A PHYSICAL MODEL FOR

TEKTITES OF METEORITIC ORIGIN

I. ANALYSIS OF DATA AND PHENOMENOLOGICAL BASIS

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ABSTRACT

A phenomenological study is made of the shock formation of tektites from a meteorite impacting on the earth. The calculation shows that if the meteorite that caused the Ries Kessel crater ejected large fragments from the parent meteorite at speeds of ~30 km/sec, these particles would interact with the terrestrial ejecta at the start of the recoil trajectory. A hypersonic ablation calculation at 20 km/sec is made for a single large fragment by extrapolating Hoshizaki's model for the heat transfer rate at an axisymmetric stagnation point.

The results of these calculations show that this physical model can yield the size and distribution of the tektite field being considered and also account for many of the various tektite characteristics. The analysis in this paper is limited to only observations, thus all refinements which do not clarify the basic physical model have been ignored.

INTRODUCTION

The purpose of this paper is to examine a physical model based upon a shock wave structure in order to explain the terrestrial origin of tektites found in the immediate vicinity of craters. Tektites in the Czechoslovanian field (moldavites) are considered in particular and with emphasis on their origin at the time of the Ries Kessel event.

A preliminary analysis of the propagation of high intensity wave discontinuities in impacting solids is currently underway. In order to reduce the problem to its essential physical characteristics an idealized model was chosen and will be discussed in a later communication. In this paper we wish to apply only the physical results as hypotheses to ascertain the relevance of that model to the facts of meteorites at hand.

A crystalline solid may be stressed into the plastic zone or beyond by the inertial reaction to a severe impact (Short, N.M., 1966, J. Geo. Educ., XIV, 4, 149). A shock wave then propagates through the material causing severe local supraplastic deformations, altering the chemistry along its path until it reaches the boundary of the material. At this point reflection and a transfer of momentum occurs which will lead to a high velocity mass ejection from the free surface of the solid, provided that this momentum transfer is above the rupture strength and response time of the solid. The directional energy of the shock wave is then converted to directional energy of the ejected fragment, thus little shock wave heating occurs to the matter that has been dislocated.

Sufficient data concerning the mechanics of crater formation and meteorite disintegration are not available in the case of the Ries Kessel, whereas a great deal of information has been accrued concerning the Barringer Crater event. Therefore, in this report, data is extrapolated from the Barringer Crater to bear on the Ries Kessel with the assumptions that the Ries Kessel and the Barringer Crater meteorites are both metallic, that the target of the meteorites are similar, and that both meteorites impacted at angles no larger than 55° from the vertical, as is implied from the relative geometries of the respective craters.

The diameter of the Barringer crater is 1300 meters, and its depth is 175 meters. According to Anders (1965), the age of the meteorite which caused the crater is estimated to be 20,000 years. Its mass is about 2×10^9 kg and its diameter ranged from 60 to 80 meters. Fragments from the Barringer Crater meteorite have exhibited characteristics which indicate:

a) shock induced pressures of 130 kb on the outer surface and 750 kb in the interior of the impacting meteorite (DeCarli and Jamieson, 1961),

b) temperatures of 700°K on the outer surface and 1100°K in the interior of the impacting meteorite. This temperature gradient is attributed to a shock wave (Lipschutz and Anders, 1961),

c) Chao, Shoemaker and Madsen (1960) found that the sandstone beneath the crater contained coesite, which is formed by pressures exceeding 20 kb,

d) Heymann (1964) relating He-3 content to sample depth in the meteorite found that specimens farthest away from the crater had been nearest the surface of the meteor and were the least shocked, while the specimens nearest the crater rim had come from deep within the meteorite body and had experienced the greatest shock.

A missile subjected to an impact sufficiently severe enough to stress the material locally to a molten state, induces a shock wave which carries the effects of the initial deformation throughout the material. The classical Rankine-Hugoniot relations are no longer valid because the post shock plasma reactions fall into the domain of non-relativistic degenerate Fermi-gas (NRF), in which post shock ionization occurs.

The condition for statistical degeneracy is that the inter-particle spacing be equal to the de Broglie thermal wave length, i.e., (Landau and Lifshitz, 1958),

$$r = \frac{h}{\sqrt{2mkT}} , \tag{1}$$

$$= \frac{h}{m_e c} \sqrt{\frac{m_e c^2}{2kT}} ,$$

$$r = \lambda_c \left(\frac{T_o}{T}\right)^{\frac{1}{2}}$$

in which $T_o = \frac{m_e c^2}{2K} = 2 \times 10^9\ {}^oK$ and is the temperature of a relativistic plasma.

$r \equiv$ average atomic spacing

$\lambda \equiv$ Compton wavelength

$= 3.86 \times 10^{-11}$ cm

Since $T = 1100^{\circ}K$, equation (1) shows $r \leq \lambda_e \times 10^3$ or $r \leq 3.86 \times 10^{-8}$ cm for a nonrelativistic degeneracy.

The average interparticle spacing is given by

$$r = \frac{1}{(ZN)^{1/3}} \qquad (3)$$

in which Z is the atomic numer (57) and N is the particle density (4.7 x 10 ^{24} per cm^3).

Thus

$$r = \frac{1}{57 \times 4.7} \times 10^{-8} \leq 3.86 \times 10^{-8}$$

This proves that the nonrelativistic degeneracy of iron will be maintained for interparticle compressions up to a factor of $\sim 10^3$, or volumetric compressibilities $\sim 10^9$.

The most important reaction to take place for the purposes of this analysis is the large post shock compression that results with the transfer of energy from the external thermal modes to internal modes thus cooling the once molten plasma. The analysis of this effect is complicated considerably by mathematics: we present the results of only one analysis (Skalafuris 1965). In Figure 1 we plot the post shock compressibility vs. the fraction of the shock wave energy that is dissipated into internal modes. A poly-electronic crystalline substance such as meteorite material which has many degrees of freedom, would provide a thermal sink to practically all the shock wave energy, thus this internal dissipated ratio should be close to unity. In view of this fact, a post shock compression of a thousand is perfectly reasonable in which case the material is far beyond the state of classical solid state analysis and well into the region of a NRF plasma. Thus we subscribe to Bjorks analysis as a realistic microscopic formulation of this problem.

R. L. Bjork (1961) made a theoretical investigation using a "Fermi-Thomas-Dirac" theory in the 10 mb range for the impacting material and target. Experimental data was available in the lower pressure ranges. Bjork assumed that an iron meteor with a velocity of 30 km/sec and weighing 1.2×10^7 kg impacted normally on the ground (tuff). Bjork gave the impacting meteorite the geometry of a right circular cylinder. His calculations estimate the crater's size to be 150 meters deep and 500 meters in radius. If limestone and sandstone were the target instead of tuff, (which is more realistic), the meteor would have to have a mass of about 6.4×10^7 kg. Clearly, Bjork's estimations of the size of the meteor for the Barringer Crater are much less than those previously quoted. We use Bjork's data to obtain a lower limit to the temperature, pressure, and recoil velocity of the Barringer Crater corroborating it with an independent shock wave calculation. It can be seen from Table 1 which is derived from Bjork's data that the surface pressures are consistent with Anders' analysis.

TABLE 1

$t - t_0$ (msec)	P_{max}(internal) (Mb)	P_{max}(rear surface) (Mb)	v_{max}(rear surface) (km/sec)
0.17	10	0	30
0.36	10	0	30
3.44	0.10	0.01	-8
6.36	0.20	0.02	-6
9.25	0.05	0.01	-6
24.80	0.005	0	-5
61.00	0	0	-4

where $t - t_0$ ≡ time after impact

P ≡ pressure due to hypersonic shock wave in meteorite

v ≡ velocity of upper surface of meteorite

msec ≡ milliseconds

Mb ≡ megabars

Theory

The diameter of the Ries Kessel is from 28 to 29 km and it has a depth of 500 meters (Chao and Shoemaker, 1960). If we assume an impact origin for the Ries Kessel, we can scale Bjork's data. Following Murphey and Vortman (1961) we assume that the volume of the crater produced is proportional to the energy of the meteorite. The Barringer Crater and Ries Kessel meteorites are assumed to have impacted with nearly the same speed (30 km/sec). Under this assumption, we then have the following relation:

$$\frac{T_{BC}}{T_{RK}} = \frac{m_{BC}}{m_{RK}} = \frac{V_{BC}}{V_{RK}} \quad . \qquad (4)$$

$T \equiv$ kinetic energy of impacting meteorite

$m \equiv$ mass

$V \equiv$ volume of crater

$m_{BC} = 64 \times 10^6$ kg

$V_{BC} = 0.075$ km^3

$V_{RK} = 225$ km^3

Therefore, the estimate drawn from Bjork's data leads to a mass of the Ries Kessel meteorite of 2×10^{11} kg.

To estimate the shock pressure built up in the meteorite, which is assumed to have the geometry of a right circular cylinder, we use the ratio,

$$\frac{P_1}{P_2} = \frac{dM_1/dt_1}{dM_2/dt_2} \quad \frac{1/A_1}{1/A_2} \quad , \tag{5}$$

in which,

$M \equiv$ linear momentum,

$A \equiv$ area of impacting surface .

Since the molecular constituents of the target are the same, the relaxation time, t, is such that $dt_1 \sim dt_2 \sim t$ for large momenta interactions. Therefore,

$$\frac{P_1}{P_2} = \frac{A_2}{A_1} \quad \frac{M_1}{M_2} \quad . \tag{6}$$

We have already hypothesized that $v_1 = v_2$ (impact velocities); therefore, let

$$\Delta M = m = \Psi\ (v, \mu, \Gamma) \quad , \tag{7}$$

in which,

$\Psi \equiv$ a characteristic function of the meteorite,

$\mu \equiv$ viscosity,

$\Gamma \equiv$ geometrical shape factor

We define $f_{12} \equiv \frac{\Psi_1}{\Psi_2}$ which is independent of radius.

Theoretical results state that the stress is independent of the mass at impacting object, (Clebsch, 1883), while experiments tend to imply that it does depend on the mass (Voigt, 1915). Since this is a phenomenological study, we adopt the latter conclusion.

Therefore,

$$\frac{P_1}{P_2} \approx \left(\frac{A_2}{A_1}\right)\left(\frac{V_1}{V_2}\right) f_{12} \ . \qquad (8)$$

Because the meteorites are assumed similar except for their size, $f_{12} = 1$; hence,

$$\frac{P_1}{P_2} \approx \frac{R_1}{R_2} \ . \qquad (9)$$

From Eq. (4) we find that $R \equiv$ radius of meteorite, and $\frac{R_1}{R_2} \approx 15$.

To determine the recoil velocity (v_1) of the meteor fragments, we use the ratio,

$$\frac{P_1}{P_2} = \frac{E_1/V_1}{E_2/V_2} = \frac{\varepsilon_1}{\varepsilon_2} \ , \qquad (10)$$

in which $\varepsilon \equiv$ specific energy, and,

$$\frac{\varepsilon_1}{\varepsilon_2} = \frac{v_1^{\ 2}}{v_2^{\ 2}} \ . \qquad (11)$$

Thus,

$$\frac{v_1}{v_2} \approx 3.9 \quad . \tag{12}$$

The temperatures for the Barringer Crater are estimated of 1100 °K internal and 700 °K external. Because of the short duration of the compression, the impact will be adiabatic with the temperature and pressure given by the following law,

$$\frac{P_1}{P_2} = \left(\frac{T_1}{T_2}\right)^{\gamma/\gamma-1} \quad . \tag{13}$$

If only translational modes are thermalized, $\gamma = 5/3$; thus, $\frac{T_1}{T_2} \sim 3$.

The temperature in the inner region of the Ries Kessel meteorite is $T_{RK_I} \approx 3300$ °K and the temperature in the outer region is $T_{RK_O} \approx 2100$ °K.

Because of the gross energies involved at impact, we assumed that the major portion of the meteorite is vaporized and the equations of an ideal gas hold. The front outer temperature calculated is sufficient to throw off the target rock, at the interface between the target and the meteorite, in a molten state.

In Table 2 we list the pressures, recoil velocity, and the time after the impact for the Ries Kessel obtained by scaling Bjork's data with our formulas. The data from Table 2 is

TABLE 2

$t - t_0$ (msec)	P(interior) (Mb)	P (exterior) (Mb)	v (rear surface) (km/sec)
0.17	150.0	0	30.0
0.36	150.0	0	30.0
3.44	1.5	0.15	-31.2
6.36	3.0	0.30	-23.4
9.25	0.75	0.15	-23.4
24.80	0.075	0	-19.5
61.00	0	0	-15.6

plotted in Figure 2. From Figure 2 it can be seen that the internal and external pressure undergo a single maximum, differing by an order of magnitude. The graph also shows that the recoil velocity peak occurs behind the internal pressure peak and falls off as the external pressure rises.

From previous calculations, Eq. (9), we estimated the size of the Ries Kessel meteorite to be roughly 300 meters in radius. The depth of the fragment blown off of the impacting meteorite corresponds to the thickness of the shock wave induced on contact. A shock wave converts organized motion to random thermal motion; hence the thickness (d) of ejected matter can be estimated by the equality (see appendix A),

$$d = \frac{zmLv^2}{f\ kT}\ , \tag{14}$$

which,

z ≡ atomic mass number,

f ≡ degrees of freedom per heavy particle,

L ≡ length of the meteorite (300 m),

v ≡ impacting velocity (30 km/sec),

kT ≡ thermal energy (at 0.33×10^4 °K),

If we choose iron with $z = 57$ and $f = 3$ consistent with assumption (13), then we obtain a thickness of about 20 meters.

We assume that this fragment has the geometry of a hemi-ellipsoid in which case its radius would be 90 meters. The volume is then about 3×10^5 m^3.

We assume that when the meteorite impacted, the terrestrial material was ejected at the time of the recoil velocity peak which was at 3.44 msec. From an examination of data we conclude that the fragment blew off after 24 msec (where $P_{exterior} = 0$) thereby intercepting terrestrial material from ground zero to about 400 meters in the atmosphere.

It is known that under hypersonic flow conditions the projectile is followed by a recirculation region which is approximately twice the length of the projectile (Fig. 3) thus, the ejecta will fill up the recirculation region which is at a relatively low pressure.

If the meteorite fragment blew off at 24 msec with a velocity of $\sim$20 km/sec (scaled from Bjork's data), it will intercept this ejected material and carry it on the fragment's surface as it goes into its trajectory.

The question of whether or not a meteorite fragment can survive such a severe recoil velocity and still remain intact seems to be resolving in favor of a coherent mass, because the ejection represents a transfer of the shock wave group velocity into direction motion rather than post shock thermal dissipation. However, these results are yet premature and we still consider this an open question for further research (Remo and Skalafuris, 1967).

The volume of the ejecta that the fragment intercepts can easily be calculated. If 5 m of ejecta lie on the top surface of this fragment, (an arbitrary but not unreasonable figure) then the ejected volume is 10^5 m^3 .

We now look into the aerodynamic effects on this projectile, being primarily concerned with the heat flux to this blunt body for ablation and the energy expended in traveling through the atmosphere (Fig. 4). In calculating the heat flux we start with a laminar stagnation point calculation. The Knudsen number in this problem remains less than unity (due to the large dimension of the body). Therefore we are assured of operating in the region of hydrodynamic flow.

Hoshizaki (1962) presented a relation for calculating the heat transfer rate at an axisymmetric stagnation point in the velocity range from 1.8 to 15 km per second. The equation has the following form:

$$q_s \sqrt{R_N} = C_{air} \left(\frac{R_N}{U_f} \; \frac{dU_e}{ds} \right)^{1/2} \rho_f^{\,1/2} \left(\frac{U_f}{10^4} \right)^{3.19} \left(1 - \frac{h_w}{h_e} \right) . \qquad (15)$$

We will use this relation (15) in the range of 20 km/sec. This expression includes the effect of variable Prandtl $\frac{\mu C_p}{k}$ and Lewis $\frac{D_{12}}{k/C_p}$ numbers and also takes into account ionization, from equilibrium chemistry.

C_p ≡ specific heat

k ≡ thermal conductivity

D_{12} ≡ chemical diffusion

Expression (15) can be simplified (Appendix B):

$$q_s \sqrt{R_N} = C_{air}\left(\frac{\rho_f}{\rho_s}\right)^{1/4} \left(\frac{U_f}{10^4}\right)^{3.19} \rho_f^{1/2} \quad (16)$$

C_{air} ≡ specific heat of air

R_N ≡ radius to center of curvature of projectile

U_f ≡ velocity of projectile

ρ_f ≡ density of medium in front of shock wave

ρ_s ≡ density of medium in stagnation zone

P_f ≡ pressure of medium in front of shock wave

P_s ≡ pressure of medium in stagnation zone

q_s ≡ heat transfer rate at the stagnation point

M_∞ ≡ mach number

Table 3 represents the amount of heat transferred in the stagnation zone, as a function of height over the earth. Effects of the heat transferred from ionic interactions can be neglected.

It is apparent from Table 3 that the thermal heating takes place mainly in the first 25 km of the trajectory. If the fragment comes off at an angle of 37°, the total heat transfer to the body at a height of 300 km is 5.8×10^{19} ergs.

TABLE 3

HEAT TRANSFER AT AERODYNAMIC STAGNATION POINT

(Densities from Rocket Panel, PHYS. REV. 88, 1027 (1952))

height (km)	ρ_f (gm/cm^3)	q_s (ergs/cm^2-sec)	Q (ergs/sec)
0 - 25	300×10^{-6}	5.8×10^{10}	3.5×10^{19}
25 - 50	7×10^{-6}	1.3×10^{9}	7.9×10^{17}
50 - 75	2.6×10^{-7}	3.4×10^{8}	2.1×10^{17}
75 -100	3.9×10^{-9}	--	--
100 -125	1×10^{-10}	--	--
125 -150	1.18×10^{-11}	--	--

where $Q = q_s A$

A = surface area in the stagnation zone

$A = 6.1 \times 10^4$ m^2

Heat transfer in stagnation zone

From this analysis the loss in velocity due to the heat transfer in the stagnation region is ~ 0.1 km/sec. If the heat of fusion-vaporization is about 10^{10} ergs/gm, we can melt off about 2×10^{9} gms of ejecta. At 300 km above the earth's surface, the loss of velocity due to the gravitational potential is 2 km/sec.

We now consider the loss of energy due to aerodynamic drag. Consider the pressures in the compression zone and the stagnation zone.

From Appendix Eq. (3),

$$P_s = P_f + 1/2\rho_f U_f^2 , \tag{17}$$

and

$$P_D \equiv P_s - P_b , \tag{18}$$

in which,

$P_b \equiv$ recirculation zone pressure,

$P_D \equiv$ drag pressure ,

$\rho_f = 328 \times 10^{-6}$ gm/cm^3 ,

$U_f = 25 \times 10^{7}$ cm/sec ,

$P_f \equiv \dfrac{\rho_f RT}{M}$,

$M \equiv$ molecular weight = 29 gm/mole,

$R \equiv$ universal gas constant =

8.315×10^7 erg-deg^{-1} c-mole^{-1},

$T \equiv$ absolute temperature = 230° K ,

$P_f = 22 \times 10^4$ ergs/cm^3,

$$P_s \approx 1/2 \rho_f \, U_f^2 \, , \qquad (19)$$

$$P_s \approx 10^9 \text{ gm/cm - sec}^2 .$$

We then have,

$$\bar{F} \equiv \int \bar{P}_s \cdot d\bar{A} \, ,$$

$$F \approx 2.4 \times 10^{17} \text{ gm/cm - sec}^2 \, , \qquad (20)$$

in which,

$d\bar{A} \equiv$ effective front normal area,

$\bar{F} \equiv$ force acting on the compression front of the projectile.

Now,

$$P_b = 1/K \, (P_s) \, , \qquad (21)$$

in which $K \equiv$ constant fraction. Then,

$$P_{drag} \equiv P_s \, (1 - 1/K) . \qquad (22)$$

Recent observations in satellite entry and shock tunnel testing have shown that while the pressure in the recirculation region is much less than the pressure in the compressional region, the recirculation region pressure is not negligible. It is also apparent that the majority of the drag occurs in the first 50 km of flight, because ρ_f falls off very rapidly. Taking into consideration back pressure (P_b) in the recirculation region, we can estimate P_{drag} by taking $K \approx 10$ and using Eq. (22). The total drag force acting on the projectile which comes off at a 37° angle causes a velocity change of about 5 km/sec on the fragment. At a height of 300 km the speed of the fragment is reduced to about 13 km/sec. Escape velocity at this height is about 9.2 km/sec.

Though it is clear from the previous results that the fragment will escape from the earth, some material on the surface of the meteorite will also return, because the molten ejecta runs down the side of the fragment and approaches its base, where it undergoes a severe pressure gradient caused by expansion waves emanating from the fragment base as shown in Fig. 5. Since the viscous force τ is small, this pressure gradient will accelerate this virtually unbound stream of molten drops from velocities of zero to almost the free stream velocity U_f. This glass-like stream will move in a direction opposite to that of the fragment, and will have a velocity "v" relative to the earth such that $0 < v < 13$ km/sec. Therefore, some droplets escape from the earth and others fall back covering a long narrow area at a distance from the Ries Kessel of roughly between 50 and 2000 km. Part II of this analysis will investigate in greater detail the dynamics of the stream of confined droplets as they pass over the meteorite surface, and leave the meteorite to enter the atmosphere.

The dense spray of molten droplets will not be dispersed upon leaving the meteorite fragment because the atmosphere above 25 km is very thin and can cause only negligible drag effects, and so droplets can even become rigid before entering the atmosphere where they will undergo aerodynamic ablation (Chapman, et.al., 1962). Since the fragment giving off these droplets is considered to be moving in a straight line, acting as a line-source, thereby accounting for the distribution of the moldavite field.

Conclusion

This model accounts for the observed assymetry in the tektite field about the Ries Kessel. It also accounts for its well defined boundaries since there is only a limited velocity range with which tektites could leave the meteorite fragment.

The dimension of the Lake Bosumtwi Crater on the Ivory Coast which is 10.5 kilometers in diamter (Vand, 1965), yields a mass of 3.4×10^{10} kg, large enough to fit into the above model.

It is interesting to note that the calculated masses of the bodies that have impacted at the Ries Kessel and Lake Bosumtwi sites are of the order of 10^{11}kg. These large masses suggest that the impacting projectiles are asteroids. The dates of the impact of these projectiles and their implications have been discussed (Cohen, 1963; Fleischer and Price, 1965; Faul, 1966; Zahringer, 1963; Barnes, 1963; Gentner and Zahringer, 1959; Schnetzler et al, 1966; Gentner et al, 1961, 1963; O'Keefe, 1963).

We stress that in this calculation, only numbers were derived which were essential to understanding the basic physical model. Many parameters such as recoil velocity, meteorite size, fragment size, could be changed without sacrifice to the results of the basic model.

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APPENDIX A

The kinetic energy of organized motion per particle in the meteorite before impact is equal to,

$$E_o = \tfrac{1}{2} A \, L \, z \, m \, v^2 \,, \tag{1}$$

in which,

$A \equiv$ cross sectional area impacting ,

$L \equiv$ length of the object ,

$z \equiv$ atomic mass ,

$m \equiv$ mass of a proton,

$v \equiv$ velocity .

This energy is delivered to translational modes whose collective capacity is ,

$$E_T = \frac{f}{2} \, (A \; d) \; kT \,, \tag{2}$$

in which,

$f \equiv$ degrees of freedom of the atomic species ,

$d \equiv$ thickness of the region of translational relaxation of the shock wave,

$k \equiv$ Boltzmann constant,

$T \equiv$ temperature .

Equating the two quantities yields,

$$d = \frac{z}{f} \frac{mLv^2}{kT} \tag{3}$$

where d is the thickness of the ejected matter.

APPENDIX B

The stagnation point heat rate is proportional to $\left(\frac{dU_e}{ds}\right)^{1/2}$, where $\frac{dU_e}{ds}$ is the velocity gradient. An expression for $\frac{dU_e}{ds}$ is

$$\frac{dU_e}{ds} = \frac{1}{R_N}\left[\frac{2\ (P_s - P_f)}{\rho_s}\right]^{1/2} \tag{1}$$

Conservation of momentum for a normal shock is represented by the following equation:

$$P_f + 1/2\ \rho_f\ U_f^{\ 2} = P_s + 1/2\ \rho_s\ U_s^{\ 2} \tag{2}$$

There exists a low mach number behind the shock wave in the stagnation zone. Therefore,

$$P_s - P_f = 1/2\ \rho_f\ U_f^{\ 2} \tag{3}$$

Then for the velocity gradient we have

$$\frac{dU_e}{ds} = \left(\frac{\rho_f}{\rho_s}\ U_f^{\ 2}\right)^{1/2}\ \frac{1}{R_N} \tag{4}$$

Where $1/6 > \frac{\rho_f}{\rho_s} > 1/10$.

Since the heat in front of the stagnation region is much greater than the heat on the surface of the projectile, $\frac{h_w}{h_e} \approx 0$. Then

$$q_s \sqrt{R_N} = C_{air} \left(\frac{\rho_f}{\rho_s} \right)^{1/4} \left(\frac{U_f}{10^4} \right)^{3.19} \rho_f^{\ 1/2} \qquad (5)$$

Hoshizaki computed the heat transfer for an equilibrium boundary layer by using Hansen's equilibrium transport properties. For flight velocities between 1.8 and 15 km/sec the heat transfer parameter $\frac{N_u}{\sqrt{R_e}}$ has the following temperature and flight velocity dependence:

$$\frac{N_u}{\sqrt{R_e}} = 0.478 \left(\frac{T_w}{500^\circ \ K} \right)^{0.2} \left(\frac{U_f}{10^4} \right)^{-0.31} \qquad (6)$$

where T_w ≡ temperature at projectile wall

N_u ≡ Nusselt number

R_e ≡ Reynolds number

and where $\left(\frac{N_u}{\sqrt{R_e}} \right)_{25 \text{ km/sec}}$ 0.235

The stagnation zone extends approximately 30° on either side of the horizontal (Fig. 3).

The amount of heat transfer is calculated, with the following values for the parameters:

$$R_N = 13.2 \text{ m}$$

$$C_{air} = 7.2 \times 10^{12} \frac{\text{ergs - cm}^{1/2}}{\text{gm}^2 - \text{sec}^2}$$

$$U_f = 25 \text{ km/sec}$$

$$\left(\frac{U_f}{10^4}\right)^{3.19} = 166$$

$$\left(\frac{\rho_f}{\rho_s}\right)^{1/4} = \frac{1}{1.57}$$

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FIGURE CAPTIONS

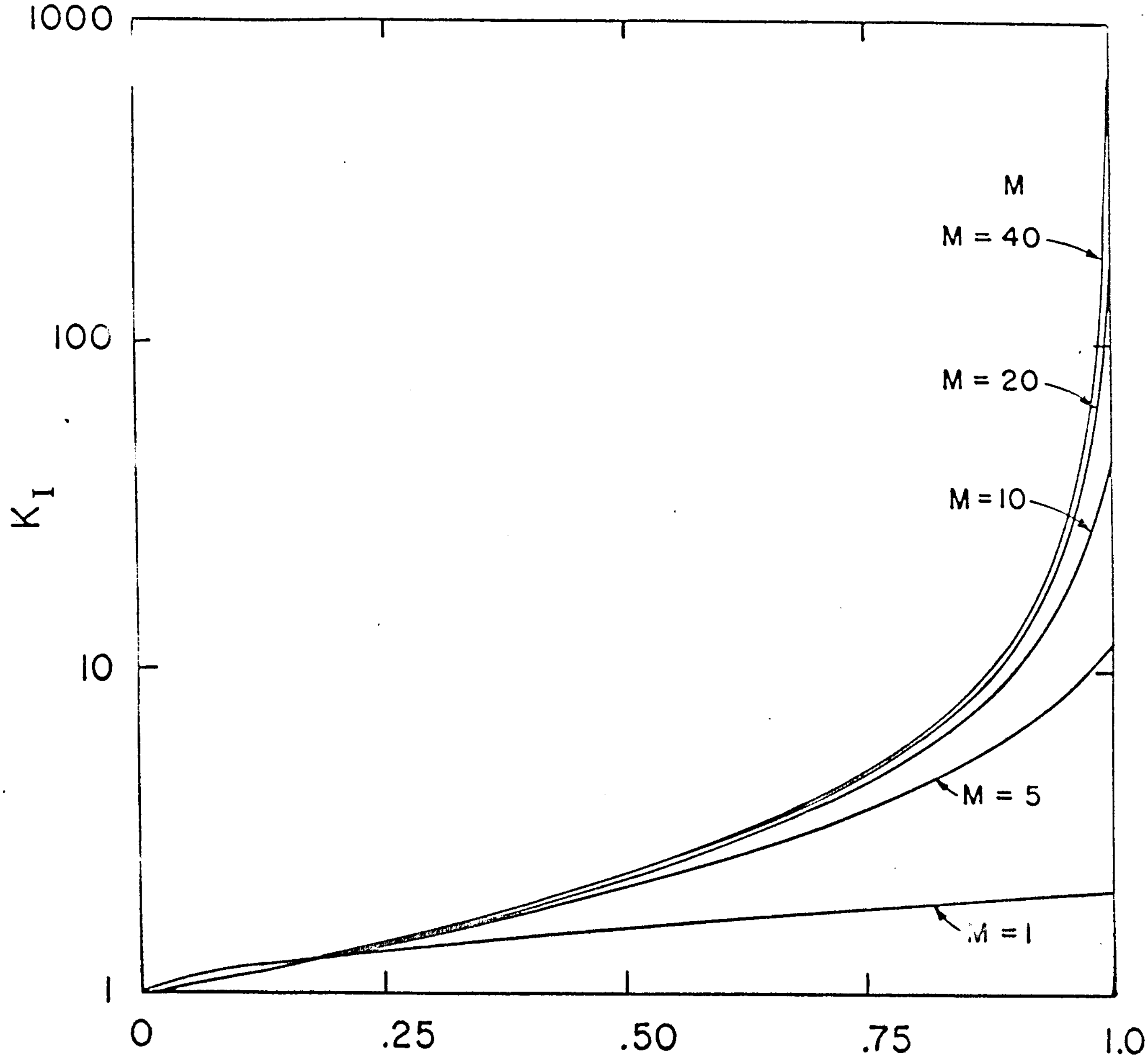
Fig. 1 - Post Shock Dissipational Compressibility

Fig. 2 - Interior, exterior pressures and recoil velocity plotted as a function of time after impact.

Fig. 3 - Shock effect due to a projectile traveling at a hypersonic speed through the atmosphere.

Fig. 4 - Diagram showing the heat transfer rate at an axisymmetric stagnation point.

Fig. 5 - Effect of the pressure gradient at the base of the projectile on the ablated material.



1000
100
10
1
K_I
0
.25
.50
.75
1.0
M
M = 40
M = 20
M = 10
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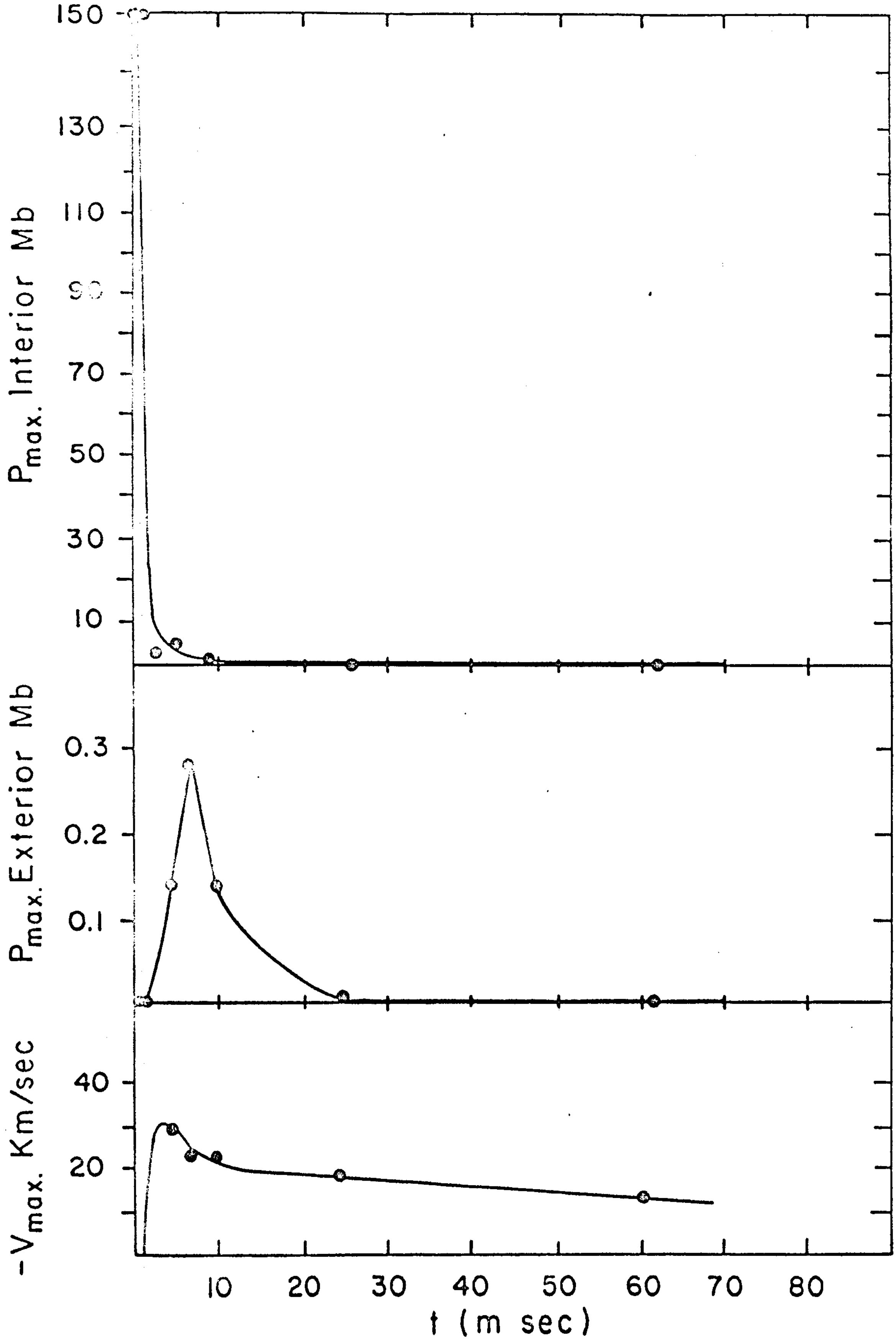
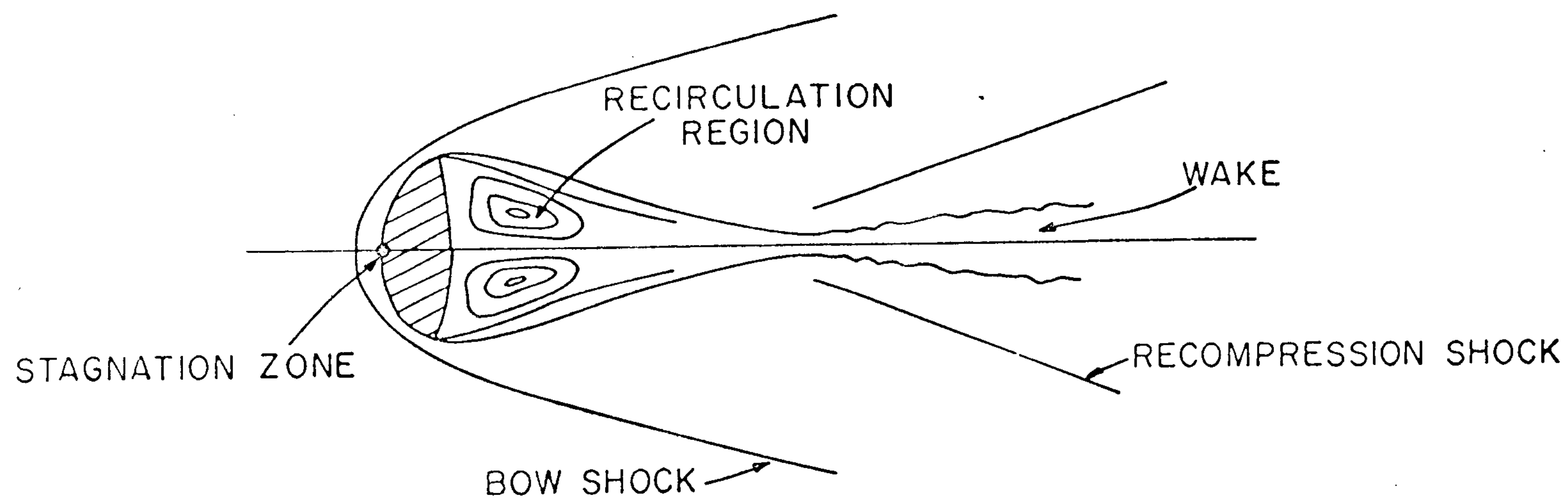
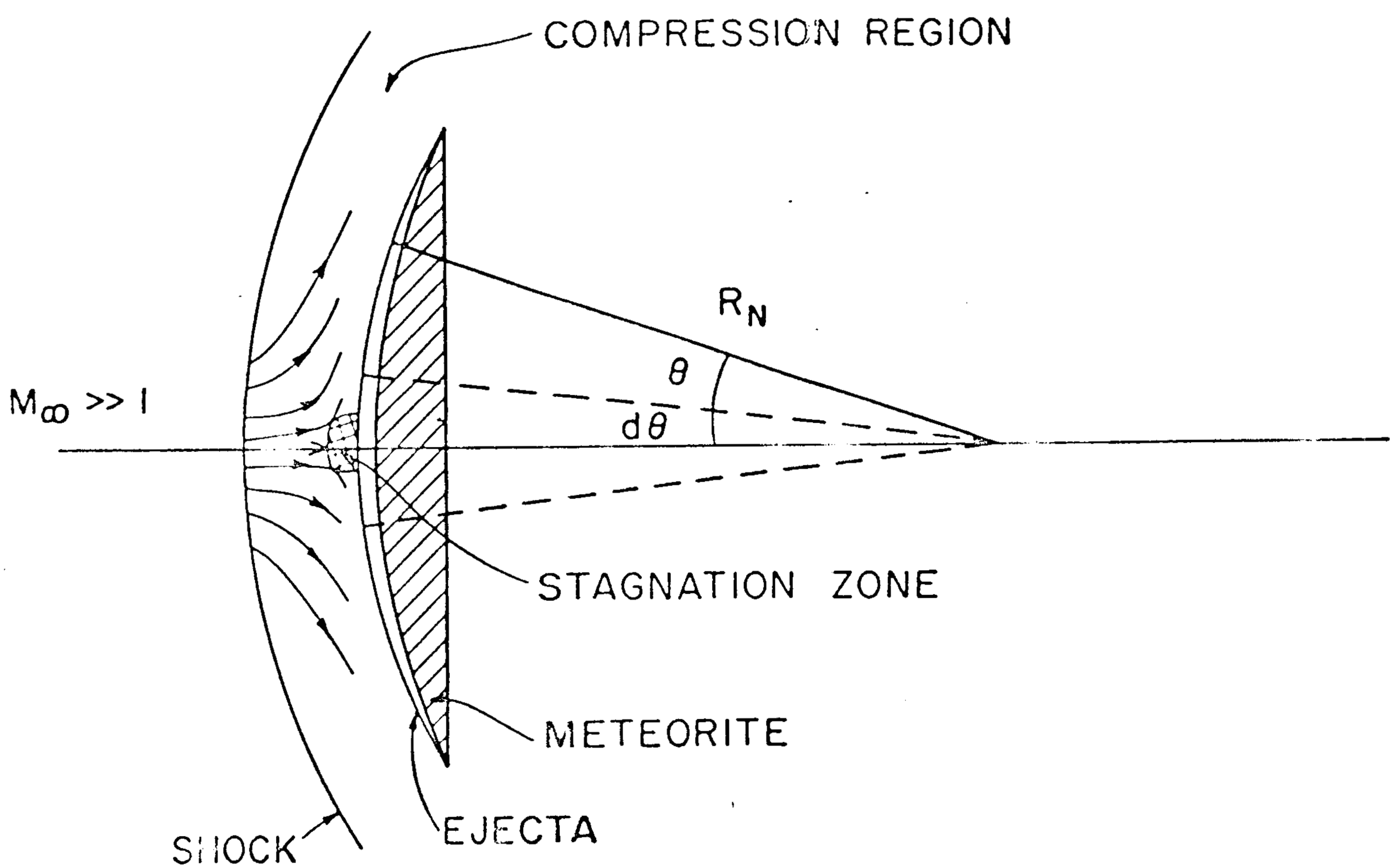
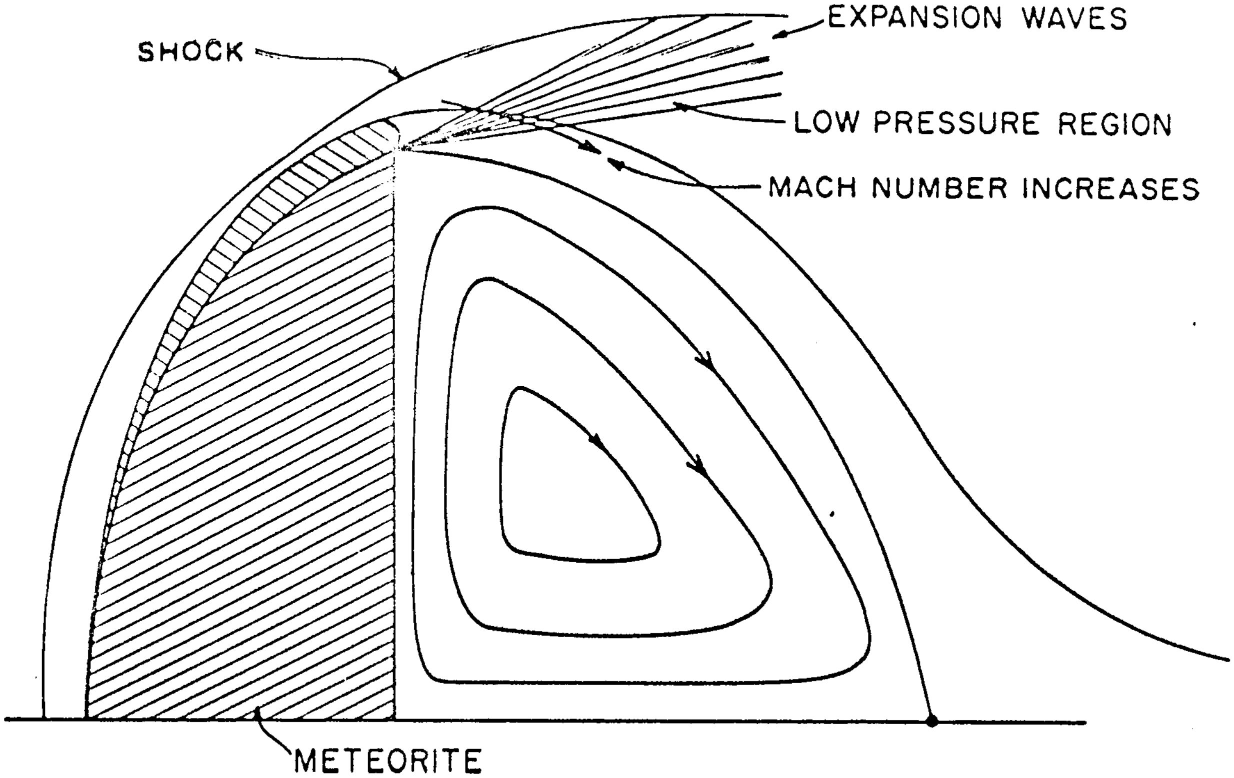
M = 1

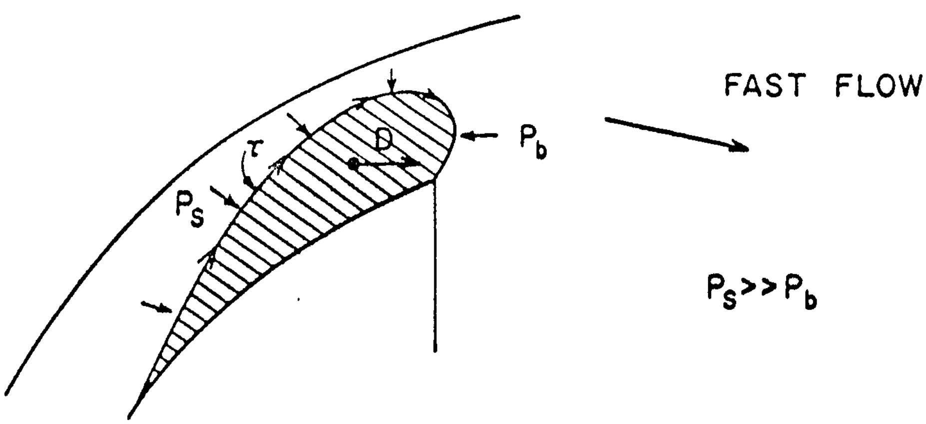


150
130
110
90
70
50
30
10
$P_{max.}$ Interior Mb
0.3
0.2
0.1
$P_{max.}$ Exterior Mb
40
20
$-V_{max.}$ Km/sec
10
20
30
40
50
60
70
80
t (m sec)


RECIRCULATION
REGION
WAKE
STAGNATION ZONE
RECOMPRESSION SHOCK
BOW SHOCK


COMPRESSION REGION
R_N
θ
$M_\infty >> 1$
$d\theta$
STAGNATION ZONE
METEORITE
SHOCK
EJECTA


EXPANSION WAVES
SHOCK
LOW PRESSURE REGION
MACH NUMBER INCREASES
METEORITE


FAST FLOW
τ
D
P_b
P_S
$P_S >> P_b$