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STUDY OF THE ABLATIVE EFFECTS ON TEKTITES

Avco Systems Division
201 Lowell Street
Wilmington, Massachusetts 01887

March 1976

Final Report for Period March 1975 - March 1976

Contract NAS5-20976
AVSD-0104-76-CR

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Paavo Sepri
Karl K. Chen

Prepared for

Goddard Space Flight Center
Greenbelt, Maryland 20771

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Preface

Many tektite surfaces show less evidence of melt flow than would be anticipated for bodies entering the earth's atmosphere at greater than escape velocities. Several examples are given to support this contention. Equations are presented which provide approximate parameters describing surface heating and tektite deceleration during atmosphere passage. Numerical estimates of these parameters using typical initial and ambient conditions support the conclusion that the commonly assumed trajectories would not have produced some of the observed surface markings. Consequently, it is suggested that tektites did not enter the atmosphere singly but rather in a swarm dense enough to afford wake shielding according to a shock envelope model which is proposed. A further aerodynamic mechanism is described which is compatible with hemispherical pits occurring on tektite surfaces.

ACKNOWLEDGEMENT

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ILLUSTRATIONS

NOMENCLATURE

a	Parameter defined by Equation (11)
A	Effective drag area of tektite
b_n	Eigenvalues described below Equation (4)
C	Specific heat
C_D	Drag Coefficient
g	Gravitational constant
K	Coefficient of thermal conductivity
m	Tektite mass
P	Parameter defined in Equation (5)
Q	Heat flux
r	Radial coordinate
R	Tektite radius
t	Time
T	Temperature
u	Horizontal velocity
v	Vertical velocity
v_f	Terminal velocity
V	Transformed temperature distribution (see p. 14)
α	Heat conduction parameter defined below Equation (1)
β	Parameter defined in Equation (5)
ρ	Mass density

Subscripts

0	Initial condition
1	Tektite property
2	Gas property
∞	Ambient gas condition
S	Evaluation at tektite surface
R	Radiation

1.0 INTRODUCTION

The question of tektite origin is difficult to resolve because many clues have vanished with the passage of time since the events occurred and because some of the remaining observations (or interpretations) appear to be mutually contradictory. It has been remarked by O'Keefe[1] that more is known about what tektites are not than about what they are. This relative void of information provides a fertile ground for speculation. Among the more prominent of past suggestions for the formation of tektite strewn fields are the following.

- Lunar volcanism
- Meteor impact with lunar surface
- Eruptions of large terrestrial volcanoes
- Molten glass spewed from meteor impacts on the earth's surface
- Cometary impact
- Ablation of a large body grazing the earth's atmosphere
- Tektite swarms from beyond the earth-moon system

The bulk of present evidence would appear to favor the moon as a source for tektites.[2]

In view of the complexity of the problem, the limited goal of the present study has been to provide supplemental information concerning aerodynamic markings on tektite surfaces. The milestone works by Chapman and his colleagues (2)-(5) have demonstrated convincingly that aerodynamic ablation has formed the ring-waves and flanges observed on some australites and javanites, and that such ablation is consistent with tektite trajectories beginning from the moon's surface. Other calculations (6) have indicated that during tektite passage through the earth's atmosphere, ablation due to melt flow should have dominated over mass loss due to vaporization. In this regard it remains puzzling that many tektite surfaces reveal very little (if any) evidence of melt flow. How is it possible for some tektites to have arrived at greater than escape velocities and apparently to have sustained so little ablation? Since the surface markings are connected with the mode of atmosphere entry, it is hoped that such investigation will provide additional information regarding tektite origin.

On the basis of previous calculations (7) one initial thought for the present study was that roughness elements might have increased the heating of tektite surfaces via turbulence and/or local separations and reattachments. This increased heating should then have increased vaporization, thereby reducing the liquid layer thickness, and consequently reducing the amount of melt flow in agreement with observation. This mechanism may have produced some of the markings on tektite surfaces, but other tektites exhibit features which indicate another extreme, namely: a lack of both melting and vaporization. This observation has provided one of the directions for the present investigation. What mode of atmosphere entry could provide less heating than one would normally anticipate? The variety of surface markings in a tektite distribution suggests that a range of heating conditions existed during atmosphere entry of a swarm of tektites such that some of them ablated significantly and others ablated imperceptibly.

In an effort to understand why some tektite surfaces had been heated less than anticipated, the equations of motion and heat transfer have been reconsidered in their unsteady form. Approximate parametric solutions of the heat conduction equation show that under some conditions it is possible for surface temperatures to have risen in times comparable to those of deceleration during atmospheric braking, thereby supporting the notion that surface temperatures could have reached the melting point marginally. However, more detailed calculations along these lines have already appeared in the literature[(8)-(10)], and if heat transfer rates are taken from these sources and are applied to the present parametric solutions, then it still appears that under normal entry conditions the surfaces should have melted even if the tektite had tumbled.

On the other hand, the parametric solutions provide clues as to how the entry conditions should have been modified in order to have prevented melting. One obvious condition is a reduction of tektite velocity relative to the local atmosphere. A reduction in velocity would have produced a concomitant reduction of surface heat transfer. Another condition is the increase of local air density since this would have produced a hastened deceleration of the tektite. Finally, a reduction of the temperature external to the tektite surface would have produced diminished heating. The search for more benign entry conditions has produced the hypersonic wake as a candidate. If the entering tektite swarm were populated densely enough, then the tektites near the perimeter could have formed a shock envelope such that the bulk of tektites would have enjoyed diminished heating in the ensuing wake. Such a dispersed mass would have decelerated more rapidly than an equivalent but more concentrated mass. Furthermore, only the lead tektites would have suffered ablation in the amount approaching that of an isolated trajectory. During descent of the swarm even the lead tektites would have experienced partial shielding as others overtook them from behind.

An enigma of a different sort presents itself for the case of tektites which obviously have sustained melt flow during aerodynamic heating. In the presence of ring waves near the stagnation point there sometimes appear hemispherical pits of diameters larger than the melt flow thickness. Due to their distribution and placement the pits clearly have been formed during the ablation process. How could such shapes have originated compatibly with the external aerodynamics and how could they have maintained their integrity in a liquid that was moving under the shear exerted by the air? Herein, two possible generating mechanisms are suggested for the pits; namely, bubbling and collisions with debris. A vortex instability observed by Johnson[(11)] is also suggested to have maintained the pit symmetry while contributing to its growth.

2.0 OBSERVATIONS CONCERNING TEKTITE SURFACE MARKINGS

The objective of this section is to present observations and arguments concerning the surface markings of tektites which are related to aerodynamic effects. The concluding opinion is that many surfaces have not received sufficient heating during atmosphere passage to raise local temperatures to the melting point or beyond.

To distinguish aerodynamic markings from those due to other causes is a difficult task because it is well known that tektites have melted at least twice. Some effects from each melting can be quite similar. In the prior melting it is clear that at least some tektites were molten throughout, and that the melting occurred in an environment of weak acceleration and weak surface loading, thereby precluding flight through an atmsophere at a high relative velocity. Plate 5 in chapter 1 of Reference 12 shows the formation of a large nearly spherical interior cavity comprising most of the tektite volume, and it is clearly the result of a bubble, indicating a total molten state. Plate 1 in chapter 2 of Reference 12 shows a tektite cross-section in which inclusions appear near the surface. Since the composition of the inclusions is different from the surrounding tektite material, one surmises that an impact occurred. The geometry suggests that the impact occurred such that both participants were molten or near molten during the event. Otherwise the crater would not have filled with molten glass to such a total extent. Plate 2 in Chapter 3 of Reference 12 shows internal striae of wavy appearance. Two possible fluid mechanical causes come to mind: the the Von Karman vortex street behind an impacting particle, or the internal wave instability present in sheared flow. However, these possibilities require intermediate Reynolds numbers and thus they are reasonable only if the molten tektite had a viscosity of less than 10 poise which would have required elevated temperatures. The second alternative receives support from similar waves observed by Chapman (Figure 5 of Reference 4) in the aerodynamically melted flange of an Australite.

Another pertinent observation has been made by Chao et al.(13) who found perfect spherical metal inclusions of a composition similar to nickel-iron meteorites (although the Ni content was somewhat lower than appears in most meteorites). The shiny surfaces reveal very little oxidation, and the glass surrounding the spheres is not under conditions of unusual strain. One concludes that both metal and glass were molten and were undergoing very little acceleration during solidification.

Some of the interpretations of the above observations may not be unique, but it seems impossible that these phenomena could have occurred if the tektites had been in solid form.

Examples of the second melting, which occurred due to aerodynamic heating, are the ring waves and flanges appearing on some tektites, although before the work of Chapman et al.[3] the origin of even these markings was questioned. By measuring the deflection of internal striae near the stagnation point surface, Chapman also showed the liquid layer thickness there to be much less than one millimeter typically. Thus, at least the central core of tektites remained solid throughout the descent. Besides these now obvious examples what other surface markings may be attributed to aerodynamic melting? Streamwise streaks such as appear in Figure 1 taken from Reference 1 seem to indicate a surface which had barely melted and had begun to flow only on part of the surface. However, thin sections taken from the surface[21] reveal these streaks to be internal striae which do not represent surface flow. Figure 7 in Reference 3 shows the anterior surface of a hollow australite button, and it is remarkable that hemispherical pits occur with increasing proliferation towards the stagnation point. Due to their distribution and existence in the midst of ring wave flow, one strongly suspects that these pits were formed during atmosphere entry. However, it is puzzling how such regular pits (and grooves) could have been formed and preserved, and why the ring wave flow did not flood some of them. One possibility is the impact of debris (or smaller tektites differentially retarded by the atmosphere) after the ring waves had been formed and were cooling in a plastic state. Such impacts could have left smooth features, but it seems improbable that the distribution would show such a regular increase of impacts toward the stagnation point. Another possibility is boiling of the liquid layer since the stagnation point is the hottest part of the surface. However, Chapman has shown experimentally[3] that at least under some conditions bubbling occurs at the flanges first because the external pressure is minimum there. Furthermore, the pit diameter appears to be greater than the liquid layer thickness, which seems to be inconsistent with the notion of bubbles. In addition, the bubbles should have skewed as the liquid layer flowed downstream, whereas the actual pit shapes remained hemispherical. No small bubbles appear to be solidified within the liquid layer, although the bubbling must have ceased before the termination of liquid movement, thereby providing time for all bubbles to have been exposed.

Also appearing in this photograph are faint streamwise streaks running through some of the pits, but these streaks are actually underlying striae exposed by millennia of surface etching (as claimed by Chapman), and they do not represent superficial aerodynamic streamers of melt flow.

The search for a fluid dynamical mechanism which could preserve hemispherical surface pits has led to the experiments of Johnson,(11) who observed the formation of unstable ring vortices of such strength that the flow caused severe bow shock disturbances. Since these vortices may be compatible with tektite surface features, the mechanism will be discussed at greater length later.

Thus far it has been argued that some pits and grooves must have existed prior to atmosphere entry and that others have been formed during entry. For intermediate examples it may be difficult to distinguish the cause. Next it will be argued that, in distinction to the two types of molten flow, there are features which indicate that some surfaces neither melted nor vaporized during tektite descent.

Initially it was believed that surface pits provided examples for refuting the existence of melt flow. Some pits have smooth interiors, sharp edges, high symmetry, and present no evidence of scouring, vortex trails, or surface wakes. The notion of boundary layer separation and reattachment within the pit could not account for the preservation of spherical symmetry. However, with the vortex mechanism previously mentioned, these features could still be compatible with melt flow. It seems impossible, on the other hand, to explain the existence of sharp protuberances and certain irregular sharp ridges and corners appearing on other tektites, unless these surfaces had not ablated aerodynamically. In Figures 2 and 3 taken from Reference 1 there are numerous such features. Sharp bends in grooves and intersections of grooves involving sharp ridges are also improbable if the surface were even slightly molten. During heating, all sharp surface features would have risen in temperature both faster and to higher values than regions of smaller curvature. Therefore, if the surface had ablated at all, the sharpest features should have rounded whether the process had been melt flow or vaporization. Although experimental ablation of graphite has revealed some sharp features, one would not expect the same of a glassy material unless the features were of a more regular nature.

The observations mentioned in this section lead to the following conclusions. At some time prior to rendezvous with the earth most tektites were in completely molten form and under conditions of minimal acceleration. Then came a period of solidification. Later, as they entered the earth's atmosphere, some tektites in the swarm underwent a second melting albeit superficial, whereas other tektites did not melt during this passage. Thus, the aerodynamic conditions must have been such that surface temperatures marginally reached the melting point for many tektites in the distribution.

Since the tektite temperature was determined by the surface heat flux, one of the important aerodynamic questions concerns the conditions under which roughness elements induced turbulent flow. As calculated by Chen[7], the increased heating due to turbulence may in some cases have increased the rate of vaporization in comparison to the rate of melting so as to have decreased the liquid layer thickness of an ablating tektite. This case is especially pertinent to those tektites in the distribution which exhibit the most mass loss. Furthermore, the surfaces of such tektites may show a surprising lack of melt flow features since the mass loss had been primarily via vaporization. On the other hand, those tektites in the distribution which exhibit sharp surface features are not likely to have undergone these high turbulent heating rates since either melting or vaprozation would have rounded the features. Therefore, one expects these tektites to have undergone laminar heating for the most part. The calculations by Chen[7] indicate that if a tektite had a smooth surface before atmosphere entry, then it would have experienced laminar heating throughout its trajectory. A tektite with a rough surface might have triggered turbulence[7] during the intermediate section of its trajectory, and thus its surface heating rate would have increased there. Thus it is clear that for a typical tektite trajectory the local Reynolds number had reached the transition value marginally. A slight variation of the ambient conditions could have produced an appreciable effect on the triggering of turbulence and, therefore, on the total amount of heating.

Based on the observations presented here, we shall attempt to explain how a tektite might have entered the atmosphere at a hypersonic velocity and still have sustained insignificant ablation.

3.0 ANALYSIS

Due to its relatively small ballistic coefficient, a typical tektite would have decelerated rather quickly during its passage through the atmosphere. Therefore, although surface heat fluxes might have been very high for a short segment of the trajectory, it is not obvious that the surface temperature did in fact rise above the melting point before the tektite had slowed sufficiently. Of course, the question of reentry has received generous attention through the space program, and studies pertinent to tektites have been published by Warmbrod,[8] Chapman,[10] and Adams and Huffaker.[9] It is not the present intention to repeat these complicated numerical calculations, but rather to establish typical time constants and parameters in the hope of finding conditions under which tektite surfaces would not have melted.

3.1 THE TEMPERATURE EQUATION

Assume that a spherically symmetric tektite, which is initially cold, is suddenly immersed into a hot medium. How fast will the surface temperature rise to the melting point? The describing equation for the tektite's internal temperature and its solution are presented by Carslaw and Jaeger[14] p. 237.

$$\frac{\partial T}{\partial t} = \frac{\alpha^2}{r^2} \frac{\partial}{\partial r} \left\{ r^2 \frac{\partial T}{\partial r} \right\} \qquad (1)$$

where $\alpha^2 = \frac{K_1}{\rho_1 C_1} = \frac{\text{coefficient of conductivity}}{\text{density x specific heat}}$

Subscript $(\ )_1$ refers to a property of the tektite, and subscript $(\ )_2$ below refers to a gas property external to the tektite. Continuity of heat flux at the tektite surface provides the following boundary condition:

$$K_1 \frac{\partial T_1}{\partial r}\Big|_{r=R} = K_2 \frac{\partial T_2}{\partial r}\Big|_{r=R} \cong K_2 \left\{ \frac{T_2 - T_S(t)}{\delta} \right\} \qquad (2)$$

where

T_2 = gas temperature external to the boundary layer

T_s (t) = tektite surface temperature

δ = equivalent thermal boundary layer thickness of the gas

Although radiant fluxes have not been explicitly included, any given value for the flux may be incorporated into the present formalism as follows. Define an equivalent radiation temperature, T_R, by:

$$Q_{RAD} \triangleq K_2 \frac{T_R}{\delta}$$

Then the value of the above gas temperature should be replaced by $T_2 + T_R$. The initial condition is:

$$T(0, r) = T_0 \qquad 0 \leq r \leq R \qquad (3)$$

One form of the solution may be written as follows:

$$\frac{T_2 - T_1(t,r)}{T_2 - T_0} = \frac{2P}{r/R} \sum_{n=1}^{\infty} e^{-\beta b_n^2 t} \left\{ \frac{b_n^2 + (P-1)^2}{b_n^2 [b_n^2 + P(P-1)]} \sin b_n \sin\left(b_n \frac{r}{R}\right) \right\} \quad (4)$$

where the sequence $\{ b_n \}$ is obtained from the transcendental equation: $b_n \cot (b_n) = 1 - P$

and:

$$\beta \triangleq \frac{K_1}{\rho_1 C_1 R^2} \quad ; \quad P \triangleq \frac{K_2 R}{K_1 \delta} \quad (5)$$

From equation (4) it can be shown that for large times the surface temperature approaches the asymptotic form:

$$\frac{T_2 - T_S(t)}{T_2 - T_0} \xrightarrow{t \uparrow} 2P \frac{e^{-\beta b_1^2 t}}{b_1^2 + P(P-1)} \quad (6)$$

However, for times approaching the initial condition, more and more terms in Equation (4) need to be retained for an accurate representation. To circumvent this unwieldy computation, we formulate the following asymptotic solution valid for short times. By employing the transformation, $V = r(T - T_0) + V_0$, the spherical problem becomes an equivalent planar one, and with a translation and inversion of sign the tektite surface shifts to $r = 0$ while the tektite center shifts to $r = R$. Then one can show that the short time solution for surface temperature has the form:

$$\frac{T_2 - T_S(t)}{T_2 - T_0} \xrightarrow{t \downarrow} \frac{P}{P-1} \left\{ -\frac{1}{P} + e^{(P-1)^2 \beta t} \operatorname{erfc}\left[(P-1)\sqrt{\beta t}\right] \right\} \quad (7)$$

Provided that: $\beta t \ll 1/4$

From the solutions presented above, it is seen that tektite surface temperatures depend on the two parameters,

$$P = K_2 R / K_1 \delta \quad \text{and} \quad \beta t = K_1 t / \rho_1 C_1 R^2 ,$$

as well as the ambient temperature and initial temperature. Figure 4 shows graphically the relation between the surface temperature and these parameters. Although both limiting solutions are drawn in the figure, the short term solution is a good approximation everywhere on the graph since the value for βt is within the inequality given under Equation (7). The slowest realistic heating time for tektites is represented by the following typical case:

$R = 2.5$ cm

$\delta / R = 10^{-2}$

$K_1 = 1.5 \times 10^{-3}$ kilowatts/m^{o} K

$\rho_1 = 2.5$ gm/cm^3

$C_1 = 1.17$ Kw-sec/Kg ^{o}K

(the values K_1, ρ_1, C_1 from Reference 1)

$K_2 = 1.2 \times 10^{-4}$ Kw/m^{o} K (from Ref. 15)

The last value represents the thermal conductivity of laminar air at approximately 2,000 ^{o}K which is the temperature of the air at a nearly melting tektite surface. The pressure dependence of this value is insignificant. For these values we obtain:

$P = 8$

$\beta = (1.22 \times 10^{+3} \text{ sec.})^{-1}$

Under these conditions it is seen from Figure 4 that it takes 33 seconds for the tektite surface to reach approximately 70% of the ambient temperature, which is a surprisingly slow rate. Among the objections one may raise to the above calculations are the following:

(1) The external temperature distribution for either tumbling or non-tumbling cases is not spherically symmetric as is assumed here.

(2) Heating during the free-molecular regime has not been realistically treated.

(3) The actual effective heat transfer coefficient of air may be much larger than the value chosen here, especially for the case of turbulent flow and higher ambient temperatures. For example, a peak value for stagnation point heating extracted from Chapman's[10] more comprehensive calculations is approximately 6.4 kw/cm^2. This corresponds to a value for P which is an order of magnitude larger than the limiting case chosen above.

Nevertheless, by variation of the parameter P, the simplified analysis leading to Figure 4 provides a convenient measure for typical thermal rise times in a tektite distribution depending on the actual heat inputs.

the actual external temperature is not spherically symmetric, one may use an average value for order of magnitude results or the stagnation point value for the fastest temperature rise. If the tektite tumbles rapidly enough, then the external field could effectively approach an averaged constant value. If the actual free molecular heating rate were given, then a conversion similar to the one of radiation could provide an equivalent external temperature and Figure 4 would indicate the rise time of surface temperature. For purposes of comparison, temperature curves have been drawn in Figure 4 for several values of the parameter P.

3.2 THE TEKTITE TRAJECTORY

It now remains to calculate typical times of tektite deceleration and to compare these with the times of surface temperature rise. Again Chapman[10] has presented numerical solutions for relatively general trajectories. Here we merely note that the limiting cases of horizontal and vertical trajectories through the atmosphere have particularly simple analytical solutions, and that time constants obtained from them will bracket the values obtained for more general trajectories.

Horizontal:

$$\frac{d}{dt}(mu) = -\frac{1}{2}\rho_\infty C_D A u^2 \qquad (8)$$

Vertical: $$\frac{d}{dt}(mv) = -\frac{1}{2}\rho_\infty C_D A v^2 + mg \tag{9}$$

where v is taken positive in the downward direction

Solutions: $$\frac{u}{u_0} = \frac{1}{1 + a u_0 t}$$

$$\frac{v - v_f}{v + v_f} = \left(\frac{v_0 - v_f}{v_0 + v_f}\right) e^{-2 a v_f t} \tag{10}$$

where

$$a = \frac{3}{8}\frac{\rho_\infty}{\rho_1}\frac{C_D}{R} \quad ; \quad v_f = \sqrt{g/a} \tag{11}$$

These solutions assume constant averaged values for the ambient density and C_D during any <u>segment</u> of the trajectory. Since the vertical trajectory is the one which produces the fastest deceleration, we shall use it for numerical estimates. The vertical velocity has two aspects to be considered: the rate of deceleration to the local terminal velocity, and the value of the terminal velocity at various altitudes. The actual velocity will never be less than the local terminal velocity. To find an approximate rate of deceleration, we assume the initial velocity to be much greater than the local terminal velocity. Then from Equation (11) we obtain:

$$\left(1-\frac{v_f}{v}\right)^2 \cong \left(1-\frac{v_f}{v_o}\right)^2 e^{-2av_f t} \cong \left(1-\frac{2v_f}{v_o}\right)\left(1-2av_f t\right)$$

or:

$$\frac{v}{v_o} \cong \frac{1}{1+av_o t} \quad \text{when} \quad \frac{v}{v_f} \gg 1 \tag{12}$$

which is the same rate of deceleration as for the local horizontal trajectory.

The local rate of deceleration and the terminal velocity have been plotted in Figure 5 as a function of altitude for a typical tektite of radius 2.5 cm and an entry velocity of 11 km/sec. At altitudes greater than 75 km, the atmosphere is so rarified that the terminal velocity is comparable to the escape velocity, while the deceleration time is extremely long. Atmosphere braking becomes effective in the vicinity of 45 km where the deceleration time is approximately 10 seconds. At altitudes below 30 km all tektites will surely have decelerated to the terminal velocity which becomes subsonic near that altitude.

3.3 CONCLUSIONS

It has been argued that characteristic rise times for tektite temperature should not exceed approximately 30 seconds, and in actual atmospheric flight the time is most likely less, perhaps totalling 5 - 10 seconds. Although tektites decelerate to their terminal velocities in periods of roughly 10 seconds at an altitude of 50 km it should be noted that peak heating occurs prior to peak deceleration.[10] Thus, it appears to be possible, although highly unlikely, that some tektites should display no evidence of surface melting if their trajectories were the usual ones assumed to originate beyond the earth. However, it is clear from these solutions that if entry conditions had been modifed somewhat from the assumed state of an undisturbed atmosphere, then it could have been possible for tektites to have remained unmolten during their descent. In the next section it will be argued that entry in the ambient of a hypersonic wake lessens the probability of tektite melting and that such an ambient arises naturally in the entry of a swarm.

From the present analysis we make the following additional observations:

- If it is assumed that the thermal boundary layer is roughly proportional to the tektite radius, then the parameters in equation (5) show that in a tektite swarm the surface melting time increases proportionally with the square of the radius.
- Equations (11) and (12) show that the characteristic time of deceleration increases <u>linearly</u> with the radius.

Hence, we hypothesize a correlation to exist between the amount of melting and tektite size. Since the smallest tektites should have experienced laminar heating throughout their trajectories, microtektites should have reached the melting point prior to peak deceleration and might have melted completely. It is consistent that microtektites are observed to have smooth molten forms. Tektites of an intermediate size (still in the laminar regime) would have been less susceptible to melting due to their larger thermal inertia. The largest tektites would again have been more susceptible to melting and/or spallation because part of their trajectories may have included a turbulent heating regime. Figure 6 shows experimental data taken from Reference 4, p. 4335, concerning the amount of ablation measured from various flanged australites. Despite the expected scatter in the data, there appears a trend of ablation increasing with radius in the region shown. By extrapolation it appears that smaller tektites were less susceptible to melting as hypothesized.

4.0 THE WAKE HYPOTHESIS

Since it is highly unlikely for a tektite to have remained unmolten if it had entered an undisturbed atmosphere at near escape velocity, we now seek another model of entry. We note in general that a tektite descending in the wake of another body would experience a deceleration that is relatively shielded in comparison with a direct entry.

Consider a swarm of tektites entering the atmosphere as shown in Figure 7. Tektites along the perimeter of the swarm enter the undisturbed atmosphere and form hypersonic shocks of highly acute angle. (We consider only the continuum portion of the descent.) Behind these first shocks the air density is increased by a factor of almost 6, and there is an accompanying increase of temperature and a decrease of fluid velocity relative to the trailing tektites. As the lead tektites decelerate, other tektites will overtake them from behind. Subsequent tektites enter in hypersonic environments at sequentially lower Mach numbers, and consequently their shock angles will be larger than those of the preceding tektites. The further downstream one goes of the enveloping shock structure, the lower is the air velocity relative to those tektites.

The shock envelope produces the following conditions for the bulk of tektites which follow in its wake, and each of these conditions goes in the direction of inhibiting tektite ablation.

(1) The effective entry velocity is reduced over the case of an undisturbed atmosphere.

(2) The lowering of velocity decreases surface heat transfer rates, and inhibits transition to turbulence.

(3) The increased ambient density hastens the moment of peak deceleration, thereby providing less time for heating.

(4) Although the atmosphere absorbs energy during the event, the net rise in gas temperature in the wake is insignificant for the heating of trailing tektites because the heat is dispersed into a large volume of gas.

(5) The brunt of aerodynamic heating is borne by the lead tektites. However, since these tektites decelerate the fastest, others will overtake them, and, therefore, the original leaders will also be partly shielded during the latter segment of their descent.

One realizes intuitively that a scattered distribution of tektites will decelerate more quickly than the same mass in a more concentrated form, because in the former case the tektites interact with a larger mass of air. However, in order for the shock envelope to be effective, the tektite swarm must not be dispersed to such an extent that each tektite enters as if singly.

Once the tektite swarm engages the atmosphere its uniform motion will cease, because its members will decelerate differentially according to size. The larger tektites are more likely to gain the lead positions, whereas the microtektites will fall far into the wake. During the process it is possible for the microtektites to become a source of high speed collisions with the larger ones.

The wake model provides another explanation for the variations observed in tektite ablation. The leaders of a swarm could have ablated significantly to produce the ring waves discussed by Chapman, and the followers could have decelerated in a more benign ambient, producing insignificant ablation. If the wake hypothesis describes the actuality, then a cautionary remark should be appended to calculations of the type performed by Chapman,(4) in which tektite trajectory conditions (V_O, γ_O) are connected with the amount of ablation. These calculations assume an undisturbed atmosphere, and if the tektite were actually partially shielded, then the results would be underestimations.

The next section addresses the question of aerodynamic pitting of tektite surfaces.

5.0 SURFACE PITTING MECHANISM

Besides the obvious ring-waves, flanges and some possible ablation streaks, what other features may be attributed to aerodynamics? Among the most prevalent surface features are highly symmetrical hemispherical pits. Could these have been influenced aerodynamically also? The striking photograph shown in Figure 7 of Reference 3 strongly suggests that the stagnation point pits were formed during or after the process of ring wave ablation. One possibility is the impact of debris coming from the upstream direction. Since the tektites entered in a swarm, rapidly decelerating microtektites could have become debris for the larger tektites. However, one might have expected the impact distribution to be more uniform (or random), rather than being maximized systematically towards the stagnation point. An alternative explanation could be bubbling during the process of melt flow since the stagnation point is the hottest part of the tektite. In counterpoint, Chapman[(3)] has observed that under some conditions bubbling occurs first at the flanges because the ambient pressure is minimum there. Moreover, if bubbling occurs in melt flow, how is it possible for the bubble diameter to exceed the melt flow thickness as appears to be the case? Here we propose an aerodynamical mechanism which can make pits grow in size while simultaneously maintaining their hemispherical shape.

The pit geometry suggests the existence of a strong trapped ring vortex. Credibility is added to this notion by the experiments of Johnson[11], who observed severe shock distortions in a hypersonic flow around a body containing forward facing cavitities in the surface. Although for some pit geometries a slight injection was required to trigger the instability, the hemispherical pit was the shape which most readily generated steady or unsteady vortices. For the case of tektites, cavity ablation could provide just the injectant necessary to trigger the vortex flow, and then the vortex could increase pit heat transfer, thereby increasing pit ablation. Cross sectional views of the two possible vortex orientations are shown schematically in Figure 8. The orientation involving outflow along the axis of symmetry provides the possibility of a strong instability which would result in an upstream jet emanating from the pit. Jets of this nature can produce[20] shock distortions of the type observed by Johnson. The frequency of shock oscillation is typically a few K_{H_Z}, which indicates that vortex formation and decay is rapid compared to possible tumbling rates of the tektites. Therefore, in a tumbling tektite, every cavity passing near the stagnation region could experience a rapid sequence of vortices which could purge accumulated melt flow. Of course, in order for shock disturbances to occur, the diameter of the pit should be comparable to the shock standoff distance. However, for smaller pits, vortices may still be trapped and cause pit growth. With the rapid vortex scouring, it is possible for the pits to ablate at a rate faster than that of the neighboring tektite surface.

As the tektite tumbles and the pit becomes displaced from the stagnation region, the ring vortex naturally becomes asymmetrical. If an oblique orientation persists long enough, then a hemispherical pit could elongate into a groove as the ring vortex stretches into a trapped horseshoe vortex with the tails trailing downstream.

The mechanism mentioned above could apply to any surface pit whether it existed before atmsophere entry, whether due to debris impact, or whether caused by bubbling. In the case of bubbling, the vortex could eat into the solid undersurface, thus keeping the eventual pit fixed near the stagnation point rather than permitting the bubble to move downstream with the melt flow.

6.0 CONCLUSIONS

The observed presence of sharp features on some tektite surfaces suggests that not all tektites have sustained significant ablation during atmospheric passage. One might maintain even further that these surfaces had not reached the melting point. In the attempt to reconcile such observations with previous expectations of higher heating rates, the equations of unsteady heat transfer and tektite motion have been reconsidered in the hope of finding conditions under which compatibly lower heating rates might occur. Evaluations of parameters appearing in these equations support the contention that under the assumed single entry conditions it is highly unlikely for any tektite to have experienced no ablation. However, the parameters indicate that tektites of intermediate size are least susceptible to melting according to their characteristic times of melting and deceleration.

A proposed explanation for the wide variation in tektite ablation is connected with tektite entry into the earth's atmosphere as a swarm rather than in single fashion. A shock envelope formed by the lead tektites might have contributed to the shielding of the majority of the tektites from the full force of aerodynamic heating. The spatial relation between a given tektite and this shock envelope is a major factor governing the amount of ablation sustained. The wake of a large body (such as a meteor) could afford similar shielding for the tektites, but other arguments render this alternative less likely.

The presence of hemispherical pits in the midst of melt flow has prompted the search for an aerodynamic mechanism to explain them. Strong ring vortices trapped in pits near the stagnation point appear to have the necessary properties, and furthermore, they have already been observed in pertinent hypersonic experiments. Such vortex instabilities could cause pit interiors to ablate at rates faster than those of the surrounding surfaces while maintaining a hemispherical geometry for the pits.

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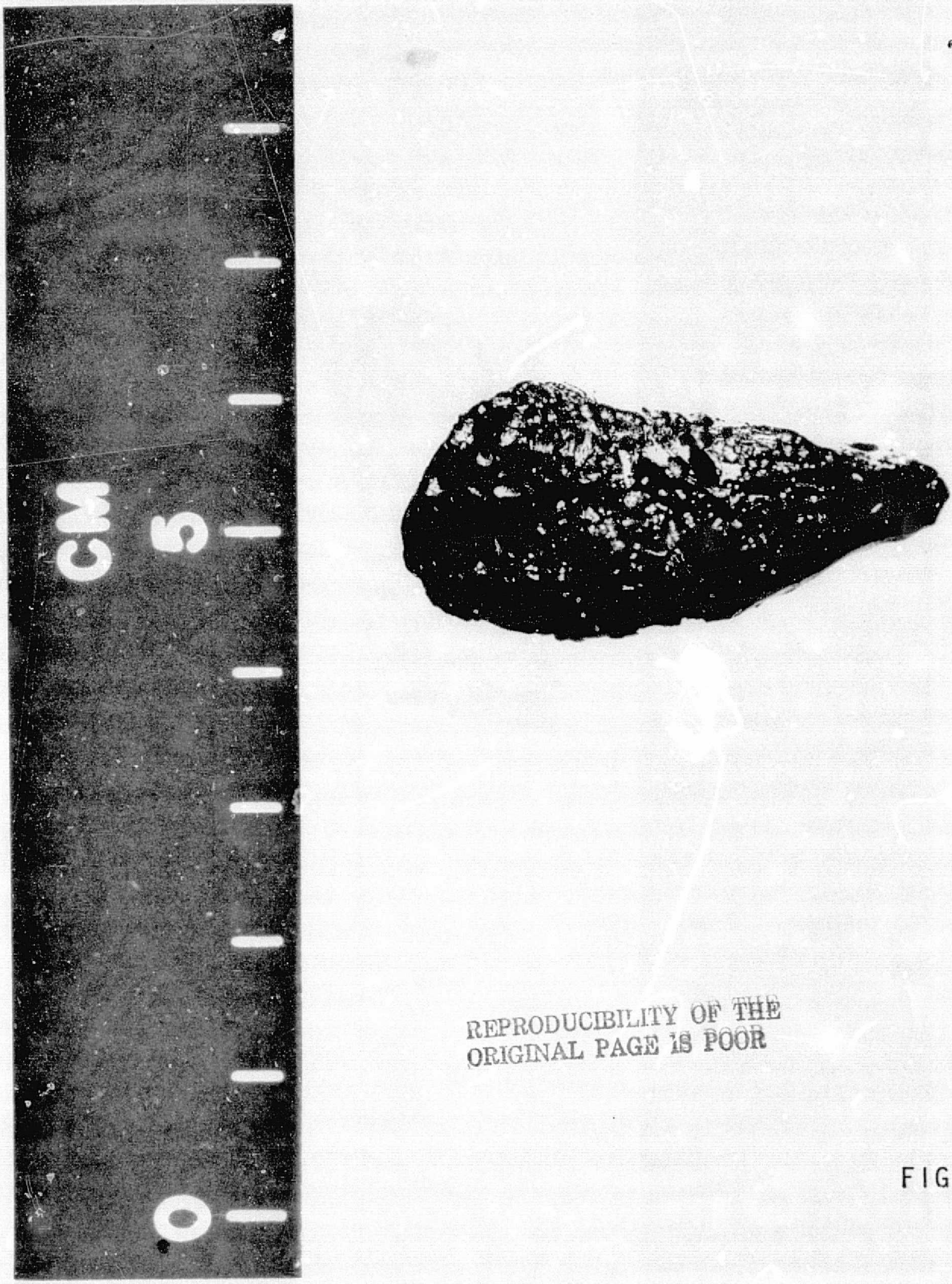


FIGURE I

TEKTITE SURFACE EXHIBITING INTERNAL STRIAE

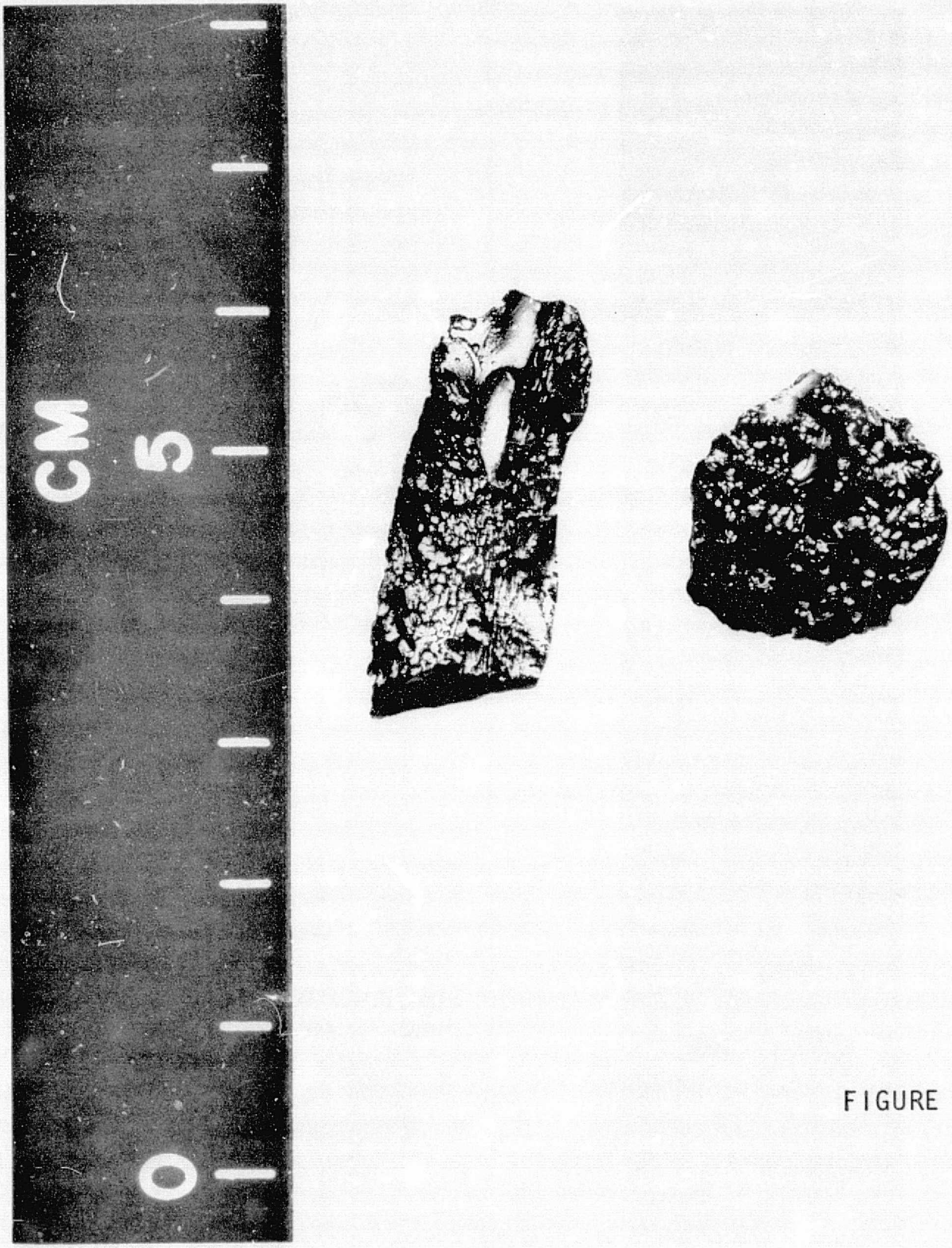


FIGURE 2

TYPICAL TEKTITES EXHIBITING SURFACE PROTUBERANCES
AND OTHER SHARP FEATURES

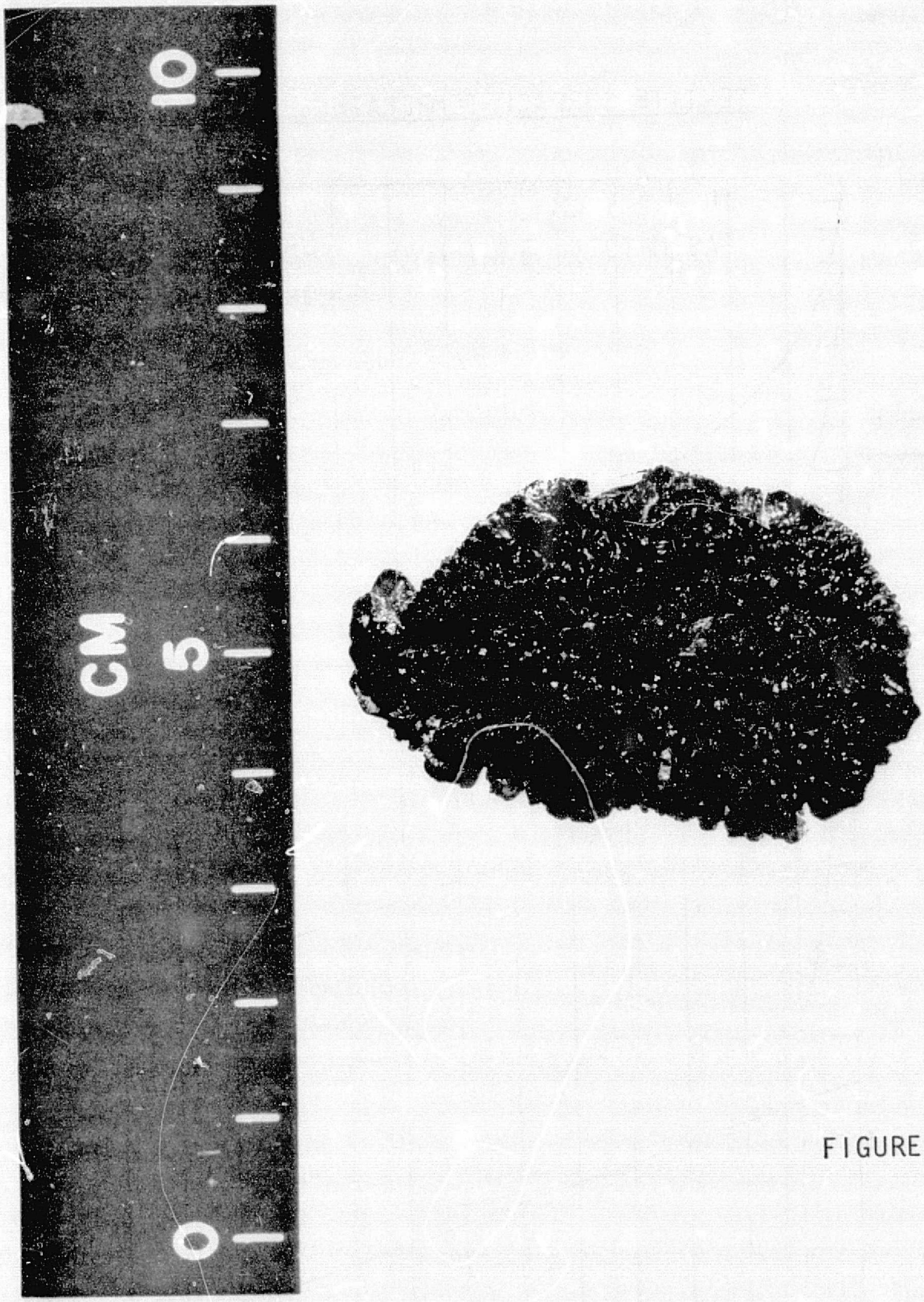


FIGURE 3

TYPICAL TEKTITE EXHIBITING SURFACE PROTUBERANCES AND OTHER SHARP FEATURES

TEKTITE SURFACE TEMPERATURE VS. TIME

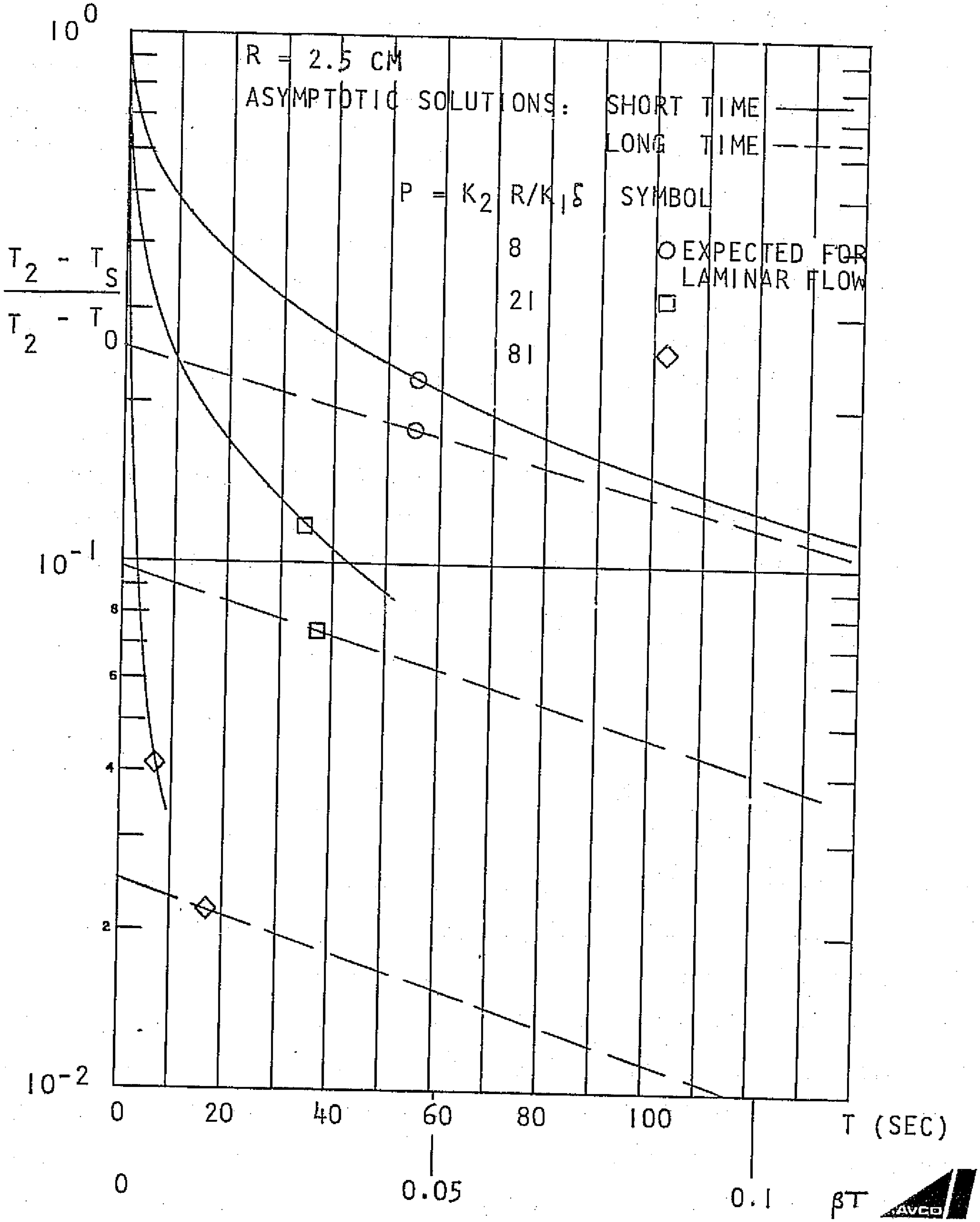


FIGURE 4

TYPICAL TEKTITE DECELERATION CHARACTERISTICS VS ALTITUDE

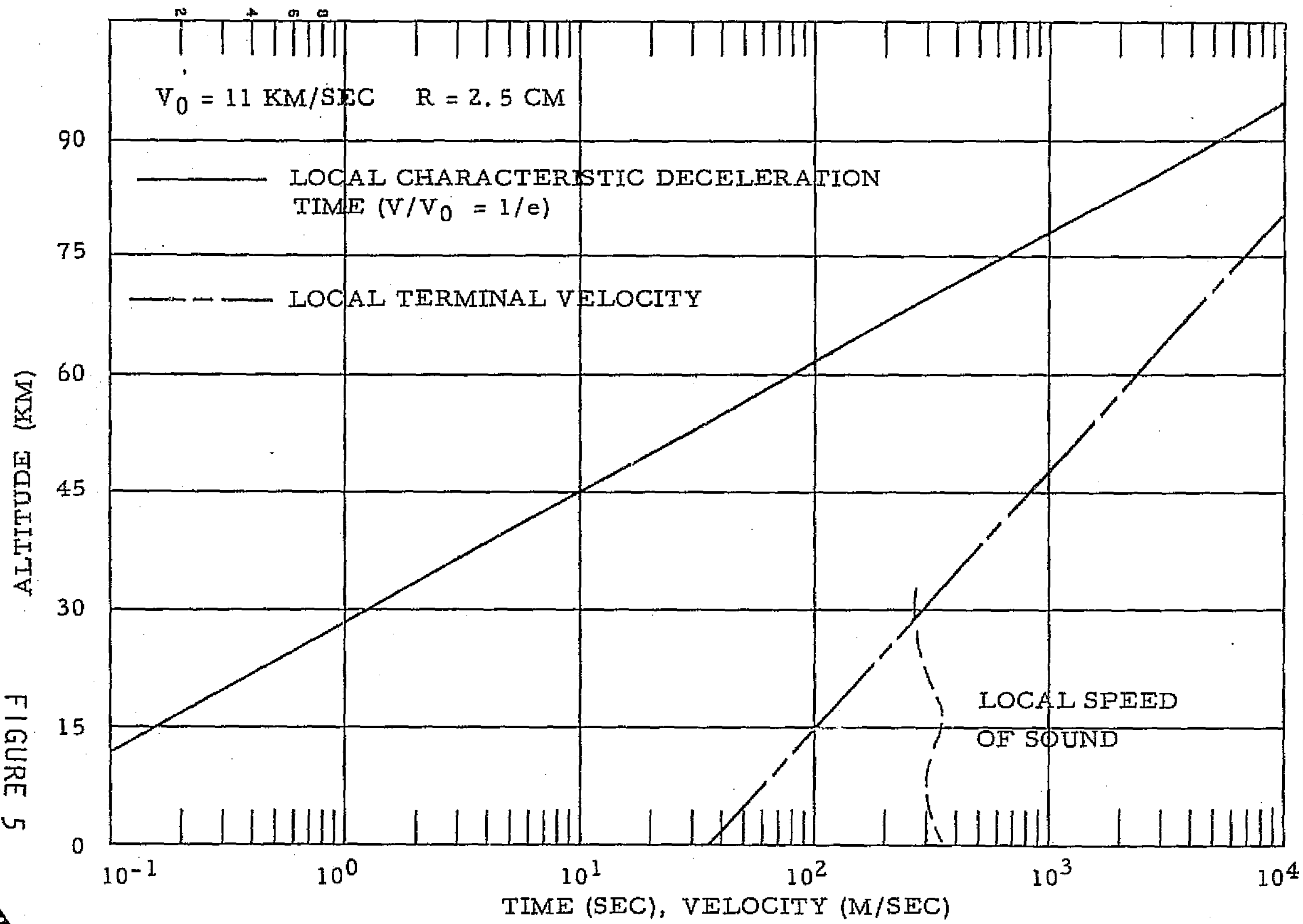


FIGURE 5

NOTE: USE TYPE B PENCIL FOR VUGRAPHS AND REPORT DATA.

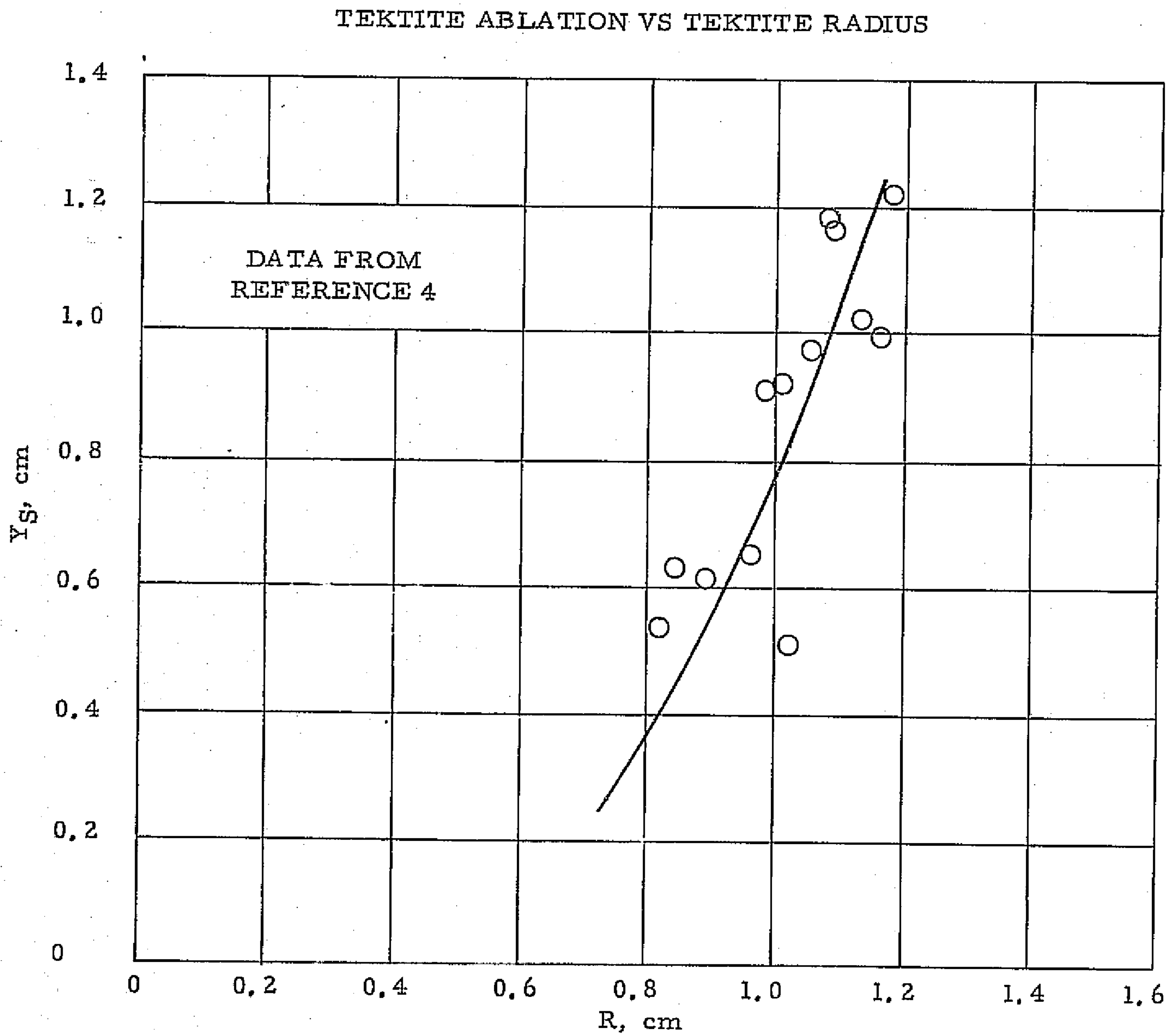
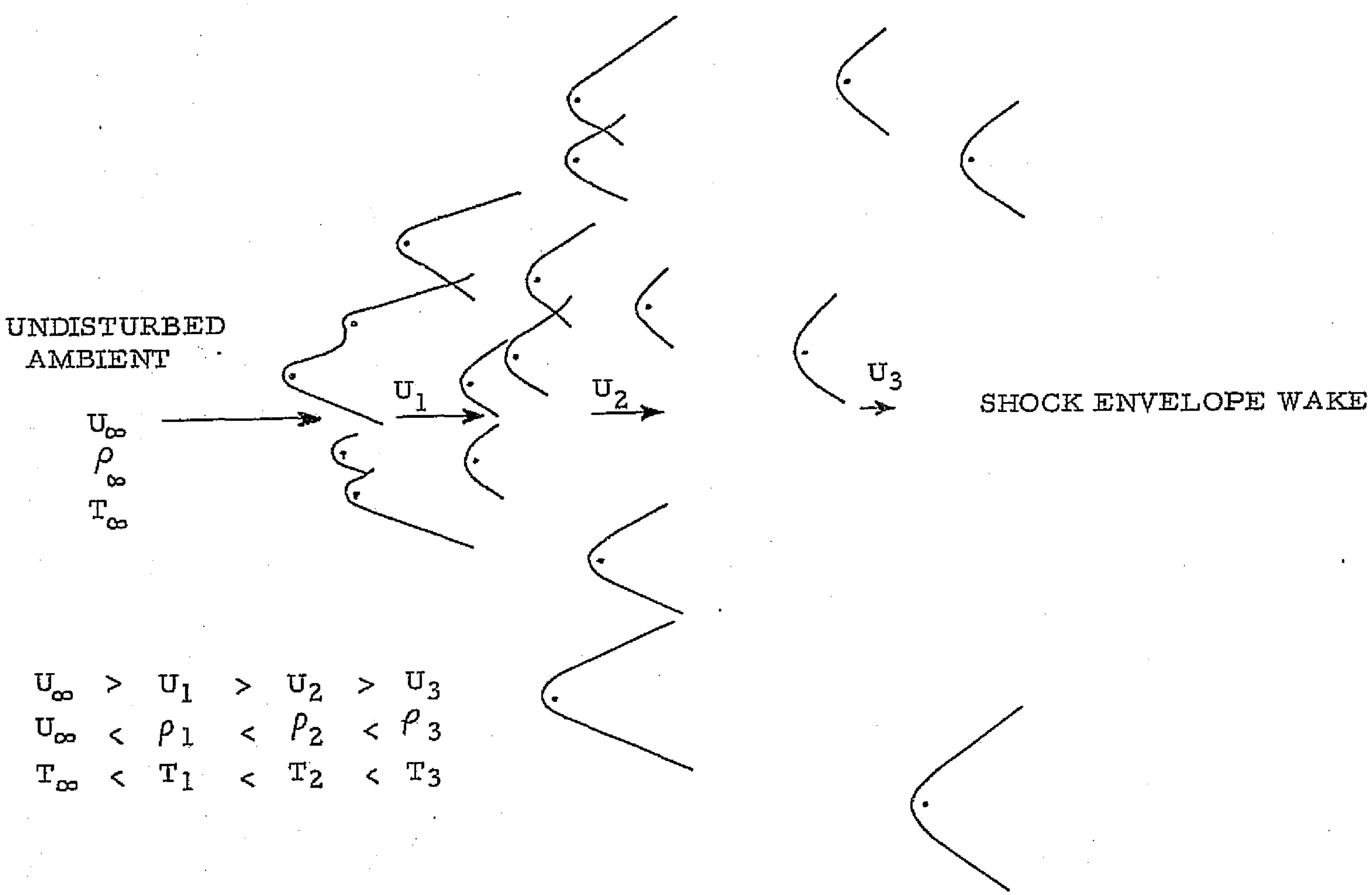

TEKTITE ABLATION VS TEKTITE RADIUS
DATA FROM
REFERENCE 4
Y_S, cm
R, cm
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6

FIGURE 6

SHOCK ENVELOPE MODEL FOR TEKTITE SWARM



$U_\infty > U_1 > U_2 > U_3$

$U_\infty < \rho_1 < \rho_2 < \rho_3$

$T_\infty < T_1 < T_2 < T_3$

FIGURE 7

RING VORTEX CONFIGURATIONS FOR A PITTED STAGNATION POINT FLOW

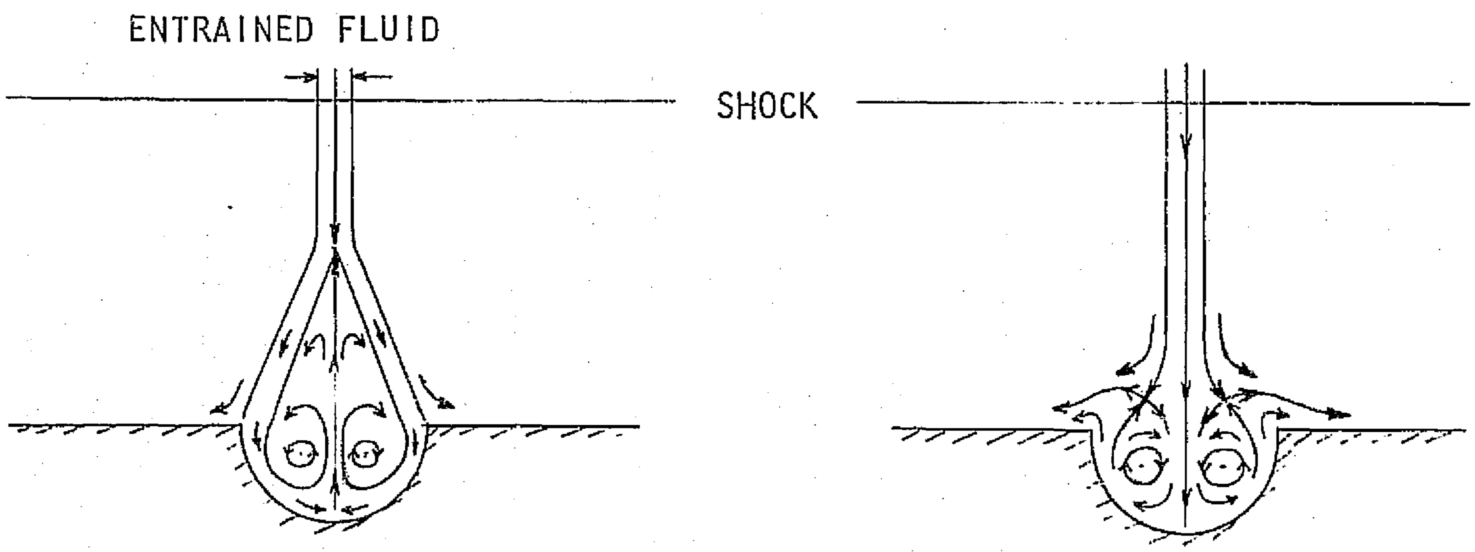


FIGURE 8

AVCO

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15. Supplementary Notes		

16. Abstract

Many tektite surfaces show less evidence of melt flow than would be anticipated for bodies entering the earth's atmosphere at greater than escape velocities. Several examples are given to support this contention. Equations are presented which provide approximate parameters describing surface heating and tektite deceleration during atmosphere passage. Numerical estimates of these parameters using typical initial and ambient conditions support the conclusion that the commonly assumed trajectories would not have produced some of the observed surface markings. Consequently, it is suggested that tektites did not enter the atmsophere singly but rather in a swarm dense enough to afford wake shielding according to a shock envelope model which is proposed. A further aerodynamic mechanism is described which is compatible with hemispherical pits occurring on tektite surfaces.

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