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STUDY OF THE ABLATIVE EFFECTS ON TEKTITES:

ATMOSPHERE ENTRY OF A SWARM OF TEKTITES

Avco Research & Systems Group
Systems Division
201 Lowell Street
Wilmington, Massachusetts 01887

February 1977

Final Report for Period March 1976 - January 1977

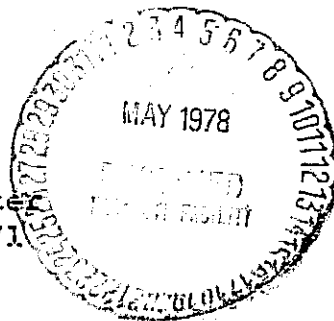Contract NAS5-22983

AVSD-0041-77-CR

by

Paavo Sepri
Karl K. Chen

Prepared for

Goddard Space Flight Center
Greenbelt, Maryland 20771

MAY 1978

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PREFACE

The large variety of ablation markings observed on recovered
tektites has lead to the swarm wake model first proposed in the
preceding investigation. Herein, further considerations are
presented in support of this model. Quantitative assessments
indicate that wake shielding might indeed have provided for sub-
stantially less heating than would have been experienced by a tektite
entering an undisturbed atmosphere along a similar trajectory.
For the case of strong wake shielding it is even possible that
the surface temperature of a falling tektite had barely reached
its melting point. It is argued that in the distribution of
tektites there is a size band (near $R = 0.5$ cm) which is least
susceptible to melting.

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ILLUSTRATIONS

LIST OF SYMBOLS

c_g	Specific heat of atmosphere
c_1	Specific heat of tektite
c_D	Drag coefficient
E_{rad}	Energy lost through radiation
E_{chem}	Energy partitioned into reactions
f	Function defined in Equation (11)
F_1, F_2, F_3	Functions defined in Equation (14)
K_1	Coefficient of thermal conductivity for tektite
ℓ	Distance of atmosphere penetration by tektite
m	Tektite mass
$\dot{m}_g$	Mass of perturbed atmosphere
$\dot{q}$	Heat flux at stagnation point
R	Tektite radius
R_e	Reynolds number
s	Distance between two tektites
s_i	Initial separation between two tektites
s_o	Constant appearing in Equation (7)
t	Time
t_c	Time required to involve tektite center thermally
T_g	Temperature of atmosphere
T_1	Tektite temperature

LIST OF SYMBOLS (Cont'd)

U_g	Velocity of perturbed atmosphere
v	Tektite velocity with respect to the earth
v_1	Velocity of leading tektite
v_2	Velocity of second tektite
v_∞	Initial tektite velocity
V	Volume of gas disturbed by tektite motion
w	Relative velocity between two tektites
w_1	Parameter defined below Equation (11)
w_2	Parameter defined below Equation (11)
y	Altitude
y_d	Altitude of maximum deceleration
y_m	Altitude of maximum heating rate
y_{Re}	Altitude of maximum Reynolds number
y_∞	Altitude of effective atmosphere limit

LIST OF SYMBOLS (Concl'd)

α Deceleration parameter defined below Equation (10)

α_0 Deceleration parameter defined below Equation (5)

β Exponential decay constant of atmospheric density

δ Velocity perturbation in hypersonic wake

ϵ Density perturbation in hypersonic wake

μ Viscosity of air

ρ Atmospheric density varying with altitude

ρ_a Atmospheric density ambient to tektite

ρ_0 Atmospheric density at sea level

ρ_1 Tektite density

$\overline{\rho_a v_a}$ Averaged wake momentum density defined below Equation (2)

θ Conical shock half angle

ATMOSPHERE ENTRY OF A SWARM OF TEKTITES

1.0 INTRODUCTION

In a preceding study[1] it was stated that several re-
covered tektites exhibit surface features which indicate that
these tektites had sustained very little ablation during their
passage through the earth's atmosphere. This observation is
rather puzzling since various calculations concerning the most
likely tektite trajectories imply heating rates compatible with
substantial ablation. A reconciliation was proposed by means of
the swarm hypothesis, which states that the lead peripheral
tektites bore the brunt of aerodynamic heating upon entry, and
that the bulk of tektites in the wake enjoyed partial shielding
at the expense of the leaders. This shielding was embodied in
a shock envelope model which implied mitigated entry conditions for
the trailing tektites through a decrease of effective entry
velocity and appropriate changes of the ambient density.
The objective of the present investigation is to analyze the
swarm hypothesis in greater depth in order to assess its viability
as a solution. It is concluded that such a circumstance could
indeed have reduced tektite ablation to the degree actually
observed.

2.0 THE MOTION OF A TEKTITE IN THE SWARM WAKE

The ambient conditions of a tektite entering in the wake of the
hypothesized shock envelope would have been composed of the effects
of a sequence of preceding tektite wakes (randomly spaced) such
that each successive wake would have amplified the pertinent
effects. In this light it is difficult to assess quantitatively
the decrease of tektite ablation. However, some appreciation of
the phenomenon should be attained through consideration of the
simpler case of single wake shielding. Therefore, we initially
restrict our attention to the descent of two tektites, one of
which follows the other somewhere in its wake.

Experimental evidence of hypersonic wake characteristics
has appeared mainly in the form of Schlieren and holographic
photography and recently in the measurement of wake velocity
profiles[2] by means of a sequential spark technique. Beyond
the near wake region the velocity defect distribution attains
a similarity form that may be approximated by a Gaussian representa-
tion such that the centerline decay approaches a power law of
exponent -1 in approximation[2]-[5]. Evidently, there is no
direct data available concerning the density structure of a
hypersonic wake; consequently, we resort to the following
theoretical argument to obtain the model required for subsequent
analysis.

2.1 Average Momentum Deficit in a Hypersonic Wake

Consider a tektite descending vertically in the earth's atmosphere. During the period in which the gravitational force is negligible, conservation of momentum may be expressed as:

$$m \, v(t) \;=\; m \, v_{\infty} \;-\; \int_{V(t)} \rho_a v_a \, dV \tag{1}$$

where the integral term represents the momentum gained by the air, and the volume of integration includes only the air disturbed by the interaction. The above may be re-written in the simple form:

$$\frac{v(t)}{v_{\infty}} \;=\; 1 \;-\; \frac{\overline{\rho_a v_a} \; V(t)}{m \, v_{\infty}} \tag{2}$$

where

$$\overline{\rho_a v_a} \;\equiv\; \frac{1}{V} \int_{V} \rho_a v_a \, dV$$

This integral represents the average momentum density gained by the disturbed atmosphere. In a hypersonic entry the disturbed atmosphere is contained in a volume bounded by the conical shock, so that:

$$V(t) \;\cong\; \frac{1}{3} \pi \tan^2(\theta) \, \ell^3(t) \tag{3}$$

where $\ell(t)$ represents the total distance penetrated by the tektite, and θ is the cone half-angle, which is typically $12°$.

Combining (2) and (3), one obtains:

$$\overline{\rho_a \mathcal{V}_a} \;=\; \frac{m\,\mathcal{V}_\infty}{\frac{\pi}{3}\tan^2(\theta)\,\ell^3}\left[\,1 - \frac{\mathcal{V}}{\mathcal{V}_\infty}\,\right] \tag{4}$$

Equation (4) provides an expression for the average momentum deficit in the wake as a function of the distance downstream of the tektite. The velocity of the tektite as a function of altitude is given approximately[6] by:

$$\frac{\mathcal{V}}{\mathcal{V}_\infty} \;=\; exp\left\{-\frac{\alpha_o}{\beta R}\left[e^{\beta y} - e^{\beta y_\infty}\right]\right\} \qquad;\quad y < 0 \tag{5}$$

where the atmospheric density is assumed to decrease exponentially with altitude:
$$\rho = \rho_o\, e^{\beta y}$$

and

$$\alpha_o = \frac{3}{8}\frac{\rho_o}{\rho_t}\,C_D \qquad \cong 2.09 \times 10^{-4}$$

$$\frac{\alpha_o}{\beta R} \cong 150 \qquad for \qquad R = 1\ cm$$

The velocity profile for such a typical entry is shown in Figure 1. Combining (4) and (5) we obtain an expression for the average momentum deficit of the total wake as a function of tektite penetration into the atmosphere:

$$\overline{\rho_a \mathcal{V}_a} \;=\; \frac{m\,\mathcal{V}_\infty}{\frac{\pi}{3}\tan^2(\theta)\,(y-y_\infty)^3}\left[\,1 - exp\left\{-\frac{\alpha_o}{\beta R}\left(e^{\beta y} - e^{\beta y_\infty}\right)\right\}\,\right] \tag{6}$$

Here, $y = 0$ denotes that earth's surface and y_∞ (<0) denotes the tektite entry altitude at velocity $\mathcal{V}_\infty$.

We now use Equation (6) in approximation in order to obtain an expression for the average momentum decay downstream of the tektite at any point along its trajectory. Let $s = (y_{00} - y) < 0$ such that $s/y_{00} \ll 1$. Then expand (6) to obtain :

$$\overline{\rho_a \mathcal{V}_a} \cong - \frac{m \mathcal{V}_\infty}{\frac{\pi}{3} \tan^2(\theta) s^3}\left[- \frac{\alpha_o s}{R}\right] = \frac{\alpha_o m \mathcal{V}_\infty}{\frac{\pi}{3} \tan^2(\theta) R s^2}$$

This expression indicates that the average momentum deficit decays inversely with the square of the distance downstream of the tektite. In combination with the previously mentioned experimental observation that the velocity deficit decays inversely with distance, the following model is proposed to describe the average density and velocity decays in the wake of a tektite:

$$\rho_a = \rho_\infty\left[1 - \frac{c}{s+s_o}\right] \quad ; \quad s < 0$$

$$\mathcal{V}_a = \mathcal{V}_\infty\left[1 + \frac{c}{s+s_o}\right] \tag{7}$$

Such that the momemtum deficit is in accord with the preceding argument:

$$\rho_a \mathcal{V}_a = \rho_\infty \mathcal{V}_\infty\left[1 - \frac{c^2}{(s+s_o)^2}\right]$$

This model shall be used to describe the ambient conditions of a tektite following at distance s in the wake of a preceding tektite. The model is not accurate in the near wake (s⟶o) where the wake decay alters its character, but it appears to be adequate for present purposes.

2.2 The Motion of a Shielded Tektite

Consider two identical tektites following vertically towards the earth's surface, one following in the wake of the other. The objective of this section is to describe the relative motion of these two tektites during their descent.

Even in the absence of a wake effect the relative spacing of the two tektites will decrease due to the lagged deceleration of the second one. A relation for this separation is obtained by noting that since both tektites may travel identical trajectories (albeit time lagged), the time lag of their passage at any point in the trajectory is independent of position along the trajectory. From this fact one obtains:

$$\frac{s(y)}{S_\infty} = \frac{\overline{v}(y_1)}{v_\infty} \tag{8}$$

where $\overline{v}$ is the value of tektite velocity at some position of the trajectory between the two tektite locations at any given altitude. As the initial tektite velocity of 11 km/sec decreases, the separation decreases commensurately. Therefore, the initial

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tektite separation may be larger than the extent of effective

wake influence, but the second tektite may close into this domain

at some later time during the trajectory.

When the motion of the second tektite is influenced by the

wake of the first, the following equations may be used to

approximate their respective motions:

$$\frac{d v_1}{dt} = - \alpha \, v_1^{2} \tag{9}$$

$$\frac{d v_2}{dt} = - \alpha \, (1+\epsilon)(v_2 - \delta v_1)^{2} \tag{10}$$

where $\alpha = \frac{3}{8} \frac{\rho_0 C_D e^{\beta y}}{\rho_1 R}$.   For the second tektite the

ambient density and velocity are represented as being perturbed

from the undisturbed atmosphere by the amounts ϵ and δ

respectively. We define the relative separation and velocity

between the two tektites as follows:

$$s \equiv y_2 - y_1 \; < 0.$$

$$w \equiv v_2 - v_1$$

Subtraction of Equations (9) and (10) leads to the equation of

relative motion between the tektites:

$$\frac{dw}{dt} = - \alpha (1+\epsilon)(w - w_1)(w - w_2) \equiv f(w) \tag{11}$$

where

$$\frac{\omega_{1,2}}{v_1} \equiv -(1-\delta) \pm \frac{1}{(1+\epsilon)^{1/2}} \cong \delta - 2 + \frac{\epsilon}{2} \; ; \; \delta - \frac{\epsilon}{2}$$

The previously mentioned wake model suggests that $\delta - \frac{\epsilon}{2} \cong \frac{\epsilon}{2} > 0$.
Since ω_1 and ω_2 are functions of s (and therefore of t),
the solution to (11) is complicated. However, a qualitative
understanding of the solution is readily apparent. For an initial
relative velocity lying between the values ω_1 and ω_2 the
forcing function $f(\omega)$ is positive. Therefore, the relative
velocity will increase until it reaches the value ω_2, whereupon
further increase of ω is not possible. The second tektite
will thus experience relative <u>acceleration</u> towards the lead
tektite until it reaches the near wake with a positive relative
velocity. Thereafter its momentum will likely carry it past the
first which will then take the role of the shielded tektite.
The analysis also demonstrates that even if the relative
velocity were initially negative, the second tektite could
catch up to the first. Therefore, not only is there a tendency
for trailing tektites to catch the leaders, but there is also
the tendency for all lead tektites to remain clustered near the
front. In this manner the peripheral tektites form a more
densely populated shield which sequentially creates a larger
and more effective wake for subsequent entries.

It is important to provide an estimate of the time required for a trailing tektite to catch the leader. Since the relative velocity between the two tektites is positive even without the wake effect, let us assume it takes the value ω_2 initially. From equation (11) the solution is simply:

$$\omega \equiv \omega_2$$

Then

$$S = \omega_2 t + S_i$$

$$t_{(S=0)} = \frac{-S_i}{\omega_2} = \frac{-S_i}{v_1 \left[\delta - \frac{\epsilon}{2} \right]}$$

The value here depends on the strength chosen for the wake. Approximations are now based on the wake model presented earlier. According to Equation (7) let:

$$\epsilon = \delta = -c \left(S + S_0 \right)^{-1}$$

Experimental data for the velocity decay in a far wake[2] indicate the values:

$$\frac{c}{2R} \cong 20$$

$$\frac{S_0}{2R} \cong 200$$

Therefore, for a tektite traveling in range $200 \leq S/2R \leq 1000$, one computes the average value:

$$\epsilon \cong \frac{20}{200 + 600} = \frac{1}{40}$$

Conclude:
$$t_{(s=0)} \cong \left(\frac{-S_i}{V_i} \right)(100)$$

Therefore, an initial tektite separation of 10 m. will have
closed in a descent of approximately 1 km. for the pair.

2.3 The Effect of Swarm Entry into the Atmosphere

In a swarm of tektites entering the atmosphere the wake
effects are further complicated by random distributions of tektite
size, location and relative velocity. Relative decelerations
are strongly dependent on tektite sizes and geometries. However,
a tendency has been demonstrated here that lead tektites will
bunch near the swarm perimeter. Tektites entering in the ensuing
wake will experience heating less than that of a normal entry
into the unperturbed atmosphere.

Tektite showers were apparently events of considerable
magnitude since some strewn fields are a few thousand miles long
and contain a great deal of mass. The initial phases of such
an event probably would have put the atmosphere into violent
motion such that the later phases may have occurred with ambient
atmospheric conditions greatly perturbed from normal. The wake
flow accompanying the descent of the lead tektites would have
compressed the atmosphere immediately behind the shock envelope
and left the higher atmosphere relatively depleted of air.

The ensuing high and low pressure areas might have caused the

generation of a toroidal vortex in the atmosphere similar to the

kind observed in a liquid subsequent to the impact of a droplet.

Although the velocity perturbation of such a vortex would

likely have been insignificant to subsequent tektite entries,

the change in the atmospheric density profiles could have been

considerable. The net effect of the motion would have been

to reduce the height of the effective atmosphere while causing

the lower altitudes to become denser. Such an alteration would

have delayed the moment of peak heating.

3.0 THE HEATING OF A TEKTITE IN THE SWARM WAKE

Whether a tektite enters in a wake or into an undisturbed atmosphere, it still must lose the same amount of kinetic energy. This energy is partitioned among several modes which are expressed by the energy balance:

$$\frac{1}{2} m \left(v_{\infty}^2 - v^2 \right) = \frac{1}{2} m_g u_g^2 + m_g C_g (\Delta T)_g + m C_t (\Delta T)_t + E_{rad} + E_{chem}$$

Several of these terms are negligible in the overall balance.

(i)   The final tektite kinetic energy is small compared with its initial value.

(ii) Momentum considerations imply that the gain of kinetic energy by the atmosphere is small compared with the initial tektite kinetic energy.

(iii) If a typical tektite were to absorb all of its kinetic energy internally, then its temperature would rise by 50,000° K. Since some of the tektites do not even reach the melting point (approx. 2,000° K), tektite heating does not account for more than a couple percent of the original energy.

(iv) After the completion of recombination of dissociated gas in the atmosphere, chemical energy levels return to their initial values, so there is little net change of this term.

Therefore, the bulk of tektite kinetic energy goes into heating of the atmosphere, radiation loss, and to a lesser extent into the latent heats of melting and vaporization of whatever tektite material is ablated. Since the total heat absorbed by a barely ablated tektite is small in comparison to the other factors, it is possible to reduce this amount significantly while the major balance of energy is only slightly altered in proportion. Here we claim that entry in a wake may cause a significant decrease of tektite heating over that of an isolated entry, and that such a decrease would be absorbed by an imperceptible increase in atmospheric heating.

3.1 Gas Cap Shielding

One aspect of decreased tektite heating in a wake may be explained qualitatively as follows. Surface heating depends on the velocities of molecular impacts and on the gas density there since these quantities are uniquely related to the kinetic energies of impacts and their frequencies. In the rarified portion of entry the air molecules strike the tektite surface directly since the mean free path is large. As the density increases, the frequency of impacts increases, but eventually a gas cap forms in front of the tektite which absorbs much of the energy of further incoming molecules. The ensuing surface heat transfer is due to conduction in the gas for which the surface

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collisions are far less energetic than the direct ones. Much
of the energy absorbed by the gas cap is swept downstream with-
out heating the tektite. Figure 2 taken from Reference 7
shows heat transfer as a function of Reynolds number for a
rarified gas flow. As applied to a tektite trajectory (at
constant velocity say) the heating is seen to increase with in-
creasing density until a peak is reached whereafter the heating
decreases. The decrease is taken to be connected with gas cap
shielding. The heating in a wake entry during the rarified
regime is diminished over that of an isolated trajectory for
two reasons. First, the relative velocity with respect to the
gas is lower. Second, the duration of peak heating is shorter.
In the early part of the trajectory the ambient density is lower
than normal because the lead tektites have displaced the ambient
air molecules. In the latter part of a shielded trajectory
the ambient density is higher than normal because air molecules
have accumulated in the preceding wakes. Over these con-
ditions a shielded tektite is subjected to peak heating for a
shorter time than otherwise.

This mechanism also provides a means for the atmosphere to
absorb a greater portion of energy than for the case of an
isolated trajectory. Entry into a delayed but steeper density
gradient results in a thicker gas cap. Although the volume

of the gas cap is larger, its temperature need not be appreciably increased because dissociation and ionization processes limit the local temperature. A larger volume of hot gas would also result in more energy loss by radiation.

3.2 Stagnation Point Heating

Although the heating of a tektite during its descent through the atmosphere is a complicated phenomenon, a relatively simple expression appears to provide a good approximation for its stagnation point heating rate. The expression has been discussed by Allan and Eggars[6], has been supported by laboratory data[8], and recently has compared favorably with data taken during an actual entry test program[9]. In metric units this expression for laminar heating is:

$$\dot{q} = \frac{312}{R^{1/2}} \left(\frac{\rho}{\rho_0} \right)^{1/2} \left(\frac{v}{11 \ km/sec} \right)^{3.15} \frac{Kw}{cm^2} \qquad (12)$$

where the tektite radius, R, is given in cm.

Figure 3 shows the heating rate as a function of altitude for a typical tektite (R = 1 cm) entry into an undisturbed exponential atmosphere. The maximum value of 6.4 kw/cm^2 occurs at an altitude of 50 km. It is easy to show that for such trajectories the value of maximum heating rate remains constant with a variation of tektite radius. However, the altitude

at which maximum heating occurs increases for smaller tektites according to the relation:

$$-\beta y_m = \ln\left\{\frac{2.3\,\beta\,\rho_o\,C_D}{\beta\,\rho_1\,R}\right\} \qquad (13)$$

From Figure 3 it is seen that the tektite experiences stagnation point heating of more than 2 kw/cm^2 for approximately 3.5 seconds of its descent. The analysis of the preceding investigation[1] indicates that such a heating rate would raise the surface temperature past the melting point in less than 0.3 seconds. Hence, a tektite entering the undisturbed atmosphere under these conditions would surely have melted superficially.

In order to use the same expression in describing heating in the swarm wake, one needs to know how the density and relative velocity profiles as a function of altitude had been altered from the undisturbed case. The ambience in the swarm wake depends on three effects: (a) The number of preceding tektites to enter the atmosphere, (b) the separation downstream of the immediately preceding tektite and (c) the degree of motion of the whole atmosphere induced by the preceding tektites. Since the length of a typical strewn field is approximately 100 times the effective height of the atmosphere, one would expect that during the later phases of a swarm event the local atmosphere

would have been in violent motion. Of course, for shallow

entry angles the wake effect would be complicated by the swarm

geometry with respect to the atmosphere and the density gradient

with altitude. However, the general wake effect during the

moments of maximum heating would have been as follows. The

ambient density would have been higher and the tektite velocity

relative to the air would have been lower than those during an

undisturbed entry. In continuum portion of entry the heating

would have been significantly reduced as seen from Equation (12).

For the sake of comparison with the undisturbed entry, suppose

the local density had been increased by a factor of four while

the local relative velocity had been decreased by a factor of two.

Then from Equation (9) it is seen that the trajectory for this

wake case would have been identical to the case of the undisturbed

entry. However, the heating rate from Equation (12) would have

been reduced by a factor of approximately 4.5 throughout the

trajectory. Thus, in Figure 3 the stagnation point heating

rate would have exceeded 1 kw/cm^2 for only approximately 1.75

seconds of the trajectory, while reaching a peak of only

1.42 kw/cm^2. If we assume that the tektite (R = 1 cm) surface

experienced an average heat flux of 0.5 kw/cm^2 and that the

temperature external to the tektite in the reduced Mach

number flow had been decreased to 4,000° K, then the previous

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analysis[1] (Figure 4) shows that the tektite surface would
have reached 2,000° K in approximately 1.5 seconds. We
conclude that under circumstances similar to these a
tektite may have entered the atmosphere at 11 km/sec and
yet have experienced heating only sufficient to have brought
the surface barely to the melting point during its descent.
Furthermore, since the wake has such a large influence on the
heating rate, it is clear that a large variety in the amounts
of ablation would have ensued among the members entering in a
swarm. Indeed, this conclusion conforms with the observations
made initially in connection with the variety of surface
markings on recovered tektites.

3.3 Turbulent Heating

The possible occurrence of turbulent flow may have
further complicated the question of tektite heating. However,
Reynolds number considerations[10] indicate that the transi-
tion to turbulence would have been a marginal event. The Rey-
nolds number peak in the trajectory occurs subsequent to the
deceleration peak which occurs subsequent to the laminar heating
peak. Hence, if transition did manage to occur during the tra-
jectory, it would have been at relatively low velocity.
Thus, the decrease in heating rate after the laminar peak
would have been more gradual if turbulence had been generated,

but the peak heating should still have occurred during the laminar phase. However, the total amount of ablation could have been significantly greater for the trajectory involving turbulent heating because the tektite surface would already have been molten as the turbulence commenced. The increased heating due to turbulence would have lengthened the segment of the trajectory for which the surface experienced melt flow and vaporization. However, the swarm wake model complicates the question of turbulence inception because the Reynolds number depends on the product of local density and velocity. Depending on the actual relative changes of these quantities, turbulence may have been either inhibited or enhanced.

3.4 The Dependence of Ablation on Tektite Size

The results for entry into an undisturbed atmosphere indicate that velocity, heating, and Reynolds number vary with altitude and tektite radius according to the following functional forms:

$$\frac{v(y,R)}{v_\infty} = F_1\left[\frac{\rho(y)}{R}\right]$$

$$\dot{q} = F_2\left[\frac{\rho}{R}\right]$$

$$R_e = \frac{\rho v R}{\mu} = R^2 F_3\left[\frac{\rho}{R}\right]$$

(14)

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Thus, in this model, every tektite would pass through the same trajectory and heating profiles except that the profiles are shifted in altitude with the location of the peaks given by:

$$- \beta y_m = \ln \left\{ \frac{\beta R}{6.3 \, \alpha_o} \right\}$$

$$- \beta y_d = \ln \left\{ \frac{\beta R}{2.0 \, \alpha_o} \right\} \qquad (15)$$

$$- \beta y_{Re} = \ln \left\{ \frac{\beta R}{\alpha_o} \right\}$$

It should be noted that the magnitude of the Reynolds number profile is amplified by the factor R^2, whereas the amplitudes in the velocity and heating profiles are independent of tektite radius.

In the light of these profiles we consider the rise in surface temperature for various tektite sizes. The short time temperature solution presented in the previous investigation[1] is valid until the time at which the tektite center begins to rise in temperature. This characteristic time is naturally shorter for smaller tektites, and the condition is expressed by:

$$\frac{K_1 t}{\rho_1 c_1 R^2} << 0.25$$

Assuming the center begins to be thermally involved when the parameter reaches the value 0.1, we obtain the relation:

$$t_c \cong 5 \, sec \left(\frac{R}{1 \, cm} \right)^2 \qquad (16)$$

Therefore, for tektites smaller than 0.5 cm in radius, the center begins to rise in temperature less than 1 second after the heating is applied to the surface. After this characteristic time is surpassed, the tektite surface temperature rises more quickly than the short time solution indicates because the center becomes a less effective heat sink in comparison to that of a larger tektite. The short time solution demonstrates that initially all tektite surface temperatures rise at the same rate (along each trajectory) provided the surface heating rate is the same, which is the case for entry into an undisturbed atmosphere. The surface temperatures of the smaller tektites rise faster than those of the larger ones only after their centers have become involved thermally.

Since it takes approximately 5 seconds along each trajectory for the tektite to reach its point of maximum heating, Equation (16) shows that all tektites of radius greater than 1 cm should begin to melt at the same relative point along their trajectories. Tektites smaller than 1 cm should begin melting progressively earlier. Since the remainder of the laminar heating profile is the same for all tektites, one would not expect much difference in the ablation of the various larger tektites. On the other hand, the Reynolds number profile increases in magnitude as R^2. Thus, for increasing diameters,

transition to turbulence occurs earlier along the relative tra-
jectories, and progressively more of the heating profile after
the laminar heating peak is augmented by the turbulent rate.
Under these circumstances one would expect the amount of
ablation observed on various tektites to increase with increasing
radius.   Indeed, Figure 6 of Reference 1 shows such a trend
markedly.

Furthermore, this graph tends to support the notion that
most tektites have experienced wake shielding to some degree.
An extrapolation of the data points suggests that many tektites
of roughly 0.4 cm radius had not ablated at all (or had
ablated very little).   If such tektites had entered the undis-
turbed atmosphere at 11 km/sec and had experienced only laminar
heating, without the benefit of wake shielding, then the analysis
had demonstrated that they should have ablated significantly.

4.0 CONCLUSIONS

The analysis of tektite heating and motion has lead to the
following conclusions:

(1) No tektite should have remained superficially un-
     molten if it had entered the undisturbed atmosphere
     at 11 km/sec.

(2) If a tektite had entered in the strong wake associated
     with the later phases of a swarm event, its heating
     could have been reduced to the point of avoiding sur-
     face melting.

(3) The surface (and internal) temperatures of microtektites
     should have risen to the melting point more rapidly
     than those of the larger tektites.

(4) The heating rates of the larger tektites should have
     been increased via turbulence, thereby making them
     more susceptible to ablation than tektites of
     intermediate sizes.

(5) Tektites of approximately 1/2 cm radius were least
     susceptible to melting because these optimized the
     trade-off between turbulent heating and the low thermal
     inertia of the smaller tektites.

(6) Much of the previously puzzling scatter in ablation

data may be attributed to the variability of heating

in a swarm wake.

In connection with the present conclusions it is interesting
to mention a general trend observed in some strewn fields in
Indo-China. In these distributions the tektites which exhibit
most ablation are found near the peripheries of the strewn fields[11].
This observation is in agreement with the notion of wake shielding
because tektites in the periphery of a swarm should have enjoyed
less of the wake effect than those towards the center.

In addition, the conclusions of this report raise implications
connected with computed re-enactments of tektite trajectories
in which ablation data is used to determine the trajectory.
Since these computations assume entry into an undisturbed
atmosphere, it would be most accurate to consider those speci-
men which exhibit the most ablation. The flanged australites
studied by Chapman[12] belong to this category, although even
these may have experienced shielding to some lesser degree.
In this regard, Chapman's calculations may provide a lower bound
on tektite entry into the atmosphere. On the other hand, the
existence of specimen with barely ablated surfaces precludes
the possibility of entry at speeds much greater than 11 km/sec.

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TYPICAL TEKTITE VELOCITY VS. ALTITUDE IN AN
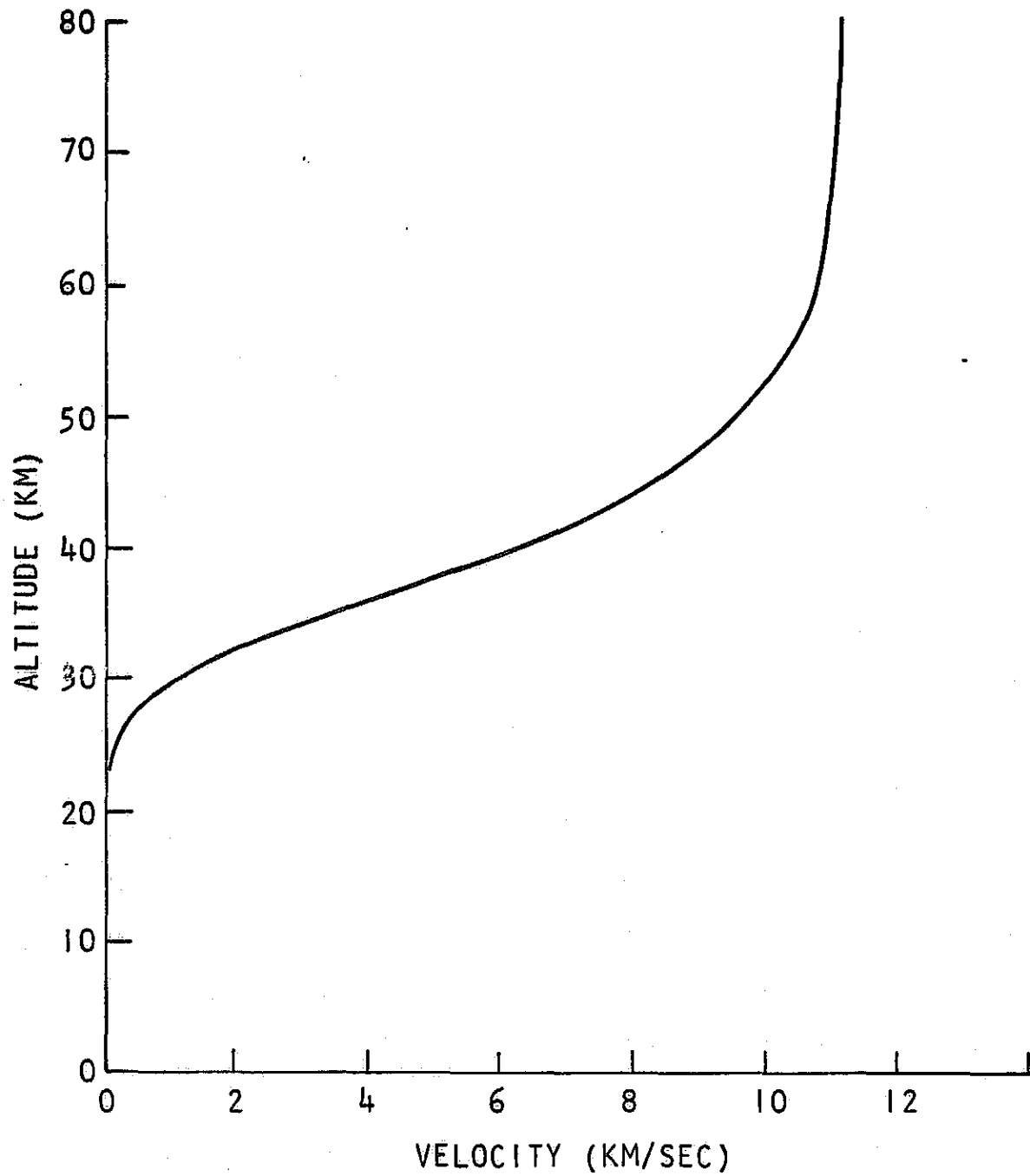UNDISTURBED EXPONENTIAL ATMOSPHERE

FIGURE 1

STAGNATION POINT HEAT TRANSFER
VS. REYNOLDS NUMBER FOR LOW DENSITY
HYPERSONIC FLOW (FROM REFERENCE 7)
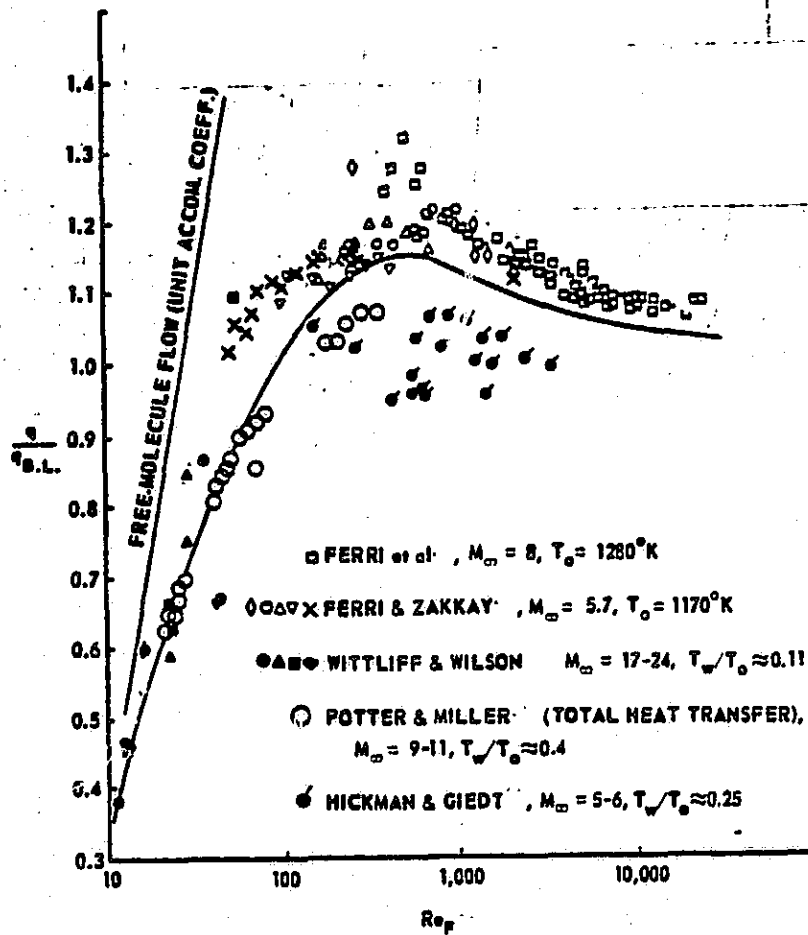
FIGURE 2

DECELERATION AND HEATING OF A TYPICAL TEKTITE VS. ALTITUDE IN AN UNDISTURBED ATMOSPHERE

FIGURE 3

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15. Supplementary Notes

16. Abstract

The large variety of ablation markings observed on re-
covered tektites has lead to the swarm wake model first
proposed in the preceding investigation. Herein, further
considerations are presented in support of this model.
Quantitative assessments indicate that wake shielding might
indeed have provided for substantially less heating than
would have been experienced by a tektite entering an un-
disturbed atmosphere along a similar trajectory. For
the case of strong wake shielding it is even possible
that the surface temperature of a falling tektite had
barely reached its melting point. It is argued that in
the distribution of tektites there is a size band
(near $R = 0.5$ cm) which is least susceptible to melting.

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