SAND-93-3866 C

Impact Shock and Penetration Fragmentation in Porous Media

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Keywords: Dynamic fragmentation, CTH, Hypervelocity penetration, low-density materials, porous materials, copper projectiles, Eulerian computational hydrodynamics

Abstract

In this paper, we discuss experimental, analytical, and computational techniques for studying the high velocity interaction of solid bodies with low density media. We assume that the velocity of the interaction is such that compressible effects in the solid are important. We are particularly interested in the dynamic mechanisms of deformation, erosion, and breakup which dominate the solid response at these high velocities. This is a problem of considerable current interest. Applications include the atmospheric propagation of high velocity aerosols, such as those that might be created in certain kinds of nuclear reactor accidents and explosive weapon accidents. An even more novel application is to the study of the impact of astrophysical bodies, such as meteors, asteroids, and comet fragments into planetary atmospheres. There is significant concern over the threats posed by impacts of these kinds on the earth. We will discuss the application of our methodology to understanding these impacts. In particular, we suggest that the experimental technique we present is applicable to scaled laboratory simulations of some of the phenomena that are believed to be important in atmospheric impacts.

This work performed at Sandia National Laboratories supported by the U. S. Department of Energy under contract number DE-AC04-94AL85000.

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1. Introduction

The high velocity motion of metals and other solid bodies entering low-density media is controlled by the compressible dynamics of the solid. A detailed understanding of this phenomenon has several applications. Details of the breakup are sensitive to the mechanical response of the aerosol to the atmosphere. The chemical reactions which may occur during this motion are also of importance and are highly dependent upon the interaction of the aerosol with the surrounding atmosphere. High velocity ejection of fragmented metal during explosive weapon accidents involves the motion of these fragments through the high temperature and moderately high density environment of high explosive reaction products during the early phase.

Much higher velocities are of concern in certain astrophysical impacts. For example, the entry of hypervelocity bodies such as meteors, asteroids, and comet fragments into planetary atmospheres, at speeds of 10 to 60 km/s, or more, are dominated by mechanical breakup mechanisms which are strongly linked to the deformation and compression of the body. The impact of the major fragments of comet Shoemaker - Levy 9 on Jupiter in July of 1994 is the most recent illustration of an event such as this occurring in nature (this event is the subject of several papers in this conference, including Crawford, *et al*, 1994). An interesting inverse problem, which has the same phenomena at its heart is the problem of capture of cosmological dust via impact collection techniques in which the dust is not thermophysically altered by the capture technique (Tsou, 1990).

The main emphasis of the present paper is directed at a laboratory technique for studying the compressible dynamics of an impactor in events such as those described above. The technique is based upon the use of a two-stage light gas gun to launch metal spheres into low-density hydrocarbon foam targets at velocities from 2 to 6 km/s. Through a variety of diagnostic techniques, including time-varying flash radiography and post-shot target recovery, we can collect experimental data directly relevant to body deformation and breakup dynamics as a function of impact velocity. Subsequent analysis, using analytic models and detailed numerical modeling, allows us to determine important physical variables, the progression of the deformation and breakup process as a function of impact velocity for fixed target properties, and to relate the important variables in scaling laws. These scaling laws suggest to us the applicability of this experimental technique and the related analysis to various physical applications, including astrophysical impacts and weapon accident dispersal scenarios.

In Section 2 of this paper we describe the experimental technique and display the results from a series of experiments which used copper spheres, traveling from 2.0 to over 4.0 km/s, to impact hydrocarbon foam targets with a density of 176 kg/m^3 . Section 3 discusses analytic modeling of these impacts. A simple picture of these impact results has broad applicability to the general phenomena and suggests the important variables to focus on in more detailed computational studies. In Section 4, we discuss the results of a series of calculations that were performed to test the validity of the analytic modeling, and to directly simulate the experiments that were performed. We will devote some attention to the details of our computational sensitivities in this section.

In Section 5 we will summarize our conclusions. We will also review one scaling interpretation of solid breakup for high velocity motion through low density media due to Pilch and Erdman (1985). There, we find that breakup phenomena observed in our experiments may correlate well with a suitably generalized *dynamic Weber Number*

(suitably generalized for solids penetrating underdense media) of the flow. The implications of this are far-reaching. A simple mechanism for scaling the laboratory results to equivalent Weber number flows may then be possible, with the potential that astrophysical impacts having similar Weber numbers may be simulated by such laboratory experiments. One comparison of calculations for both the highest velocity experiment and for the Shoemaker - Levy 9 comet impact in the atmosphere of Jupiter (further discussed by Crawford, *et al*, 1994) further illustrates this potential correlation.

An early version of this work, with supplementary material, appears in Grady and Trucano (1994).

2. Experiment

High velocity penetration and erosion experiments were performed by launching spherical copper projectiles to velocities ranging from about 2.0 to 4.0 km/s into a polyurethane foam target. Saboted copper spheres were accelerated to the final velocity with a Sandia two-stage light gas gun. Copper spheres 3.18 mm in diameter with a mass of 150 mg were used. After exiting the launch tube muzzle, the lexan sabot segments were separated from the copper sphere by a partial backfill of inert gas (nitrogen) within the previously evacuated flight-range tanks that terminate the gun. Free flight of the copper sphere over approximately 15 meters occurred before impact and penetration of the foam target. Velocity was measured during passage of the metal sphere through two magnetic excitation coils separated by a fixed distance. Excitation from the second coil was also used to trigger two flash x-ray systems at specific time delays during penetration of the foam target. Radiographic images provided diagnostic data regarding position, time and state of deformation, fragmentation, or erosion of the penetrating sphere. The experimental configuration is suggested in Figure 1.

Targets were machined from large sections of polyurethane foam into targets 75 mm by 75 mm in cross-section and 315 mm in length. The bulk density of the foam was 176 kg/m^3 . Impact of the copper projectile occurred at the center of the cross-section and penetration proceeded along the long axis of the foam target.

At the lowest impact velocities (approximately 2.2 and 2.5 km/s) copper projectiles penetrated the full length of the foam targets coming to rest against a plastic barrier immediately behind the foam target. Only minimal projectile deformation was noted in these tests. A slight depression observed in the post-shot projectile was probably due to impact on the plastic barrier at the back of the foam. Weight measurements of the projectiles before and after indicated less than 0.5% mass loss due to the penetration erosion process.

For the experiments over the velocity range of approximately 2.9 - 3.3 km/s shock and stagnation pressures upon entry into the foam environment led to severe deformation and flattening of the copper projectile. Radiographic records indicated subsequent stable penetration of the dish-shaped projectiles. Deceleration rates were significantly higher and penetration was arrested within the foam target at about 1/2 to 3/4 of the target length. Post-test measurement of the mass indicated an erosion loss of approximately 3 mg (2%) of the original 150 mg mass.

At velocities of about 4.3 km/s, stress levels on entry were sufficient to cause explosive shattering and multiple fragmentation of the initial spherical projectiles. Several dozen fragments came to rest within the foam environment distributed over the length of the foam target.

Images from the radiographic records of the three regimes of penetration behavior outlined above are illustrated by the sketch in Figure 2. In each case the projectile or fragments were still in motion at the time of the radiograph, however deformation or fragmentation had reached completion.

The second magnetic velocity coil used to time delay trigger the two flash x-ray units was positioned about 20 mm in front of the impact face of the foam target. Consequently, with the measured impact velocity, the time and corresponding depth of penetration at two stations could be determined with acceptable accuracy (1 mm). The final depth of penetration was determined through a post-test radiograph of the foam target.

Data for the test series are provided in Table 1. The pairs (X_1, T_1) and (X_2, T_2) , respectively, refer to the current depth of penetration and the corresponding time relative to first foam contact as determined from the first and second flash radiographs. In several cases radiographs were missed due to system triggering difficulties. When the projectile arrested within the foam target, the final depth of penetration X_f determined from post-test radiography is also provided in Table 1.

3. Analysis

Impact stress and the foam Hugoniot

A number of aspects of the present problem are quite adequately addressed and understood by treating the foam environment as a locking solid. A locking solid is assumed to have a porous or distended density ρ_{oo} and a compressed or locking density $\rho_o > \rho_{oo}$. Further, all porosity is assumed to be removed through a compressive shock wave without heating due to pore collapse. In the locked state the material is assumed to be incompressible for analytic purposes ($\rho = \rho_o$ for all pressures $p > 0$).

It is readily shown that the Rankine - Hugoniot relations then lead to expressions for the shock velocity U_s and the Hugoniot pressure p_h , in terms of the Hugoniot particle velocity, u_h

$$\begin{aligned} U_s &= \frac{u_h}{1 - \rho_{oo}/\rho_o} \\ p_h &= \frac{\rho_{oo} u_h^2}{1 - \rho_{oo}/\rho_o} \end{aligned} \quad (1)$$

The empirical relationship $U_s = C_o + Su_h$ between U_s and u_h is accurate for many materials. From (1) a locking solid yields a degenerate form of this relationship with $C_o = 0$ and $S = (1 - \rho_{oo}/\rho_o)^{-1}$. For purposes of later comparisons it is noted that equation (1)_b becomes,

$$p_h = \rho_{oo} S u_h^2. \quad (2)$$

S is typically close to 1 for density ratios $\rho_{oo}/\rho_o \ll 1$, for which the locking solid description makes the greatest sense. For the polyurethane foam used in the present experiments $\rho_{oo} = 176 \text{ kg/m}^3$, $\rho_o = 1265 \text{ kg/m}^3$, and consequently $\rho_{oo}/\rho_o = 0.14$ and $S = 1.16$.

At early times in the copper sphere - foam impact, we neglect the spherical curvature of the contact surface between the two materials and nominally apply planar shock relations. The resulting estimate of the impact pressure is then

$$p_h \approx \rho_{oo} S u_I^2, \quad (3)$$

where u_I is the impact velocity. Values of the impact pressure from (3) and from hydrodynamic calculations (discussed in Section 4) are compared in Table 2.

The shock ellipsoid and impact energy

The duration and magnitude of the shock energy coupled into the projectile by the foam can be estimated by using an analysis originally due to Ang (1990). Referring to the geometry illustrated in Figure 3, for a spherical projectile undergoing normal impact at a velocity u_I on a planar surface the radius of the projectile - foam contact surface at time t is

$$a = u_I t \sqrt{\frac{2R}{u_I t} - 1}. \quad (4)$$

Define the point at the contact interface at the radius a as the *collision point*. The velocity of the collision point is determined by differentiating equation (4),

$$\dot{a} = u_I \left(\frac{R}{u_I t} - 1 \right) / \sqrt{\frac{2R}{u_I t} - 1}. \quad (5)$$

The contact velocity is initially infinite ($t = 0$ in (5)) and decreases with time. As the angle between the tangent of the impacting sphere and the target surface at the contact point increases, the contact velocity will continue to decrease, ultimately allowing a lateral release wave to propagate inward and quench the shock coupling phase. Note that $\dot{a} = 0$ when $t = R/u_I$. Here, R is the initial radius of the projectile.

A reasonable assumption is that shock waves will couple into both materials over the lateral distance at which $\dot{a}$ reduces to the release wave velocity in the faster material. We will approximate the release velocity by the shock velocity U_s in the faster material. (Release waves are dispersive but U_s is equal to the release velocity at one-half of the Hugoniot particle velocity in a linear shock-velocity versus particle-velocity material.) Using (5), the axial thickness b_c of the stress pulse transmitted to the projectile by the foam is given by

$$b_c = \frac{1}{2} U_{s1} (t_1 + t_2) . \quad (6)$$

In (6), t_1 is the time at which $\dot{a} = U_s$:

$$U_s = u_l \left(\frac{R}{u_l t_1} - 1 \right) / \sqrt{\frac{2R}{u_l t_1} - 1} . \quad (7)$$

If the corresponding radius at this time is

$$a_c = u_l t_1 \sqrt{\frac{2R}{u_l t_1} - 1} , \quad (8)$$

then t_2 is the time given by

$$t_2 = a_c / U_s . \quad (9)$$

An estimate of the region of shock coupling into the projectile is then an ellipsoidal volume, called the *shock ellipsoid*, with major axis a_c and minor axis b_c . The coupled shock energy (kinetic and internal) is given by the approximation

$$E_s = \frac{4\pi}{3} a_c^2 b_c \frac{p_h^2}{\rho U_{s1}^2} . \quad (10)$$

In this paper we use the term *quasi-steady state* flow. By this, we have in mind the flow pattern that results when the transient stress states in the projectile have disappeared, being replaced by a "quasi-steady" state distribution that changes slowly compared to the characteristic time required for the initial shock ellipsoid to propagate through the projectile. This is the present analog of an aerodynamic steady state, but accounts for the compressible response of the projectile. Figure 4 depicts the quasi-steady state pressure distribution on axis in a schematic fashion. As the velocity of the projectile steadily falls during the course of penetration the bow shock and stagnation pressure amplitudes also steadily decrease. But these changes occur more slowly than reverberation times in the projectile. This is discussed further in below.

The energy given in (10) is approximate. Also, there is not a clear transition time between the shock and the quasi-steady hydrodynamic phases of penetration. Nevertheless, comparisons of equation (10) with shock wave simulations

(Kipp, et al. 1993) of spherical impacts on denser planar surfaces than the present foam targets have shown reasonably good agreement (within about 25%). (See below). We will discuss this approximation further in Section 4.

The portion of the shock energy coupled into the projectile which is dissipated in shock heating is negligible at the present shock amplitudes. The portion which is converted into kinetic energy associated with change in the penetration velocity on impact is also typically less than 10%. Therefore, it is fair to argue that most of the shock energy in (10) will go into plastic distortion of the projectile and radial kinetic energy of fragments if the impact is sufficiently intense. We can thus use (10) as an upper bound on the direct impact energy which is available for projectile deformation and break-up.

Calculations show, in fact, that the presently calculated shock energy coupled into the projectile is insufficient to account for the observed deformation and fragmentation in the experiments. At 4 km/s the shock energy calculated from equation (10) is only about 0.1 J. The energy growth in the projectile observed in shock wave calculations over approximately 0.5 microsecond after projectile impact is 0.16, 0.35, and 1.0 J for, respectively, 2.21, 2.9, and 4.28 km/s impact velocities. This time is roughly the time necessary for the computed stress ellipsoid to form in the projectile. For comparison the plastic work required to deform a copper sphere into a flattened disc comparable to that observed in tests F-13 through F-15 is approximately

$$W_d = \frac{4\pi}{3} Y \epsilon \approx 3.3 \text{ J}, \quad (11)$$

where a flow stress of $Y = 0.2 \text{ GPa}$ and a deformation strain of $\epsilon = 1$ was assumed for copper. Consequently, it seems to be necessary to pursue some of the issues of penetration by non-deforming impactors to address the ultimate deformation and fragmentation of the impacting projectile.

This observation is also born out by the computational simulations described later in the text. Numerical calculations indicate that the shock ellipsoid analysis is more appropriate for higher impedance targets but becomes less so for the present distended target material. A shock ellipsoid structure is also seen to form most clearly for the highest velocity impact.

Steady penetration in compressible media

Assume that sufficient time has passed after impact so that transient stress states in the projectile have decayed and conditions approaching quasi-steady penetration behavior have ensued. Because of the highly compressible nature of the porous media, penetration is supersonic over the full range of interest. The flow will be approximately as illustrated in Figure 4. In the present section a non-deforming spherical projectile will be discussed, which is certainly accurate for the lowest impact velocities in the present experiments.

Penetration in compressible material has been generally treated by various authors (e.g., Haugstad and Dullum, 1981; Zlatin and Kozhushko, 1980). Appropriate constitutive relations for shock compression in a porous locking solid were derived previously (equations (1) -(3)). From the steady nature of the supersonic flow the velocity of the shock wave

U_s is necessarily equal to the penetration velocity u . Thus, the Hugoniot particle velocity u_D and pressure immediately behind the detached shock wave in Figure 4 can be determined in terms of the density of the foam and the penetration velocity u (which is less than the initial impact velocity u_I)

$$\begin{aligned} u_D &= u/S \\ p_D &= \left(\rho_{oo} u^2 \right) / S \end{aligned} \quad (12)$$

Note that the Hugoniot density behind the shock wave is that of the locked solid, $\rho_D = \rho_o$ and that $S = (1 - \rho_{oo}/\rho_o)^{-1}$. Equation (12) is a scaled Bernoulli pressure where the scaling factor is $1/S$.

Bernoulli's equation for incompressible flow can then be applied along the axis of symmetry of the flow to establish the pressure p_s at the stagnation point,

$$p_s = p_D + \frac{1}{2} \rho_o (u - u_D)^2. \quad (13)$$

Combining equations (12) and (13) we arrive at the following formula,

$$p_s = \rho_{oo} \frac{1+S}{2S} u^2, \quad (14)$$

yet another scaled Bernoulli pressure. Comparison of the quasi-steady state stagnation pressure with the impact shock pressure (equation (4)) shows that for highly compressible media the stagnation pressure is comparable with the impact shock pressure. For the present material properties ($S=1.16$) we estimate that the initial stagnation pressure p_s is about 80% of the impact shock pressure.

Consequently, during penetration into underdense media the transition from shock to hydrodynamic penetration is weak with only about a 20% drop in stopping pressure. Stress gradients in the penetrating particle can be sufficient to cause continued plastic deformation and fragmentation during the deeper hydrodynamic phase of penetration. Further note that in the quasi-steady state approximation, the ratio of the stagnation pressure to the bow shock pressure at any time is a *constant which is independent of impact velocity*:

$$p_s/p_D = (1+S)/2 = 1.08. \quad (15)$$

The bow stagnation pressure is always approximately 8% higher than the bow shock amplitude in this treatment.

Penetration characteristics

The final depths of penetration as a function of the impact velocity are shown in Figure 5 for the series of experiments performed. Several regimes of behavior were encountered over the range of impact velocities investigated. For impact velocities below about 2.7 km/s the penetrating projectile remained undeformed and fully penetrated the 0.3 m long

foam block. The depths in excess of 0.5 m reported in Figure 5 were estimated through x-ray deceleration data. Undeformed projectile penetration occurred in Test #F-12 at an impact velocity of 2.21 km/s (see Table 1). Separate flash radiographs (Figure 1) provided transient penetration-depth-versus-time data at two positions shown in Figure 6. The general penetration characteristics are compatible with steady hydrodynamic penetration theory. Between about 2.7-4.0 km/s substantial plastic distortion into a flattened disc-shaped body without fragmentation led to a more rapid stable deceleration and significantly reduced final penetration depth. For penetration velocities above about 4 km/s shock and hydrodynamic penetration forces on the body were sufficient to cause shattering of the projectile with subsequent multiple trajectories. Fragments are scattered generally along the path of penetration. The depth identified in Figure 5 is that of the deepest observed fragment. Within a given regime of impact velocities, the depth of penetration increases with increasing impact velocity. Because of transitions in penetration behavior the general trend is decreasing penetration depth with increasing impact velocity.

Hydrodynamic deceleration of a spherical projectile is approximated by the following equation of motion,

$$m \frac{du}{dt} = -\frac{1}{2} \rho'_{oo} u^2 A_{eff}, \quad (16)$$

where m is the projectile mass and $\rho'_{oo} = \rho_{oo} (1 + S)/S$ is the reduced density (in (14)). In equation (16), $A_{eff} = cA_g$ is the effective area over which the scaled Bernoulli pressure $\rho'_{oo} u^2/2$ applies, A_g is the geometric projected area, and c is a dimensionless coefficient of order unity. Introducing the projectile diameter d and density ρ_p , equation (16) becomes,

$$\frac{du}{dt} = -\frac{3\rho'_{oo} c}{4\rho_p} \frac{u^2}{d} = -\alpha u^2. \quad (17)$$

Note that deceleration should be approximately constant over a range of velocity since α is small. Solving (17), we determine the penetration velocity

$$u = \frac{u_I}{(1 + \alpha u_I t)}, \quad (18)$$

and depth of penetration,

$$x = \frac{1}{\alpha} \ln(1 + \alpha u_I t). \quad (19)$$

Solutions assuming $c = 0.5$ and $c = 1.0$ are compared with the experimental penetration data in Figure 6. The solution with $c = 0.5$ agrees well in form and magnitude with the penetration data.

Note that (19) predicts logarithmic divergence of the penetration depth as a function of time. The criterion we suggest for predicting a finite depth is that penetration will cease when the scaled Bernoulli pressure $\rho'_{oo} u^2/2$ decreases to

the yield strength of the foam which, for the present material, is about 10 MPa. With equations (18) and (19), a final depth of penetration of 0.53 m is predicted and provides the point for the test displayed in Figure 5.

3. Computational Simulations of Penetration

The CTH Eulerian hydrocode (McGlaun, *et al*, 1990) has been used to simulate the experiments described above. One purpose of the numerical simulations is to provide information which complements the analytical modeling. By doing this, we hope to achieve a more complete understanding of the phenomena taking place in the experiments. We can also enhance our understanding of the limitations of the analytic model by investigating its underlying assumptions in the context of the numerical simulations.

CTH is a multidimensional Eulerian strong shock hydrodynamics code which has been used extensively to simulate hypervelocity impact phenomenology (Trucano and McGlaun, 1990) and lower velocity eroding penetrator impacts involving, for example, penetration of monolithic metal targets by metal long-rod penetrators (Hertel, 1990). In the current experiments, the velocity range passes from a low velocity regime, where the penetrator remains undeformed, to a high velocity range in which the penetrator deforms and breaks up. It has traditionally been difficult to simulate the penetration of a deforming, non-eroding impactor with multimaterial Eulerian hydrocodes. Silling (1994) has developed special algorithms to treat this situation more accurately in CTH. (See Silling, 1992 for an application of these algorithms.) The primary problem that occurs is numerical diffusion of the penetrator-target interface due to the single velocity field which is enforced in mixed material cells in CTH. This causes impactor material shedding simply because the velocity of a cell consisting of both projectile and foam will be less than the true velocity of the projectile. We have not applied Silling's algorithms in the calculations reported here. We are mainly interested in the penetration event prior to the time when the numerical erosion of the penetrator dominates the problem.

The copper impactor was modeled using an ANEOS equation of state (Thompson, 1989) that includes melting and vaporization, coupled with an elastic/perfectly plastic constitutive treatment. The polyurethane foam was modeled using the snowplow model for porous materials implemented in CTH, in addition to an ANEOS equation of state description for the fully dense material (polyurethane). This model is similar to the locking solid model discussed above, but the fully dense material is treated as compressible. The most important material parameters for these materials are listed in Table 3 below. There, c_0 is the bulk sound speed, s is the slope of the linear $u_s - u_p$ relationship for the material, Γ_0 is the reference Grüneisen parameter used in the equation of state, ν is the Poisson ratio, Y_0 is the ambient yield strength, and P_{frac} is the assumed spall strength of the material. Note that the reference density for the foam listed in Table 3 is that of the solid density material. The porous density used in the calculations was the same as in the experiments, 0.176 g/cc. In the calculations the foam was treated as a fluid, without strength. This is reasonable, given the very large density difference between the copper projectile and the foam, and the very small yield strength of the foam. Absence of foam strength will introduce an error in the computed deceleration of the projectile near its termination point in the foam, but this error is small compared to inaccuracies associated with numerical erosion of the projectile and the computational equation of state for the foam. We also applied an arbitrary high fracture strength to the foam because we are uninterested in foam fracture in the present discussion. Normal

impact of the copper sphere upon the target was assumed in all cases. This allows us to perform 2-D axisymmetric simulations of the experiments.

We have examined the initial impact dynamics of the projectiles in the experiments in some detail in order to confirm the shock ellipsoid concept discussed in Section 3. These calculations use a computational resolution of 160 zones per projectile diameter. Figure 7 shows the state of the projectile-target pressure field at a problem time of 0.7 μ sec for simulations of experiments F-12, F-13, and F-16 (2.21, 2.9, and 4.28 km/s impact velocities respectively). As can clearly be seen in the figure, the pressure field, depicted by contours of constant pressure, deviates considerably from the simple "shock ellipsoid" picture presented in Section 3. This is primarily due to the fact that the multidimensional character of rarefaction wave propagation in the target is more complex than in the analysis of Section 3. For the velocities of 2.21 and 2.9 km/s, an ellipsoidal pressure region does form, but it does not detach itself from the general pressure field at the front of the projectile. In the case of the highest impact velocity, 4.28 km/s, a detached shock ellipsoid forms. In all cases, the peak pressure in these ellipsoidal islands strongly attenuates from the initial impact pressures as the ellipsoid propagates across the projectile. We infer that the shock ellipsoid model is qualitatively correct for the present experiments, and becomes quantitatively more accurate as the impact pressures increase.

Also, note that by the 0.7 μ sec time of Figure 7, the ellipsoids have propagated to the rear of the projectile and are reflecting from the aft boundary as a rarefaction wave. At this point, a tensile region evolves at the rear of the projectile, as the lateral and rear rarefactions interact. The peak tensile pressure found in the body of the projectile is a function of impact velocity. Peak tensile pressures computed in the copper for the 2.21 and 2.9 km/s impact velocities are approximately 5 kbars. The projectile is thus predicted not to spall in these cases, and this correlates with the experimental observations. At 4.28 km/s, the computed peak tensile pressure is near 20 kbars, which is sufficient to spall some material from the rear of the projectile due to the initial impact. Radiographs are not available close enough to the impact time to see whether this prediction is correct. The projectile does not fracture in our calculations because we set the numerical fracture strength to 25 kbars. This is unrealistically high, but we did not want to influence the overall amplitude of tensile states in the projectile by allowing fracture.

In Figure 8 we show the axial, quasi-steady state distributions of the pressure, density, and temperature at 1.0 μ sec after impact for all three experimental velocities. Again, we emphasize that because of projectile deceleration and compressible response, this state changes in time, but slowly compared to reverberation times in the projectile. The reader should observe that the detached shock region ahead of the projectile is resolved with over 10 computational zones. Artificial viscosity is used in CTH, but this produces shock smearing only over 4 zones. Thus, the structure of the pressure in this region is not simply an artifact of the artificial viscosity but is a reasonable representation of the real pressure distribution. Note that the stagnation pressure is higher than the bow shock pressure, as predicted by the analytic modeling. The calculations predict that the ratio is not constant however, although the variation in the increase of stagnation to bow shock pressure is relatively small, from 5% to 17%, depending upon the impact velocity. The largest relative difference between the computational and analytic predictions of p_D/p_s is approximately 3%, an excellent correlation between a simple analytic model and a complex numerical simulation. Accurate prediction of the pressure fields preceding the projectile during the early phases of the penetration event is one of the strongest aspects of the analytic model. These quantities (and others) have been summarized in Table 4.

A tensile region is observable in the projectile for each velocity in Figure 8. This tensile region is not at its peak amplitude at 1.0 μ sec. Reverberations within the projectile create considerable evolution of this tensile region as time progresses.

As the impact velocity varies from 2.21 km/s to 4.28 km/s, the impact pressure experienced by the projectile at the central contact point increases from approximately 10 kbars to nearly 38 kbars. Within one microsecond this pressure falls to the stagnation values p_s reported in Table 4. The values of p_s are sufficient to deform copper for the 2.9 km/s and 4.28 km/s velocities, while the value listed for 2.21 km/s does not persist in the transient penetration event for a sufficient time to produce projectile deformation. This is in agreement with the observed experimental projectile deformations observed as a function of impact velocity.

The bow shock pressure in our calculations increases from 7 to approximately 23 kbars with increasing impact velocity. The bow shock temperature at the highest impact velocity is approximately 2500 K. This temperature falls sharply to room temperature within the body of the projectile, as seen in Figure 8. The time over which we are calculating is insufficient for significant thermal conduction to take place. Such a strong thermal gradient could potentially induce fracture near the tip of the projectile under the right circumstances (a thermal spall phenomenon), but on the millisecond time scales of thermal diffusion.

The early time computational results discussed above do not have numerical artifacts related to the artificial mixing of foam and projectile along the boundary between the two materials. To study longer time evolution of the projectile deformation we have also performed coarser zoned calculations, in which the resolution was decreased by over a factor of three. For $v=2.21$ km/s the projectile remains undeformed during the first microsecond of the impact, in agreement with the experimental radiographs (see Figure 2). The computed shape of the projectile at 16.0 μ sec is shown in Figure 9. There, we see that CTH predicts a small frontal flattening of the projectile which is approximately steady state through 16.0 μ sec. The experimental radiographs show that permanent deformation of the copper sphere should not occur at this impact velocity. It is possible that the observed flattening of the projectile in this calculation is compatible with non-permanent deformation at 16.0 μ sec, but it is also possible that numerical erosion has also scoured some material from the front of the projectile.

The resolution difference between the early time and the longer time calculations does not strongly influence the dynamical variables at the times of interest in this paper. We have compared dynamic variables for these two calculations in Figure 10 at 1.0 μ sec. The largest difference appears in the pressure, where the tensile region of the projectile is significantly different between the two different resolutions. This is not unexpected because tensile state predictions are known to be sensitive to zone size in CTH calculations.

For 4.28 km/s a longer duration, coarser zoned calculation, also shown in Figure 9, shows that the projectile is very deformed. The severe deformations indicate breakup of this projectile, but a particular depth of breakup can not be determined from the pictured calculation. (Remember that we have predicted the possibility of some spall during the initial contact phase with the target at this impact velocity.) A important question is what percentage of the pictured projectile distortion is due to numerical diffusion? At later times we may not be able to trust the visual depiction of the projectile state because of the numerical erosion problem.

Equation (19) predicts the penetration depth, though it ignores the complexity of the initial impact interactions. The CTH calculations model the complexity of the initial impact quite well. We do not run the calculations until the projectile stops (impractical in a direct simulation). Can we approximate the penetration depth of the projectile into the foam in each case by extrapolating the CTH predicted projectile deceleration data? The simplest approach is to approximate the CTH computed projectile velocity curves by straight lines, and then extrapolate to zero velocity for these linear decelerations. In Figure 11 we have plotted the computed axial speeds of the longer time, coarse zoned calculations for a distribution of Lagrangian tracer particles lying throughout the projectile, overlaid with lines. Nonlinearity in the computed deceleration curves is most apparent for the highest velocity impact of 4.28 km/s. Because a linear fit is such a crude approximation, we do not even bother to fit these lines using least squares, but only as an overlay.

The results from this linear deceleration approximation are given in Table 5. There, a is the approximate linear deceleration in km/s^2 from the linear overlays of the velocity vs time curves in Figure 11, d_{approx} is the predicted penetration depth resulting from the linear deceleration, and d_{exp} is the corresponding experimental depth of penetration taken from Figure 5. The approximate depths of penetration in Table 5 are much smaller than the experimental depths. The simple linear extrapolation is inadequate for reasonably predicting penetration depths, at least on the time scale given in Figure 11.

Equation (17) supports the claim that linear deceleration is a good approximation for the penetration process (at least for the lower velocity impacts) in the quasi-steady state regime. In Figure 11, we have also plotted the velocity prediction of (18) for the 4.28 km/s case, choosing the constant $c = 1$. This equation does not correctly predict the initial penetration depth properly. The CTH computations show a greater deceleration than is predicted by (18), even at the time of 16 microseconds. Thus, we have apparently not yet calculated into the "asymptotic" regime which is governed by (18). The 2.21 and 2.9 km/s impact cases also show greater deceleration up to 16 microseconds than predicted by (18), but one component of this deceleration may also be the numerical diffusion of the projectile, as well as the initial impact nonlinearities.

This illustration of the failure of a simple extrapolation of penetration depth from the initial stages of the hydrocode calculation has implications for more general applications of similar simulations, such as aerothermal breakup of astrophysical bodies. There, nonlinearities and catastrophic breakup dominate, so that an asymptotic formula such as (18) has less applicability. It seems likely that computational techniques that allow a complete calculation of the entire penetration process will be required to better understand these events.

The projectile deceleration observed in Figure 11 is roughly independent of the numerical resolution. This statement is true only as long as the zoning is not so coarse as to introduce significant numerical erosion of the projectile in the early times of the deceleration.

4. Discussion

Similarity to Shoemaker-Levy 9 Impact Simulations

Understanding the detailed dynamics of the impacts of meteors, asteroids, and comet fragments in planetary atmospheres is of great current interest. The recent impact of periodic comet Shoemaker-Levy 9 in the atmosphere of Jupiter has provided a significant impetus to work in this field. Several papers in this conference are devoted to computational studies of this event. The paper of Crawford, *et al*, 1994 computationally studies the impact of a prototype S-L9 comet fragment using techniques related to the numerical methodology in this paper. Interest in asteroid and comet impacts has heightened over the years as we have become more aware of the influence of impacts upon the Earth's geological record.

Astrophysical bodies striking a planetary atmosphere can demise by directly striking the solid surface of the planet, by ablating their entire mass during atmospheric transit, or by catastrophic disruption while in the atmosphere. The latter type of event, in particular, is not completely understood. One possible mechanism for such breakup is unstable hydrodynamic breakup, similar to the fashion in which high velocity aerosol droplets may fragment while moving through a fluid. Another possible mechanism is mechanical breakup due to solid body failure and fragmentation, either under severe deformation loads or due to wave propagation induced spall, or both. It is likely that the specific mechanism is a function of the composition of the asteroid, the impact velocity, and the particular atmospheric density gradient. This latter point also implies that the angle of attack of the asteroid may partially determine its breakup behavior. These breakup mechanisms are, of course, also the subject of interest in this paper.

There are both similarities and differences in the details of atmospheric impacts as opposed to the laboratory experiments that we have studied here. However, in both cases, long time-scale deformation energy due to penetration resistance, whether by a tenuous atmospheric fluid or a low-density foam, are important in providing energy necessary for catastrophic disruption. To highlight this issue, we have shown two impact calculations in Figure 12. The first is a simulation of our 4.28 km/s experiment at 5.0 μ sec. The second is the 60 km/s impact of a 3 km diameter ice fragment in the Jovian atmosphere at 3.0 s into the calculation. Both of these calculations were performed using a reverse ballistics approach, in which the target strikes a stationary projectile. We have observed that this technique reduces numerical diffusion of the projectile during the calculations. (The S-L9 impact also uses a moving grid option for even greater accuracy. See Crawford, *et al*, 1994 for details.)

The similarity of the deformation of the two bodies is striking and important. Pilch and Erdman (1985) have exhaustively classified droplet breakup data in terms of the Weber number of the flows. The deformation seen in Figure 12 is immediately recognized as characteristic of the *sheet stripping* regime of droplet breakup, which is defined by Weber numbers in the range of 300. The Weber number, a dimensionless ratio of opposing force over cohesive force of the droplet, can be generalized to the case of a solid fragment in a fluid (as in the SL-9 calculation) by defining it to be P_S/Y_0 , where P_S is the opposing pressure on the body and Y_0 is the yield strength of the body. For this definition, the Weber number of the comet fragment in Figure 12b is approximately 300, an interesting fact.

This generalized definition doesn't work for the 4.28 km/s experimental case where a solid moves through a solid. There, if we define the impact Hugoniot pressure to be the opposing pressure we arrive at a value of approximately 10. The lower velocity experiments have even smaller generalized Weber numbers. In Pilch and Erdman's classification, this Weber number is too small for breakup to occur. While this is true for the lowest velocity cases (which is also an interesting correlation), it is not true for the 4.28 km/s case. Impact of the solid introduces significant shock coupling at the moment of impact for high enough velocities. This does not happen in the case of the comet impact, even though the impact velocity is 60 km/s. This is because of the gentle atmospheric density gradient.

The deformations of laboratory sphere and astrophysical comet fragment are so tantalizingly close in Figure 12 that we speculate that an additional generalization of the Weber number for the case of impact into a low-density solid would yield values closer to Pilch and Erdman's scaling behavior. If this is true, then a rather direct path to performing laboratory simulations of events such as asteroid impacts seems possible. We also stress that we can adapt the experimental conditions to provide much more gentle impact conditions through controlled density gradients in the foam target. Foams of density near 0.001 g/cc can be manufactured (with some difficulty) so that the potential scope of such experiments is very large. These experiments would then also offer the possibility of computational benchmarking related to asteroid and similar impacts that could be very important for more complete understanding of these enormously energetic impacts.

Conclusions

An experimental method has been initiated which successfully simulates the entry shock and hydrodynamic penetration forces presented to a high velocity particle (2-4 km/s) by an underdense media. Experimental data characterizing the penetration process, and modes of particle deformation and breakup have been presented. Copper projectiles exhibited minimal hydroerosion (less than 2%) within the velocity range. A detailed analysis of erosion products, which would come to rest in the foam along the penetration channel, was not performed.

Transition modes in particle deformation and breakup were clearly identified as shock and hydrodynamic forces on the particle strengthened with penetration velocity. Analytic models of aspects of the penetration and fragmentation process are useful in revealing the physical mechanisms active in the event.

Computational simulations of the penetration and breakup event have been performed with the CTH wavecode. Details of the initial phases of the penetration events which are inaccessible to direct experimental observation were studied numerically. The computational results generally supported the analytic model which was developed in Section 3. In particular, the calculations were in agreement with results concerning details of the bow shock and the stagnation pressure felt by the projectile. The analytic treatment of the deceleration of the projectile seems to be inaccurate, predicting too little deceleration at early times and (probably) too great deceleration at late times. This accounts for the relative success of the model in predicting the overall penetration depth for the highest velocity penetration event in Figure 6. The calculations suggest that the shock ellipsoid picture in Section 3 requires some modification at the lower velocities of the experimental data. Principal thermodynamic and deformation features of penetration were successfully predicted, including the qualitative projectile deformation trends observed in the

experiments as the impact velocity increased. A simple linear deceleration fit and extrapolation of the simulated decelerations was inadequate to predict experimental penetration depths.

The time-dependent deceleration experienced by the projectile and important details of projectile fragmentation at the highest impact velocities have not been adequately treated in the current work, since experimental data near the time of impact were not gathered. We have also not discussed issues related to inaccurate material response of the copper projectiles and uncertainties in the foam equation of state. These topics will be discussed in future work.

Acknowledgments

We wish to thank Randy Hickman for performing the impact experiments, and David Crawford and Mark Boslough for reviewing this manuscript. An anonymous reviewer provided many helpful comments for a early version of our manuscript.

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Table 1: Experimental Results.

Test Number	Impact velocity	X_1	T_1	X_2	T_2	X_f
	km/s	mm	μ s	mm	μ s	mm
F-9	2.48	---	---	---	---	a
F-12	2.21	53.5	27.0	215.1	154.1	a
F-13	2.90	45.3	18.5	138.3	105.4	215
F-14	3.13	---	---	154.3	107.6	261
F-15	3.27	---	---	141.9	97.3	239
F-16	4.28	---	---	113.1 ^c	100.0	198.0 ^c

a. Complete penetration

b. --- implies no x-ray obtained.

c. Projectile fragmented — dynamic depth is approximate center-of-mass
— post-test depth is deepest fragment.

Table 2: Comparison of the Hugoniot impact pressure estimated from (3) and from shock wave calculations. The approximation (3) improves with higher impact velocities. There is no direct measurement of p_h in the present experiments. The superscript I indicates that these values are for the impact Hugoniot pressure.

Impact Velocity (km/s)	$p_{h, (4.3)}^I$ (kbars)	$p_{h, comp}^I$ (kbars)	$\left \frac{p_{h, (4.3)}^I - p_{h, comp}^I}{p_{h, comp}^I} \right $
2.29	9.97	10.8	0.077
2.9	17.17	16.3	0.053
4.23	37.40	37.1	0.008

Table 3: Summary of ANEOS parameters for the CTH calculations.

Parameter	Copper	Polyurethane Foam ^a
ρ (kg/m ³)	8940	1265
c_0 (km/s)	3.94	2.0
s	1.489	2.101
Γ_0	1.99	0.91
ν	0.355	Fluid
Y_0 (kbars)	3.5	Fluid
P_{frac} (kbars)	25	Large (~1000)

^aThese are the solid reference properties of the foam. The initial porous density is 176 kg/m³.

Table 4: Computed quasi-steady state conditions as a function of impact velocity. The analytic value of P_D/P_s is given by (15).

u_i (km/s)	P_D (kbars)	P_s (kbars)	P_D/P_s	P_D/P_s (anal.)	P_{min} (kbars)	T_D (K)
2.21	7.4	7.8	0.95	0.926	~ 5	1000
2.9	14	17	0.92	0.926	~ 8	1500
4.28	23	25	0.92	0.926	~ 20	2500

Table 5: Upper bounds for computed depths of penetration vs experimental data.

u_i (km/s)	a (km/s ²)	t_{stop} (μsec)	d_{approx} (mm)	d_{exp} (mm)
2.21	2.56×10^4	~ 86	~ 95	~ 500
2.9	5.62×10^4	~ 51	~ 74	~ 250
4.28	1.26×10^5	~ 34	~ 73	~ 200 ^a

^a Depth of penetration of fragments.

Figure 1. Sketch of the experimental configuration for radiographic diagnostic of hydroerosion fragmentation experiment. The timing and configuration are representative of a 3 km/s impact velocity.

Figure 2. A schematic of the radiographic images of the copper projectile during penetration within the polyurethane foam environment illustrating the three regimes of penetration behavior. The corresponding penetration depths and times are given in Table 1.

Figure 3. Geometry of shock wave coupling upon normal impact of a spherical particle on a planar surface.

Figure 4. Supersonic penetration in compressible media.

Figure 5. Depth of penetration of copper projectiles into polyurethane foam targets.

Figure 6. Transient penetration depth and time determined from flash x-ray for Test # F-12

Figure 7. Pressures in the impactor at 0.7 microseconds, for the three different impact velocities. Notice that the resolution of the calculations is sufficient to resolved a detached bow shock at this time. Ellipsoidal regions of pressure have formed in all of the calculations, but it is only for the highest impact velocity case that the shock ellipsoid has fully decoupled from the pressure field at the impact side of the copper projectile. These calculations are highly resolved, with 160 zones across the diameter of the projectile.

Figure 8. Thermodynamic profile at quasi-steady state conditions for the 2.21 (F-12), 2.9 (F-13), and 4.28 (F-16) km/s impacts at 1.0 μ sec.

Figure 9. Later-time projectile deformation for (A) 2.21 (16.0 μ sec) and (B) 4.28 km/s (16.0 μ sec) impacts. The CTH calculations that simulated these deformations had approximately one-third the resolution of the projectile of the calculations shown in Figure 7.

Figure 10. Comparison of high and low resolution simulations of experiment F-12, $v=2.21$ km/s. The solid curve is the high resolution calculation, while the dashed curve is the low resolution calculation. The axial velocity of the sphere is negative in this figure because the initial impact direction was in the negative axial direction.

Figure 11. Axial velocity of the simulated projectiles for 2.21, 2.9 and 4.28 km/s impact velocities. The circles correspond to the prediction of the analytic velocity formula (18) for the case of 4.28 km/s and a choice of $c=1$ in the given equation.

4.28 km/s impact at 5.0 μ sec

Figure 12. Comparison of high resolution reverse ballistic simulations of experiment F-16, $v=4.28$ km/s and of a Shoemaker-Levy 9 comet fragment impact on Jupiter at 60 km/s. Both projectiles are undergoing sheet-stripping deformation (Pilch and Erdman, 1985). The generalized Weber number of the S-L9 impact predicts this, but a further generalization of this dimensionless number is needed to fully explain the experimental projectile deformation.