

Physics of interplanetary dust capture via impact into organic polymer foams

William W. Anderson and Thomas J. Ahrens

Lindhurst Laboratory of Experimental Geophysics, Seismological Laboratory
California Institute of Technology, Pasadena

Abstract. The physics of hypervelocity impacts into foams is of interest because of the possible application to interplanetary dust particle (IDP) capture by spacecraft. We present a model for the phenomena occurring in such impacts into low-density organic polymer foams. Particles smaller than foam cells behave as if the foam is a series of solid slabs and are fragmented and, at higher velocities, thermally altered. Particles much larger than the foam cells behave as if the foam were a continuum, allowing the use of a continuum mechanics model to describe the effects of drag and ablation. Fragmentation is expected to be a major process, especially for aggregates of small grains. Calculations based on these arguments accurately predict experimental data and, for hypothetical IDPs, indicate that recovery of organic materials will be low for encounter velocities greater than 5 km s^{-1} . For an organic particle $100 \mu\text{m}$ in diameter, $\sim 35\%$ of the original mass would be collected in an impact at 5 km s^{-1} , dropping to $\sim 10\%$ at 10 km s^{-1} and $\sim 0\%$ at 15 km s^{-1} . For the same velocities the recovery ratios for troilite (FeS) are $\sim 95\%$, 65% , and 50% , and for olivine (Mg_2SiO_4) they are $\sim 98\%$, 80% , and 65% , demonstrating that inorganic materials are much more easily collected. The density of the collector material has only a second-order effect, changing the recovered mass by $<10\%$ of the original mass.

Introduction

A spacecraft encountering an interplanetary dust particle (IDP) at a relative velocity of several kilometers per second may be used to capture that particle for in situ analysis or for analysis upon Earth return. In this paper we study the impact of a dust particle into a low-density medium (i.e., a foam) such that the foam dissipates the kinetic energy of impact over a sufficient distance to stop the particle without destroying it.

Previous Studies

Previous theoretical work has not been undertaken to understand the physics of hypervelocity impact into very low density solid media. However, a large number of experimental data have been collected [Werle *et al.*, 1981; Tsou *et al.*, 1984, 1986, 1988; Peng *et al.*, 1988] (P. Tsou *et al.*, personal communication, 1993). Most of these data are for aluminum projectiles, which, while not completely accurate representations of interplanetary dust particles, allow models to be tested and provide a basis for extrapolation to the regime of relevance to IDP sampling missions. A number of commercially available materials have been tested, with the result that polystyrene foams and silica aerogels have the best properties for this application [Tsou *et al.*, 1986, 1988, 1989; Barrett *et al.*, 1992].

Theoretical Treatment

The present model examines the phenomenon of hypervelocity impact into organic polymer foams. We will specifi-

cally consider polystyrene because of the extensive body of experimental data that exists for this material. However, the model should be generally applicable to any organic polymer, provided the correct material properties are used.

There are three regimes into which a particle-collector combination may be placed, based on the relationship between the IDP diameter, d_p , and the characteristic microstructural lengths scales of the foam. If d_w is the thickness of a cell wall in the foam and d_f is the diameter of a cell, the three regions may be approximately defined as follows: (1) $d_p \leq d_w$, (2) $d_w < d_p \leq d_f$, and (3) $d_p > d_f$. Particles in regimes 1 and 2 will behave as if the cell walls were solid blocks of the material from which the foam is made. Particles in regime 3 will see the foam as a continuum.

We consider regimes 1 and 2 only briefly. The processes affecting particles in these regimes are those associated with the shock wave generated upon impact into a cell wall, followed by adiabatic release to zero pressure. Since particles in regimes 1 and 2 see the impact as occurring into the solid material rather than into a low-density foam, they are shocked to much higher pressures than their counterparts in regime 3. For impact into polystyrene, this amounts to a pressure increase by a factor of as much as 20 for commercially available foam bulk densities. Figure 1 shows shock pressure as a function of impact velocity for impact into solid polystyrene by particles of troilite, olivine (forsterite: Mg_2SiO_4), and organic matter (here modeled by polystyrene). The cross on each curve represents the condition required to produce partial melting in the impacting particle upon release to zero pressure, which might be considered the threshold for unacceptable thermal alteration in such cases. For organic materials, 2 km s^{-1} is an upper limit for collection of very small unaltered grains. As we would

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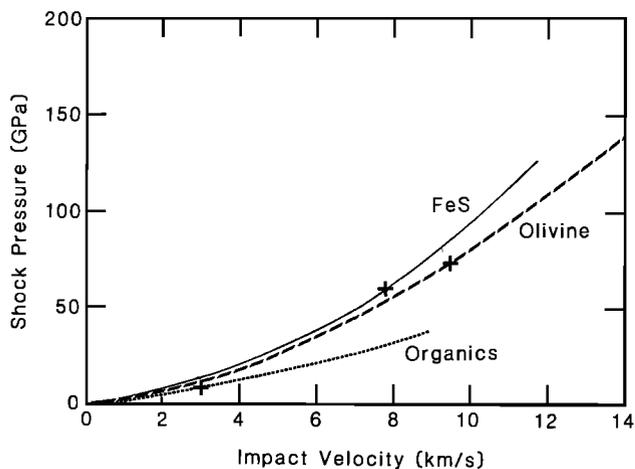


Figure 1. Shock pressure from impacts into nonporous polystyrene.

expect, inorganic materials are much harder, with alteration threshold impact velocities of 8–10 km s⁻¹.

Particles in regime 3 behave quite differently from those in regimes 1 and 2. Because they see the foam as a very low density continuum, the processes can be described by fluid mechanics. In some respects, the present treatment is similar to the physics of meteors [e.g., Öpik, 1958]. However, there are important differences, which will be noted as they occur in our discussion. The particle will be preceded by a bow shock wave (Figure 2), behind which is a flow of shocked foam around the particle. A viscous boundary layer exists at the surface of the particle. At some point the flow will separate, isolating the surface of the particle from the shocked material. The primary processes are drag, ablation, and fragmentation.

Drag

In order to develop a model for deceleration of the dust particle, it is best to begin by considering the shock wave which precedes the particle. The change in conditions across a steady, normal, planar shock wave is constrained by the Rankine-Hugoniot conservation equations [Zel'dovich and Raizer, 1967]:

$$U_s \rho_0 = (U_s - u_p) \rho_H \quad (1)$$

$$P_H = U_s u_p \rho_0 + P_0 \quad (2)$$

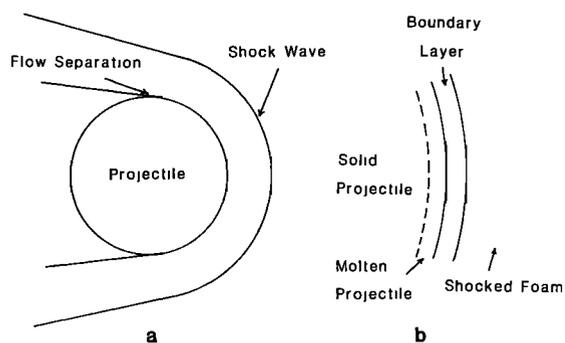


Figure 2. Conceptual model for a particle passing through a low-density foam at high velocity.

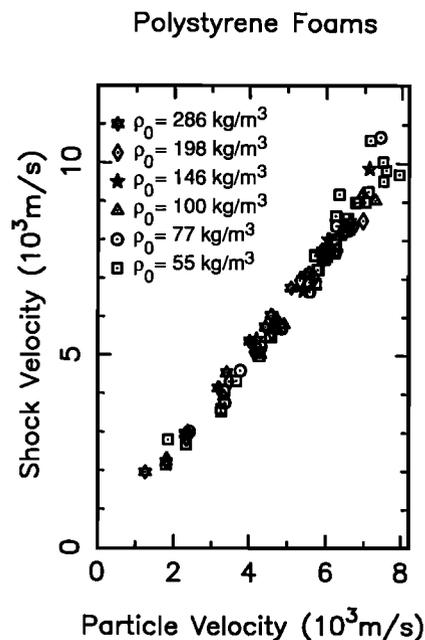


Figure 3. $U_s - u_p$ shock Hugoniot data for polystyrene foams. Data from Marsh [1980].

$$E_H - E_0 = (P_0 + P_H)(V_0 - V_H)/2 = u_p^2/2 \quad (3)$$

where U_s and u_p are the shock wave velocity and postshock particle velocity, respectively (both in the rest frame of the unshocked material), ρ is the mass density, P is pressure, V is specific volume, E is specific internal energy, and the subscripts zero and H refer to the unshocked and shocked (Hugoniot) states, respectively. Often, U_s is written as a polynomial function of u_p , which we take to second order for the present study:

$$U_s = C_0 + s u_p + s' u_p^2 \quad (4)$$

While the lowest commercially available polystyrene foam density is $\sim 10 \text{ kg m}^{-3}$, the lowest density for which shock wave Hugoniot data are available is 55 kg m^{-3} . Marsh [1980] presents data for polystyrene foams with densities ranging from 55 to $\sim 300 \text{ kg m}^{-3}$. Examination of these data in the $U_s - u_p$ plane (Figure 3) shows that, even with a variation of a factor of 5 in initial density, the $U_s - u_p$ Hugoniot curves are very similar. We find C_0 , s , and s' to be well represented by

$$C_0 = a_c + b_c \rho_0^2 \quad (5)$$

$$s = a_s + b_s \rho_0^2 \quad (6)$$

$$s' = a_{s'} + b_{s'} \rho_0^2 \quad (7)$$

with $a_c = 336.9 \text{ m s}^{-1}$, $b_c = -0.002171 \text{ m}^7 \text{ kg}^{-2} \text{ s}^{-1}$, $a_s = 0.90525$, $b_s = 5.029 \times 10^{-6} \text{ m}^6 \text{ kg}^{-2}$, $a_{s'} = 5.155 \times 10^{-5} \text{ s m}^{-1}$, and $b_{s'} = -7.713 \times 10^{-10} \text{ m}^5 \text{ s kg}^{-2}$. Table 1 gives the resulting values of C_0 , s , and s' for polystyrene foams with the initial densities used in this study.

Generally, the bulk sound speed of a material defines the lower limit on the velocity of a steady shock wave. A wave traveling at the bulk sound speed C_b of the solid polymer must travel around the cells rather than directly across them.

Table 1. Hugoniot Parameters for Polystyrene Foams

$\rho_0, \text{kg m}^{-3}$	$C_0, \text{m s}^{-1}$	s	$s', \text{s m}^{-1}$
32.1	334.7	0.9104	5.076×10^{-5}
28.5	335.1	0.9093	5.092×10^{-5}
20.0	336.0	0.9073	5.124×10^{-5}
10.0	336.7	0.9058	5.147×10^{-5}
1.0	336.9	0.9053	5.154×10^{-5}

Even for highly distended foams, however, this only increases the path by a factor of $\sim \pi/2$, since the cells are roughly spherical. Thus the effective bulk sound speed C_f of the foam, which we take as a lower limit on U_s , is $C_f \approx 2C_b/\pi$. For nonporous polystyrene, the bulk sound speed is $C_b = 1898 \text{ m s}^{-1}$ [Marsh, 1980], so the effective bulk sound speed of polystyrene foams is $C_f \approx 1203 \text{ m s}^{-1}$.

For dust particle velocities $u > C_f$, decelerating forces arise from two sources: the pressure difference across the particle and the viscous stresses set up in the boundary layer. Let us begin by considering the pressure effects.

The "ambient" pressure P_H of the shocked foam is, taking $P_0 = 0$ in (2) and setting U_s equal to the velocity u of the dust particle (required for the shock wave to remain steady),

$$P_H = \rho_0 u u_p \tag{8}$$

Using (4), we can get u_p as a function of u , so that P_H can be written solely as a function of u . In addition, to this ambient shock pressure, the forward facing surface of the dust particle experiences a dynamic pressure P_D , which for a surface element whose normal makes an angle θ with the velocity vector of the dust particle is

$$P_D = [\rho_H(u - u_p)^2 \cos^2 \theta]/2 \tag{9}$$

By definition, the pressure exerted on the particle by the foam must vanish where the flow separates. The pressure gradient which gives rise to this phenomenon exists because of the requirement to accelerate the shocked foam, which comes to rest against the surface of the dust particle, around the particle. We will assume that separation occurs at $\theta = \pi/2$. Since there is already a gradient built into P_D , we satisfy the requirement that the surface pressure P'_H associated with P_H decrease to zero at $\theta = \pi/2$ by approximating P'_H as

$$P'_H = P_H \cos \theta \tag{10}$$

To get the component of pressure acting parallel to the velocity vector of the dust particle, we must further multiply P'_H and P_D by $\cos \theta$. Thus, taking $P = 0$ at $\theta > \pi/2$, the total pressure force acting to decelerate the dust particle is given by the surface integral:

$$F = \int (P_H \cos^2 \theta + P_D \cos \theta) ds \tag{11}$$

The viscous shear stress τ_s in the boundary layer is given by

$$\tau_s = \eta \dot{\epsilon} \tag{12}$$

where η is the absolute viscosity and $\dot{\epsilon}$ is the shear strain rate, which we take to be

$$\dot{\epsilon} = \frac{u - u_p}{\delta} \tag{13}$$

where δ is the characteristic thickness of the boundary layer. In meteor phenomena, viscous forces are usually neglected except at very low velocities, but we cannot make that simplification here. There are a number of models which may be used to estimate η . Since, as we shall see later, the shocked foam may be expected to act in much the same way as a molten polymer because of kinetic constraints on the rate of decomposition, we use a model which is relevant to such a material, namely, that of Bueche [1962], who finds for high shear rates,

$$\eta \sim \left(\frac{\rho T}{\dot{\epsilon} M} \right)^n \tag{14}$$

where M is the average molecular weight of a polymer chain and $n \approx 1/2$. Although increasing T causes M to decrease because of bonds being broken, the extent to which this happens on the timescales required for the present problem is low, so that the dependence of M on T is weak relative to the system at equilibrium. For the present study, we take the quantity M/T constant, thus making η independent of both M and T . We take η as

$$\eta = \eta_0 \left(\frac{\rho \delta}{u - u_p} \right)^{1/2} \tag{15}$$

where η_0 is empirically determined. Now, $\delta \sim l/Re^{1/2}$, where l is the linear dimension of the body and Re is the Reynolds number of the fluid flow [Landau and Lifshitz, 1959]. Using $l = d_p$, Re in this case is

$$Re = \frac{\rho d_p (u - u_p)}{\eta} \tag{16}$$

Combining (15) and (16) and solving for δ , we get

$$\delta = \delta_0 \left[\frac{d_p^2 \eta_0^2}{\rho (u - u_p)^3} \right]^{1/3} \tag{17}$$

where δ_0 is an empirical scaling factor.

Unlike P , τ_s acts parallel to the surface, so the stress acting directly to decelerate the particle goes as $\tau_s \sin \theta$. Additional energy is dissipated, moving this viscous fluid laterally, so that the actual total force is simply $\tau_s A$, where A is the frontal surface area of the particle. We must account for the spherical geometry of the system in our model by multiplying by $(1 + \delta/r)^2$, where r is the radius of curvature of the surface. Thus the viscous force acting to decelerate the particle is

$$F = \tau_s (1 + \delta/r)^2 A \tag{18}$$

The total deceleration then is

$$\frac{du}{dt} = -\frac{1}{m} \int [P_H \cos^2 \theta + P_D \cos \theta + \tau_s (1 + \delta/r)^2] ds \tag{19}$$

where m is the mass of the dust particle.

At velocities $u < C_f$, the foregoing treatment is invalid because there is no shock wave and the properties of the material surrounding the particle are very different from those of the shocked foam. Under these circumstances, the particle is decelerated by overcoming the crushing strength, S_T , of the foam. Although the simplest approach would be to take S_T as constant, the data presented by *Tsou et al.* [1988] indicate that polymer foams typically obey $S_T \propto u$. Expecting S_T to be proportional to the foam density, we model S_T as

$$S_T = S_{Tr}(\rho_0/\rho_r)u \quad (20)$$

where the reference value S_{Tr} for a reference density ρ_r is determined from data. This strength is expected to operate over some finite radius of deformation r_d , which should be close to the cell size of the foam, so that the particle has an effective cross-sectional area, $A_{\text{eff},s}$, which is given by

$$A_{\text{eff},s} = \pi(d_p + 2r_d)^2/4 \quad (21)$$

One important note is in order. When the dust particle itself is small compared to r_d , then r_d should decrease rapidly with decreasing particle diameter. This is very important for the extrapolation of laboratory data to the proper size regimes for interplanetary dust particles. In the present model, we assume the limiting case of $r_d = 0$ when $d_p < r_d$. The deceleration resulting from S_T is

$$\frac{du}{dt} = -\frac{S_T u A_{\text{eff},s}}{m} \quad (22)$$

At very low velocities, of the order of 1–10 m s⁻¹, the discrete nature of the foam becomes important, with single cell walls acting as barriers with finite strength even at $u = 0$.

Ablation

At high velocities, the dust particle may lose mass by thermal ablation as it passes through the foam. This is limited by the rate of supply of the effective heat of ablation, H_{eff} , to the particle, so that

$$\frac{dm}{dt} = -\frac{QA_{\text{ab}}}{H_{\text{eff}}} \quad (23)$$

where Q is the heat flux at the particle surface and A_{ab} is the surface area being ablated. The heat that drives the ablation comes from two sources. First is the energy deposited in the foam by passage of the shock wave (e.g., (3)). The second source of heat is the viscous dissipation of kinetic energy in the boundary layer. The heat from this second source is generated and deposited directly at the surface and is given by

$$Q_V = \tau \dot{\epsilon} \delta / 2 \quad (24)$$

but the heat from the ambient shocked foam is not, so that we must consider the transport phenomena involved.

The diffusive heat flux across a boundary layer of thickness δ is [*Carslaw and Jaeger*, 1959]

$$Q_D = \frac{K}{\delta} (1 + \delta/r)(T_f - T_a) \quad (25)$$

where K is the thermal conductivity, r is the radius of curvature of the surface, and T_f and T_a are the temperature of the shocked foam and the ablating surface, respectively. The Debye model for the thermal conductivity of a dielectric is [*Kittel*, 1956]

$$K = CUA/3 \quad (26)$$

where C is the heat capacity per unit volume, U is the bulk sound velocity, and Λ is the phonon mean free path. Λ is found to vary as $1/T$ at high temperatures [*Kittel*, 1956]. Also, $C = C_V \rho$. Since C_V is approximately constant at high temperatures, $C \propto \rho$. For U , we have

$$U = (K_S/\rho)^{1/2} \quad (27)$$

where K_S is the isentropic bulk modulus. At the high energy densities and low mass densities characterizing the shocked foam, we might expect $K_S \propto P$. Thus, to first order, $U \propto (P/\rho)^{1/2}$. We will use

$$K = K_0 \frac{(P\rho)^{1/2}}{T} \quad (28)$$

where K_0 is chosen to fit laboratory impact data.

Heat transfer also occurs by radiative transport, although this phenomenon is important only at the highest velocities we will be considering. The radiative flux at the particle surface is

$$Q_R = \sigma \epsilon [T_f^4(1 + \tau_r/r)^2 - T_a^4] \quad (29)$$

where τ_r is the photon mean free path, ϵ is the emissivity (assumed to be frequency independent), and σ is the Stefan-Boltzmann constant.

Calculation of T_f

Equations (25) and (29) require the calculation of T_f . Normally, this is fairly simple, as when considering meteor phenomena. Because of the nature of the material making up the foam, however, we expect that chemical reactions, namely, decomposition, could have a significant effect on the value of T_f .

Since the high pressure properties of the decomposition products of polystyrene are not well known, we will assume that the volume difference between polystyrene and its decomposition products at high pressures is negligible. We will also assume that the energy difference $E_H - E_0$ in (3) is all thermal, consisting of heat required for increasing the temperature and the energy taken up by endothermic chemical reactions.

We begin by calculating the equilibrium state of the system by minimizing the Gibbs free energy G :

$$G = E + PV - TS \quad (30)$$

where S is the molar entropy. For each species, we calculate the molar internal energy at the conditions of the shocked foam by

$$E_H \approx E_0 + C_V(T_f - T_0) \quad (31)$$

where the subscript zero refers to ambient conditions (i.e., 1 bar, 298 K). The value of S at T_f is

$$S_f = S_0 + C_V \ln(T_f/T_0) \quad (32)$$

Table 2. Thermochemical Properties of Polystyrene and Decomposition Products at 1 Bar and 298 K

Compound	μ , kg mol ⁻¹	ΔG_{f0} , J mol ⁻¹	S_0 , J mol ⁻¹ K ⁻¹	C_{P0} , J mol ⁻¹ K ⁻¹	References
Polystyrene	0.104153	170,146	169.4	178.7	1,2
Styrene	0.104153	202,380	237.6	182.6	1
Benzene	0.078115	124,349	173.3	135.6	1,3
1, 3-Hexadiene-5-yne	0.078115	404,940	328.4	156.1	1,2,5
1-Butene-3-yne	0.052077	313,373	212.4	113.4	1,2,5
Acetylene	0.026038	216,597	133.9	56.6	1,2,4,6
C ₂	0.024022	789,111	132.4	55.6	2,4,6
H ₂	0.002016	7,397	63.7	41.3	2,4,6
C	0.012011	674,940	40.0	24.9	5,6,7
H	0.001008	199,580	40.0	24.9	5,6,7
C ⁺	0.012011	1,762,480	36.6	49.8	5,6,7
H ⁺	0.001008	1,513,290	34.2	49.8	5,6,7

References: 1, *Dean* [1985]; 2, *van Krevelen* [1972]; 3, *Weast* [1980]; 4, $C_{P0} = C_{P0, \text{gas}} + 1.5R$; 5, systematics established from similar compounds; 6, *Chase et al.* [1985]; and 7, $C_{P0} = 3R$ (+3R per free electron).

We approximate the constant volume heat capacity C_V , which is nearly independent of T above the Debye temperature, by the ambient value of the constant pressure heat capacity C_{P0} . Equations (31) and (32) may be used with the ambient values of S_0 , C_{P0} , and the Gibbs free energy of formation, ΔG_{f0} (Table 2) to estimate the equilibrium composition under a given set of conditions.

Under the assumptions we have made, T_f is given by

$$T_f = T_0 + \frac{E_H - \Delta E}{C_{P0, \text{polymer}}} = \frac{u_p^2/2 - \Delta E}{C_{P0, \text{polymer}}} \quad (33)$$

where

$$\Delta E = \left[\sum \frac{m_i(\Delta G_{fH,i} + T_H S_{H,i})}{\mu_i} \right]_{\text{products}} - \left[\frac{\Delta G_{fH} + T_H S_H}{\mu} \right]_{\text{polymer}} \quad (34)$$

is the portion of the shock energy that is taken up in decomposition of the polymer, m_i is the mass fraction of species i , and μ is the molecular weight.

If the system reaches equilibrium, ΔE would be maximized. At moderate values of T_f , however, kinetic timescales are long enough that a given parcel of shocked foam will not attain equilibrium while in contact with the dust particle. Let us assume that the weakest bond in the polymer will control the reaction rate. For polystyrene, this is the polymer bond, with an energy $E_b = 0.326$ MJ per mole of styrene monomer [*van Krevelen*, 1972]. Taking this as the activation energy which must be provided in order to initiate decomposition, we use an Arrhenius-type relation to estimate the fraction of the bonds which actually will have sufficient energy, this being $e^{-E_b/RT}$. Let us also assume that the timescale for bond breakage is approximately the vibration period. Taking the vibration frequency as

$$\nu = \frac{E_b}{hN_A} \quad (35)$$

where h is Planck's constant and N_A is Avogadro's number, and combining it with the fraction of bonds capable of breaking, we get a unimolecular rate constant for decomposition:

$$k = \frac{E_b}{hN_A} e^{-E_b/RT} \quad (36)$$

The timescale for the foam to be in contact with the particle is

$$\tau = \frac{d_p}{u - u_p} \quad (37)$$

so that the fraction χ of the equilibrium value of ΔE actually expended in driving chemical reactions is

$$\chi = e^{-1/\tau k} = \exp \left[\frac{(u_p - u)hN_A}{d_p E_b} e^{E_b/RT} \right] \quad (38)$$

Thus

$$T_H = T_0 + \frac{u_p^2/2 - \chi \Delta E_{\text{eq}}}{C_{P0}} \quad (39)$$

where ΔE_{eq} is the equilibrium value of ΔE .

Fragmentation

A particle may fragment by one or both of two mechanisms during impact with and passage through the foam. First, the initial shock experienced upon impact with the foam may produce stresses which exceed the dynamic crushing strength of the particle. Second, the nonhydrostatic stresses due to the differential pressure across the particle may cause the particle to undergo tensile fracture.

Although a quantitative treatment of fragmentation is beyond the scope of this study, several qualitative observations can be stated. The static compressive strengths of single crystals of many minerals fall into the range from 0.1 to 3 GPa. This is also the same range as the pressures achieved for impacts at several kilometers per second into

Table 3. Properties Used for Polystyrene in the Present Study

Property	Value	Unit
η_0	1000	$\text{kg}^{1/2} \text{m}^{1/2} \text{s}^{1/2}$
δ_0	50	$\text{s}^{-2/3}$
S_{Tr}	6558	Pa s m^{-1}
r_d	2.24×10^{-4}	m
K_0	100	$\text{m}^3 \text{s}^{-2}$
ρ_r	28.5	kg m^{-3}

the foam densities we consider here. Since dynamic strengths of materials are often much higher than static strengths, this suggests that single crystal grains may escape fragmentation during an impact. However, most interplanetary dust particles collected from the stratosphere are highly porous aggregates of numerous smaller grains. Such particles are relatively weak and will therefore be easily fragmented. Since stresses are greatest at the time of initial impact, that is the time at which fragmentation will occur.

The primary question is, What are the consequences of fragmentation? Since fragmentation is strictly a mechanical process, the identities of phases and chemical compounds are not compromised. The primary effect of fragmentation is to break a single large particle down into smaller particles, with consequent implications for ablation and deceleration that can be determined from the foregoing discussions. From a practical standpoint, other than smaller particles generally being more rapidly ablated and difficult to analyze in the laboratory, dispersing a dust particle also destroys information on the spatial relationships of phases within the particle.

Model Results

We now present results of calculations using our model in comparison with existing experimental data and to make specific predictions concerning interplanetary dust collection. We assume for our calculations that size regime 3 is appropriate. There is thus a practical limit to the application of this model to particles, which is driven by the microstructural length scales of the foam. Since we expect size regimes 1 and 2 to be less favorable for particle capture, we assume that efforts would be concentrated toward taking size regime 3 down to the smallest particles possible.

In the calculations using the foregoing model, we have made several important assumptions. First, we assume that the impacting dust particle is spherical and that its spatial

orientation is constant, so that the same side is always in contact with the shocked foam. Second, while the mass loss terms in the model are integrated over the surface of the particle, in reality the value of δ varies over the surface, reaching a minimum at $\theta = 0$, so that more mass is lost at low values of θ than at high values. Thus we assume that the rate of mass loss varies linearly from a maximum at $\theta = 0$ to zero at $\theta = \pi/2$. This results in the ablating surface always being a portion of a sphere, but with increasing radius of curvature as mass is lost, until 50% of the mass is lost, at which time $r = \infty$, i.e., the front surface is planar. We assume that, once this occurs, the front surface remains planar.

We have also included the effects of the transient shock wave that is generated upon the initial impact with the foam. The primary effect of this shock wave is to slow the particle slightly.

Comparison With Experimental Data

Several equations in the model contain empirical constants. Specifically, these are η_0 in (15), δ_0 in (17), S_{Tr} in (20), r_d in (21), and K_0 in (28). We use the experimental data from Tsou (personal communication, 1993), Peng *et al.* [1988], and Tsou *et al.* [1988] to constrain these constants. S_{Tr} and r_d can be obtained independent of the other parameters by integrating (22) to get the stopping distances measured in experiments in which the impact velocity is lower than C_f . These values are then held constant while η_0 , δ_0 , and K_0 are constrained simultaneously from the high impact velocity data with (17) and (23). Table 3 lists all the values used for polystyrene in the present study, based on the experimental data. Table 4 lists properties assumed for the impacting particles.

Most of the experimental data are for foam densities near 30 kg m^{-3} . The calculations for comparison were performed for densities of 32.1 and 28.5 kg m^{-3} . Figure 4 shows the results of the calculations for Al projectiles, along with experimental data. The data are best modeled by using $T_a \approx 1200 \text{ K}$, with the corresponding H_{eff} being the enthalpy difference for aluminum between T_a and 298 K. Aluminum melts at 933 K and vaporizes at 2791 K [Chase *et al.*, 1985]. The intermediate value of T_a is best explained by requiring the viscosity of the liquid to drop to a certain threshold value before the flow of shocked foam around the particle can strip the melted material away from the surface.

Calculation for Interplanetary Dust

For hypothetical dust particles, we consider four different materials: iron metal, troilite (FeS), olivine (Mg_2SiO_4), and organic material, which we assume has the properties of

Table 4. Properties of Materials Assumed for Impacting Particles

Material	ρ , kg m^{-3}	C_0 , m s^{-1}	s	T_a , K	H_{eff} , MJ kg^{-1}	References
Aluminum	2750	5330	1.34	1200	1.38	1, 2
Iron	7850	3995	1.58	3133	8.65	2, 3
Troilite	4602	2947	1.578	3133	8.00	2, 4, 5
Forsterite	3200	6285	0.565	3662	19.52	1, 2, 5, 6
Organics	1046	2233	1.636	550	1.00	1, 7

References: 1, Chase *et al.* [1985]; 2, Marsh [1980]; 3, Brown and McQueen [1986]; 4, Brown *et al.* [1984]; 5, Weast [1977]; 6, Hugoniot parameters for enstatite are used; and 7, van Krevelen [1972].

polystyrene. Table 4 gives the properties of these materials. It should be noted that T_a for all of these materials is the vaporization temperature, with H_{eff} being the corresponding enthalpy difference from 298 K. The reason that we use the vaporization temperature is that the absolute viscosities of the liquid phases of these materials never drop to the value for aluminum at 1200 K, so we assume that, even though the materials have melted, they cannot be stripped away by the flow of shocked foam around the particle. The value of H_{eff} for organic material is the depolymerization enthalpy of polystyrene, with an extra term for a limited amount for further decomposition. It should be considered as very uncertain. We choose not to perform calculations specifically for hydrous silicates, although such phases are common in IDPs. Hydrous phases can be expected to alter (by dehydration) at temperatures well below the ablation temperature, so a particle that is not completely ablated may still be substantially altered. If the alteration can be detected and the original phase determined, then such alteration might be acceptable for some applications. In such cases, the important question is the amount of ablation, rather than alteration. The alteration has the effect of changing H_{eff} slightly, but T_a remains the same. Thus hydrous phases can be considered to be similar to anhydrous equivalents from the standpoint of ablation.

We have considered only single solid grains, rather than aggregates of smaller grains. As we have already noted, dust particles which are aggregates of smaller grains will probably fragment into those smaller grains upon impact. Each fragment, which we can take to be a (more or less) solid single phase, will then act as a dust particle in its own right, with little "memory" of its previous life as part of a larger particle. For this reason, we are most interested in the survival of single crystal grains, rather than aggregates. The one comment we can make about the ablation of an aggregate of grains bound together by a matrix is that ablation for the aggregate as a whole is controlled by destruction of the matrix, so that the value of H_{eff} is that for the matrix, reduced by the factor of the proportion of matrix in the aggregate. T_a is simply that of the matrix material.

Figure 5 shows the effects of particle composition on the survival of particles during impacts, with organic particles being significantly ablated for impact velocities in excess of

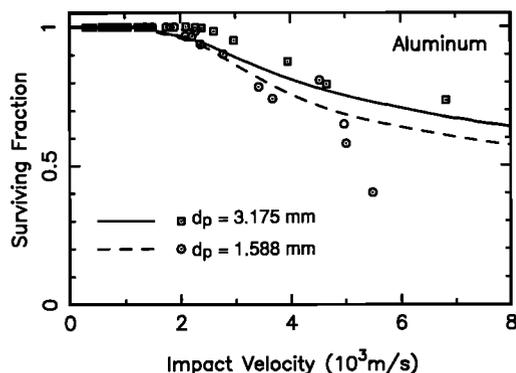


Figure 4. Calculation results for survival of aluminum spheres impacting 28.5 kg/m^3 polystyrene foam. The results are compared with the experimental data of *Tsou et al.* [1988] and *Peng et al.* [1988].

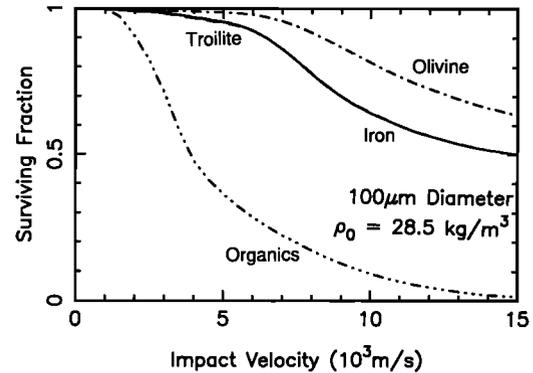


Figure 5. Results for survival of 100- μm diameter dust particles impacting 28.5 kg/m^3 polystyrene foam.

4–5 km s^{-1} . Inorganic particles, on the other hand, survive to considerably higher impact velocities.

The results in Figure 5 are for 100- μm diameter particles, which are relatively large. Figure 6 shows the effects of decreasing the particle size for troilite, olivine, and organic materials. We see that the threshold impact velocity for significant survival becomes more sharply defined for smaller particles, but remains at about the same values for a given particle composition. For organic particles with $d_p < 100 \mu\text{m}$, recovery drops to less than 10% of the initial mass at impact velocities greater than 4–5 km s^{-1} . This represents a threshold velocity for recovery. For metals, sulfides, and silicates, this threshold increases to 8–15 km s^{-1} . Since organic chemistry is an important aspect of interplanetary dust studies, this result is a very strong constraint. Encounters in excess of 5 km s^{-1} may preclude the useful collection of most organic material for study. This conclusion is for a collector made of polystyrene, although it is probably true for most materials, as the energy densities imparted by a shock wave of a given velocity to very distended materials is only weakly dependent on the composition of the material.

Figure 7 shows the result of varying the density of the foam. While foam density has an effect on the survival of an impacting particle, this effect is not significant, being less than a factor of 2 for an order of magnitude change in foam density. This is because of the similarity between different Hugoniot curves for different densities and the density scaling of the viscous dissipation in the boundary layer.

Discussion

The limit of 4–5 km s^{-1} for useful recovery of organic materials is reasonable, as is a limit of 8–15 km s^{-1} for metals, sulfides, and silicates. Recovery of these materials from organic polymer foams would in principle be straightforward, but cosmogenic organic materials may be difficult to distinguish from the final decomposition products of such foams. Inorganic collector materials might be necessary for this application. It should also be remembered that the properties of the materials which actually exist in interplanetary dust may vary widely. H_{eff} , for instance, may vary by a factor of several, depending on the materials involved.

The emphasis of the present study has been on organic foams, and polystyrene in particular, although other organic foams should not give radically different results. However,

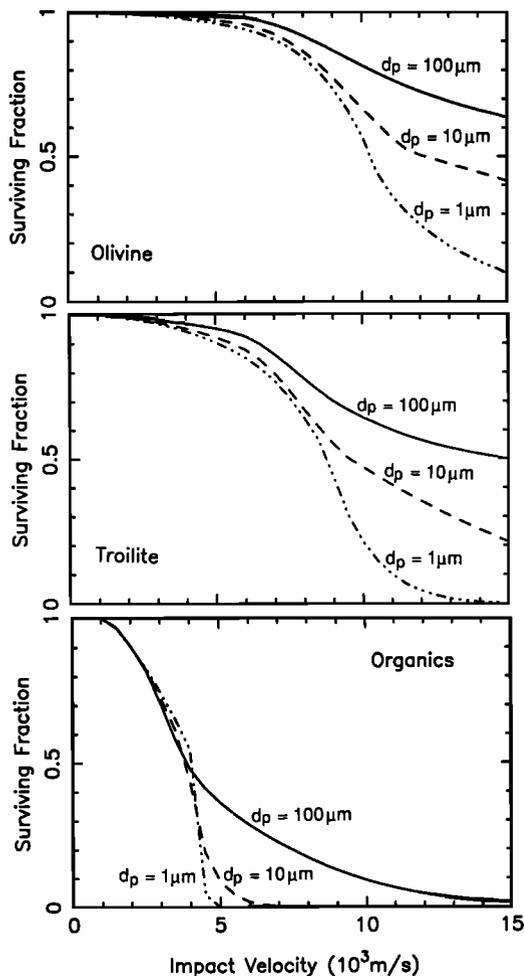


Figure 6. Results for troilite, olivine, and organic particles of different diameters impacting 28.5 kg/m^3 polystyrene.

inorganic materials, most notably SiO_2 aerogels, are also under consideration as possible collection media. Although the physical processes at work in an impact are the same regardless of the material involved, the properties of inorganic materials are different enough from those of organic materials that the relative importance of various phenomena may be very different, perhaps invalidating some of the assumptions made in the present study. In the case of SiO_2 , for example, viscosity is so great in the shocked foam that viscous dissipation may be the dominant source of drag. High viscosity could also be expected to have a significant effect on the thickness of the viscous boundary layer. In fact, this "layer" might be considerably thicker than the particle diameter. This suggestion is supported by the observations of Barrett *et al.* [1992]. They note that particles with $d_p \sim 105\text{--}120 \mu\text{m}$ (nonspherical) which have impacted SiO_2 aerogels at hypervelocity are encased in molten aerogel when they come to rest.

While we have not attempted to quantify the effects of the ratio of the dust particle diameter d_p to the foam cell diameter d_f , we do expect this ratio to have an effect on the survival of a particle during impact, especially as d_f approaches d_p . The work of Griffiths *et al.* [1991] shows that decreasing d_p/d_f from 6 to 3 significantly decreases the recovery of aluminum spheres impacting polystyrene foams.

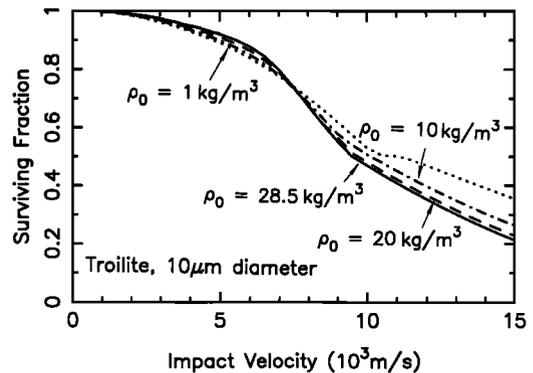


Figure 7. Results for $10\text{-}\mu\text{m}$ diameter troilite particles impacting foams of different densities.

We suggest that the present model may be a limiting case for large d_p/d_f .

A number of recommendations are suggested by the calculations and by the equations presented. These recommendations apply to the areas of collector materials development, mission planning/spacecraft design, and further experiments. In the area of materials development, both inorganic and organic foams should be developed, with very small cells (ideally, $d_f \ll 1 \mu\text{m}$). The best materials would be characterized by a large number of low-energy covalent bonds and a high specific heat to minimize the value of T_f .

To maximize the scientific return of a collection mission, a variety of collector materials, including both organic and inorganic foams, should be used. Encounter velocities should not exceed 5 km s^{-1} if recovery of organic materials is to be attempted, but this constraint relaxes to velocities of $8\text{--}15 \text{ km s}^{-1}$ if only inorganic materials are to be collected. Also, methods need to be developed to minimize and account for contamination of spacecraft instruments by decomposition products from the foams.

Experiments should be continued with polystyrene foams, with projectiles of various compositions and structures, and with very small ($d_p \leq 100 \mu\text{m}$) particles. Experiments should also be conducted with a variety of other collector materials, both to evaluate the materials and to develop techniques for the recovery of the dust particles from the foams on return to Earth.

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- T.J. Ahrens and W. W. Anderson, Lindhurst Laboratory of Experimental Geophysics, Seismological Laboratory, California Institute of Technology, Pasadena, CA 91125.

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