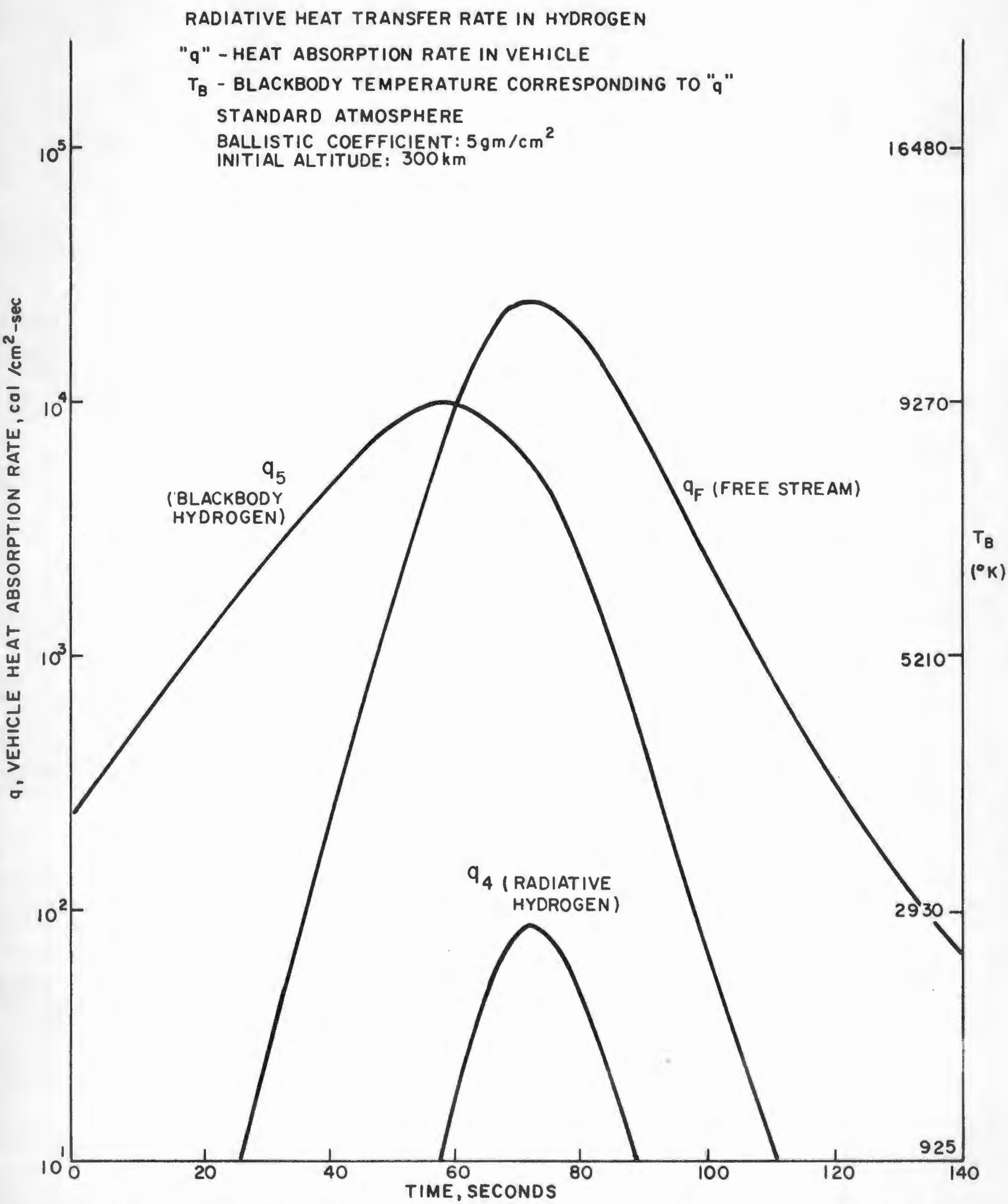

FIGURE C-2. ESTIMATED RADIATIVE HEAT ABSORPTION RATES - JUPITER GRAZING ENTRY

Table C-1

COMPARISON OF PREDICTIONS
OF RADIATIVE HEAT TRANSFER EXPRESSIONS

Velocity (km/sec)	Atmospheric Density g/cm^3	q_4 (cal/cm^2-sec)	q_5 (cal/cm^2-sec)	q_6 (cal/cm^2-sec)	q_F (cal/cm^2-sec)
36	10-8	1.57	3.55×10^3	2.63×10^5	5.57×10^3
36	10^{-6}	6.25×10^3	1.29×10^4	7.25×10^5	5.57×10^5
60	10^{-8}	33.6	2.33×10^4	4.6×10^6	2.58×10^4
60	10^{-6}	1.34×10^5	8.46×10^4	1.27×10^7	2.58×10^6

*All expressions (except q_F) give estimated radiative heat transfer rates; q_4 is radiative rate for H_2; q_5 is blackbody rate for H_2 (an upper bound on H_2 radiative heating estimates); q_6 is blackbody rate for He; and q_F is free stream heating (an upper bound on all heating rates).

H_2-He mixtures. As the temperature in mixtures of the two goes up, much of the free stream energy will be absorbed in hydrogen dissociation. In fact, because hydrogen would be almost completely dissociated before either H or He begins to ionize, the properties of H-He mixtures can be estimated by averaging properties of individual components, i.e., up to the point of large electron number densities. Above electron mole fractions of 10^{-2}, however, the cross-sections for electron ionization become of first order importance as does the probability of ionizing collisions of hydrogen and He atoms. The risks involved in simple averaging of thermophysical properties of high temperature gas mixtures become too great when ionization must be considered.

Because the emissivity of the shock layer depends so strongly on the shock thickness, and since the opacity of the shock layer is crucial to the estimation of radiative heat flux, the shock structure problem requires serious attention. The magnitude of the calculated radiative heat flux makes it imperative that the radiation absorption in the vehicle be minimized. Possible techniques or devices to suppress the stagnation temperature include vehicle reflectance maximization, low temperature ablators, and gas boundary layer injection. Low temperature ablators and gas injection would seem to hold the greatest promise, mainly because of their potential effects on the shock layer temperatures.

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