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AUTHOR(S) G. R. Spillman, DRA/NDR

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Los Alamos National Laboratory
Los Alamos, New Mexico 87545

A SIMPLE DEFENSE CONSERVATIVE MODEL FOR MASS REQUIREMENTS OF HYPERVELOCITY PROJECTILE IMPACT SHIELDS FOR REENTRY VEHICLES

George R. Spillman
Los Alamos National Laboratory, Los Alamos, NM 87544

ABSTRACT

Simple analytical modeling of the physics of interaction of hypervelocity (50-100 km/s) projectiles with a bumper shield countermeasure is given. The interaction of projectile and bumper expansion between bumper and underlying vehicle and interaction of bumper/projectile debris cloud with vehicle are examined. Projectile/bumper interactions are treated with ideal gas strongshock and rarefaction equations. Projectile shock decay from bumper rarefaction is approximated by an impulsive shock similarity solution. A crude model for edge rarefactions is derived. Expansion of debris is treated as an expansion superimposed upon a translation with partition derived from a simple inelastic collision model. The effect of nonunity aspect ratio of compressed debris is included. Debris colliding elastically with the vehicle will impart momentum equal to twice the incident normal component. Impulse may be reduced up to a factor of 2 by stagnation radiative losses for small projectiles and large bumper/vehicle stand-off. Impulse can be inhanced by vehicle ablation from radiative coupling, shock heating (inadequate stand-off), or liquid droplet microcratering (inadequate bumper thickness). Estimates of required bumper mass are given for a specific example.

INTRODUCTION

We consider the physics of the problem of bumper shield countermeasuring reentry vehicles against high hypervelocity (>50 km/s) defensive projectiles. The hypervelocity impact bumper is a concept borrowed from the design of meteoroid impact protection for spacecraft (Zukas and colleagues, 1982). The concept as applied to a conical reentry vehicle (RV) is illustrated in Fig. 1, in which we indicate a small, high-velocity projectile incident upon a thin balloon (the bumper) surrounding an impulse-hardened conical RV. The strong shock interaction between bumper and projectile causes them to vaporize, which results in an expanding vapor cloud that blast-loads the underlying vehicle. The basic assumption of the projectile interaction with the vehicle is changed from that of a solid, penetrating collision to that of the blast load from a low-density cloud, which makes the interaction problem more analogous to that of the impulse loading because of x rays.

In the following we will consider the example of tungsten for both incident projectile and bumper shield. We will assume a simple right circular cylinder with unit aspect ratio (length = diameter) incident normally with its circular face striking the bumper. Since the specific kinetic energy of the projectile is well above vaporization energy, we will use ideal gas equations for treating the various interactions with nominally $\gamma = 1.5$. We will use a rough estimate (Bennett, May 1984) of 19 Mbar as the minimum shock pressure for which tungsten completely vaporizes on relief.

INTERACTION OF BUMPER AND PROJECTILE

The impact produces equal strong shocks in the bumper and projectile with equal thermal and translational velocities, and with a compression of about a factor of 5 for $\gamma = 1.5$ (as appropriate for tungsten at these high velocities). Conditions behind the shock will be modified by edge rarefactions and, after the shock emerges from bumper or back of the projectile, it will be modified by rarefactions from those surfaces. We first consider the effects of rarefaction from the back of the bumper, ignoring effects of edge rarefactions.

The various velocities of concern are v_p = projectile velocity, $u_p = v_p/2$ = directed velocity behind the shock = thermal rms velocity behind the shock, v_s = shock velocity = $[(\gamma + 1)/2]\, u_m = [(\gamma + 1)/4]\, v_p$, and C_A = adiabatic speed of sound behind the shock. Here we consider the length of the projectile to be ℓ and the bumper thickness to be $\epsilon\ell$.

We now consider the minimum bumper thickness such that a rarefaction from the back surface of the bumper cannot catch up with the shock in the projectile. The times for the shock to reach the back of the projectile and bumper, respectively, are

$$t_p^s = \ell/v_s \qquad (1)$$

and

$$t_B^s = \epsilon\ell/v_s \quad , \qquad (2)$$

where v_s is the shock speed. Behind the shock the compression and speed of sound, respectively, are

$$\eta = \frac{\eta + 1}{\eta - 1} \tag{3}$$

and

$$c_A = \sqrt{\frac{\gamma(\gamma - 1)}{2}} \left(\frac{\gamma + 1}{2}\right) \quad . \tag{4}$$

Then the total time for the shock to reach the back of the bumper and the following rarefaction to reach the rear of the projectile is

$$t_R^\rho = \frac{\epsilon\ell}{v} + \frac{1 + \epsilon)\ell}{\eta C_A} = \frac{\ell}{v_s} \left[\epsilon + (1 + \epsilon) \sqrt{\frac{\gamma - 1}{2\gamma}}\right] \quad . \tag{5}$$

The time to penetrate the distance $\epsilon\ell$ is

$$t_R^P = \frac{\ell}{v_s} \left[\epsilon + (\delta + \epsilon) \sqrt{\frac{\gamma - 1}{2\gamma}}\right] \quad . \tag{6}$$

The rarefaction catches the shock when $\delta\ell = V_S t_R^P$, or when

$$\frac{\delta}{\epsilon} = \frac{1 + \sqrt{(\gamma - 1)/2\gamma}}{1 - \sqrt{(\gamma - 1)/2\gamma}} \quad , \quad (= 2.38 \text{ for } \gamma = 1.5) \tag{7}$$

We will now assume that the similarity solution for an impulsively loaded, free surface, holds for the shock once the bumper rarefaction has overtaken the shock; that is,

$$P_S \sim X^{-n} \quad , \tag{8}$$

where n is a weak function of γ, having values of 4/3, 1.275, and 1.191 at γ = 1.4, 5/3, and 2.8, respectively. The use of

$$P_s = P_S^0 \left[\frac{(\delta + \epsilon)\ell}{(1 + \epsilon)\ell}\right]^n = P_S^0 \left[\frac{3.4\epsilon}{1 + \epsilon}\right]^{4/3} \tag{9}$$

In the absence of a rarefaction from the back of the bumper or projectile, the head of the edge rarefaction from the contact surface intersects the shock at a radius

$$r = r_p - v_s t \sqrt{\frac{\gamma - 1}{\gamma + 1}} \quad , \tag{10}$$

which has the value $r = 0.1\ r_p$ when the shock reaches the rear of our nominal unit aspect ratio projectile. Therefore, edge rarefactions are important--even for our nominal projectile. We now attempt a crude quantification of the effect of the edge rarefaction on shock decay in the projectile.

Recall the equations for the idiabatic rarefaction of an ideal gas bounded initially at X = 0 are

$$\frac{C}{C_0} = \frac{2}{\gamma + 1} - \frac{\gamma - 1}{\gamma + 1}\frac{X}{C_0 t} = \text{adiabatic speed of sound} \tag{11}$$

$$\rho = \rho_0\left(\frac{C}{C_0}\right)^{2/(\gamma - 1)} \quad \text{= density} \tag{12}$$

$$P = P_0\left(\frac{C}{C_0}\right)^{2\gamma/(\gamma - 1)} \quad \text{= pressure} \tag{13}$$

$$I = I_0\left(\frac{C}{C_0}\right)^{2} \quad \text{= internal energy} \quad , \tag{14}$$

where the subscript zero refers to the undisturbed region. For a planar rarefaction, we obtain the average pressure between $X = -C_0 t$ (head of the rarefaction) and $X = 0$ (edge of projectile) as

$$\bar{P} = \frac{P_0}{C_0 t} \int_{-C_0 t}^{0} \left[\frac{2}{\gamma + 1} - \frac{\gamma - 1}{\gamma + 1} \frac{X}{C_0 t}\right]^{2\gamma/(\gamma - 1)} dx \quad . \tag{15}$$

We now assume that this planar rarefaction holds behind our shock front in a cylindrical geometry and that the reduced pressure is immediately communicated to the shock front. If the rarefaction has traveled the distance $dx = +C_0 dt$, the average pressure over the whole shock front is

$$\bar{\bar{P}} = \bar{P} \left[1 - \left(1 - \frac{dx}{r_p}\right)^2\right] + P_0 \left(1 - \frac{dx}{r_p}\right)^2 \quad . \tag{16}$$

We obtain as estimates of the effect of edge rarefaction on the average shock pressure

$$P = P_0 e^{-0.43 \int V_S dt / r_P} \quad (\gamma = 1.5) \tag{17}$$

Recently, The edge effect on shock decay was investigated (Taylor, October 1985) using steady-state 2D approximation and obtained a different form--but similar quantitative results for the shock decay. We assume for our nominal projectile (ℓ = $2r_p$) that the net effective decay is given by the product of planar and edge effect decay. If we require that the rear surface shock be greater than vaporization pressure, we have

$$P_S^0 \left(\frac{3.4\ \epsilon}{1 + \epsilon}\right)^{4/3} \geq 2.36\ P_v \tag{18}$$

or

$$\epsilon \geq \left[3.4 \left(\frac{P_S^0}{2.36\ P_v}\right)^{3/4} - 1\right]^{-1} \quad . \tag{19}$$

When the above condition is not satisfied, we may expect a portion of the projectile to emerge as liquid or solid rather than vapor, which has implications for interactions with the underlying structure.

We will make a "cookie cutter" approximation to determine the mass of bumper principally involved in the collision; i.e., we assume that the bumper mass involved in the collision is that in direct line of the incoming projectile. A mass, m_p, is incident and a mass, $m_p(1 + \epsilon)$ emerges containing the incident momentum and energy. Note that this assumption pertains only to the mass sharing the main energy and momentum and not to the size of a hole produced in the bumper. One-dimensional synthesis suggests that at our high velocities, less than 2.5% of the energy is transferred laterally into a bumper of $\epsilon = 1/4$ and 2D steady-state approximations (Taylor, June 1985) and 2D hydrodynamics calculations (Oyer, 1985) support the cookie-cutter assumption.

VOID REGION EXPANSION

As the projectile and ejected bumper material emerge from the back of the bumper, it is compressed and heated, but still has a net translational velocity. Some of the existing heat energy will be converted to kinetic energy of expansion and the overall expansion may be viewed as a superposition of the net translational velocity and the local expansion velocity.

We consider first the unreal case of a spherical expansion in which the material emerges as a sphere with half the energy in translational and half in internal energy with all internal convertible to expansion kinetic energy. If the sphere expands as a thin shell, then the shell remains tangent to the bumper at $\theta = 180°$ (see Fig. 2) and expands at the projectile velocity (v_p) at $\theta = 0°$. In the center-of-mass frame, the expanding balloon has a uniform mass distribution in solid angle. The emerging debris will not be in the form of a sphere. If we could ignore the edge rarefactions until the shocks emerged from front and back, for the case of $\epsilon = 1$ the emerging debris could be characterized as a disk of diameter equal to the projectile diameter and a length 40% of the projectile length (a linear compression of twice the projectile length by a factor of 5). We could then expect translational and expansion velocities to each be one-half of the projectile velocity, but the uniformity of mass distribution with solid angle would be lost. Since rarefactions in any direction will move the same distance in a given amount of time, the mass moving in a particular direction will be approximately proportional to the area of the compressed debris normal to that direction. For a thin face, however, the effective area will be reduced about a factor of 2 by rarefactions from other face. From this discussion, we make an assumption that the radio of dm/d cos θ in the axial and radial directioons is proportional to areas normal to $\theta = 0°$ and $\theta = 90°$ gives

$$\left(\frac{dm}{d\cos\theta}\right)_{0°} / \left(\frac{dm}{d\cos\theta}\right)_{90°} = r_p/\bar{\ell} \quad \text{where } \bar{\ell} = \text{disk thickness.} \tag{20}$$

We define $\mu = \cos\theta$ and arbitrarily fit the two directions with the form a + b μ. Additionally, we assume that the expansion is as from a disk starting at uniform compression η, given from the strong shock equations such that $\bar{\ell} = \ell_p(1 + \epsilon)/\eta$, and using $\eta = 5$ for $\gamma = 1.5$. We obtain

$$\frac{dm}{d\mu} \sim 1 + \mu^2 \left(\frac{1.5 - \epsilon}{1 + \epsilon}\right) \tag{21}$$

We now consider a very simple inelastic collision model for the effect of bumper thickness on expansion velocity. We assume that the expansion will again be uniform in direction in the center-of-mass coordinate system. Defining v_p' as center-of-mass translational velocity and v_T as expansion velocity allows us to obtain from energy and momentum conservation

$$v_p' = v_p/(1 + \epsilon); \; v_T = v_p \epsilon^{1/2}/(1 + \epsilon) \tag{22}$$

and simple geometry gives (see Fig. 2)

$$(\tan\phi)_{max} = \epsilon^{1/2}\sin\theta/(1 + \epsilon^{1/2}\cos\theta) \qquad (23)$$

and the maximum value is

$$(\tan\phi)_{max} = \sqrt{\epsilon/(1 + \epsilon)} \text{ at } \theta = \cos^{-1}(-\sqrt{\epsilon}) \quad . \qquad (24)$$

The item of most interest in the expansion is the angular distribution of the axial component of the momentum. This we may write as

$$\frac{d(mv_N)}{d\cos\phi} = v_N \frac{dm}{d\mu}/d(\cos\phi)/d\mu \qquad (25)$$

where v_N is the axial velocity given by

$$v_N = v_N' + v_T \cos\theta = v_P (1 + \epsilon^{1/2}\cos\theta)/(1 + \epsilon) \qquad (26)$$

under assumption of expansion as a thin shell at velocity v_T in all directions from the center of mass. Since θ is double valued for any ϕ, there are two values to sum for Eq. (25). From Eq. (23), we obtain

$$\frac{d\cos\phi}{d\mu} = \left(\frac{\sqrt{\epsilon}\cos\theta}{1 + \sqrt{\epsilon}\cos\theta} + \frac{\epsilon\cos^2\theta}{(1 + \sqrt{\epsilon}\cos\theta)^2}\right) \frac{\sin\phi\cos^2\phi}{\sin\theta} \quad , \qquad (27)$$

which is most convenient to use in this mixed form. We use Eqs. (21), (23), (25), (26), and (27) to numerically evaluate $dmv_N/d\cos\theta$ and normalize to the incident momentum; this is plotted in Fig. 3. The plots show a peak at $\phi = \phi_{max}$ because of the assumption of infinitesimal debris shell thickness.

Finite thickness will tend to remove this double-peaked structure. We may note the tendency toward uniform distribution for $\phi < \phi_{max}$ for small ϵ, even for the infinitesimal shell thickness. Note also that the strict limitation of debris to angles $\phi \le \phi_{max}$ is an artifact of assigning the rms value of velocity to expansion for all mass points. From Eq. (24), we may obtain for small ϵ

$$\frac{1}{m_p v_p} \frac{dmv_N}{d\cos\theta} = \frac{2}{\epsilon} \qquad \phi < \phi_{max} \ (\epsilon << 1) \tag{28}$$

$$= 0 \qquad \phi > \phi_{max}$$

INTERACTION OF DEBRIS WITH UNDERLYING STRUCTURE

The debris cloud striking the underlying structure may interact elastically or inelastically. If the collision is elastic, twice the normal component of the incident momentum will be delivered to the structure. The momentum transfer to the structure may be reduced to the normal incident component if the debris can radiate away all internal energy on stagnation without causing any ablation of the underlying structure. The momentum may be enhanced by several possible mechanisms causing ablation, including shock heating, radiative transfer from the stagnating debris, and microcratering by liquid droplets or solid fragments. We assume that avoidance of each of these potential momentum enhancement mechanisms is a countermeasure design goal. We discuss each mechanism to some degree.

To be able to estimate impact and stagnation densities and times, we will assume that the expanding debris shell is 0.2 times a radius thick. Shock ablation may be circumvented by achieving a large density discontinuity between the debris cloud and the material of the underlying structure. This is achieved by debris cloud expansion via an adequate combination of separation between bumper and underlying structure and bumper thickness. Our calculations indicate that reducing the incident vapor impulse/area to a reasonable level seems likely to avoid shock ablation. At least, it is defense conservative to assume so.

At 70 km/s impact velocity, the stagnation temperature of a low-Z debris cloud may be of order $3X10^5$, and that of a high-Z debris cloud may be twice as high. At such high temperatures, there is a possibility of significant radiative energy transfer. The maximum radiative flux from a stagnating layer is the blackbody value. For a layer of optical thickness $\tau << 1$, the flux is reduced approximately by the factor 2τ. For $\tau >> 1$, the radiative rate is reduced by the diffusion process. For a slab in steady-state radiating from one face with a uniform heat source, the radiative flux is given by

$$F = \frac{2\sigma T^4}{1 + 3/4\tau} , \qquad (29)$$

where σ is the Stefan-Boltzmann constant and T is the internal temperature at optical depth τ. [This is derivable analagously to the Milne problem diffusion solution (Zel'dovich and Raizer, 1966) by setting the divergence of the flux equal to a nonzero constant.]

We have used Eq. (29) with strong shock equations, together with a factor for radiative collapse to give stagnation density, temperature, and radiative flux--and somewhat arbitrarily defined the condition of radiative flux at one-half stagnation time becoming larger than one-half of rate of kinetic energy flux into the stagnation region as a transition from nonradiative stagnation to radiative stagnation. Using this procedure, we find that those expansions to low density (and large area) tend to lose energy radiatively; those of lesser expansion do not, e.g., for tungsten projectiles in the mass range of 1 to 10 g, stagnations on underlying structure such that the momentum/area incident is less than about 4 ktap tend to lose energy radiatively. On structures closer such that incident momentum is much higher, radiative loss is small.

For high-density particles incident (such as liquid droplets) ejecta from craters can give significant momentum enhancement (e.g., about a factor of 5 for projectiles incident on aluminum at 70 km/s) (Dienes and Walsh, 1970). The minimum size of an atomic cluster that acts as a cratering projectile may be estimated by finding the minimum aggregate of atoms that have sufficient energy melt a hemisphere of depth equal to the atomic range. Such estimates of minimum mass corresponds to large molecules.

A more restrictive condition on the size of liquid droplets that may give momentum enhancement comes from a requirement that they must be able to penetrate the stagnating vapor. This condition we may express in terms of the vapor impulse/area and projectile velocity. The areal density of stagnating vapor is $m/A = L/v_p$, where L is the momentum/area in the stagnating vapor. The droplets will penetrate the stagnating vapor effectively if

$$\rho_D R_D >> \frac{1}{2} m/A = L/2v_p \quad , \tag{30}$$

where ρ_D and R_D are droplet density and radius, respectively; i.e., if $R_D >> L/2\rho v_p$ or, equivalently, $m_D >> \pi L^3/6\rho^2 v_p^3$. For v_p = 70 km/s, ρ = 19.3 g/cm^2 and L = 10^5 taps, this requirement is $m_D >> 4X10^{-12}$ kg. Unless the droplets are vaporized in the stagnation layer before reaching the underlying structure, even very small droplets can cause momentum enhancement by microcratering. The effect of possible droplet vaporization by the radiation field or other heat transfer in the stagnation layer has not been adequately considered and may lead to requirements of larger droplet masses for microcratering. For the present, we assume that the bumper is failing to perform adequately if the shock in the projectile drops below that required for full vaporization on release.

APPLICATIONS

We have applied the above physics to estimating minimum bumper mass to reduce blast loading below an assumed lethal impulse/area level for projectiles of various mass and velocities incident on a specific target. The target selected is a cone of 2 m length and 10° cone half-angle. The mass of the bumper shield will be its areal density times its area. For very small stand-off (h) the area essentially does not vary with increasing h, but the impulse/area falls off as h^{-2}. In such a region, the bumper weight can be decreased by reducing thickness and increasing stand-off (provided that we do not drop below the full vaporization regime). At large stand-off, the area increases as h^2 and, using our asymptotic expression for the angular distribution of momentum [Eq. (28)], we see there is no further gain to be made by increasing the stanbd-off further. But, also, we limit the bumper thickness according to Eq. (19). For projectile masses of 1 g or more or impulse levels below 120 ktap, this limit does not have a large effect on bumper mass estimates.

This minimization process has been applied to estimation of required bumper shell mass s optimized against specific projectile mass and velocity for the conical vehicle described above. Some results for a projectile velocity of 50 km/s and an impulse loading of 120 ktap on the underlying vehicle are shown in Fig. 4. Here, the curve labeled leakage probability of 1 - ϵ corresponds to normal impact of the projectile as modeled herein. Other values of leakage probability correspond to the probability of the angle of incidence for a random direction of the projectile, resulting in less than 120-ktap impulse. In modeling oblique impact, we assume that the effective thickness of the bumper is increased by the reciprocal of the cosine of the angle between the trajectory and the normal to the surface and that the angular distribution about the trajectory line is unchanged. Since the debris cloud (Kinslow, 1970) is deflected toward the normal, we believe this results in an overly conservative estimate of leakage.

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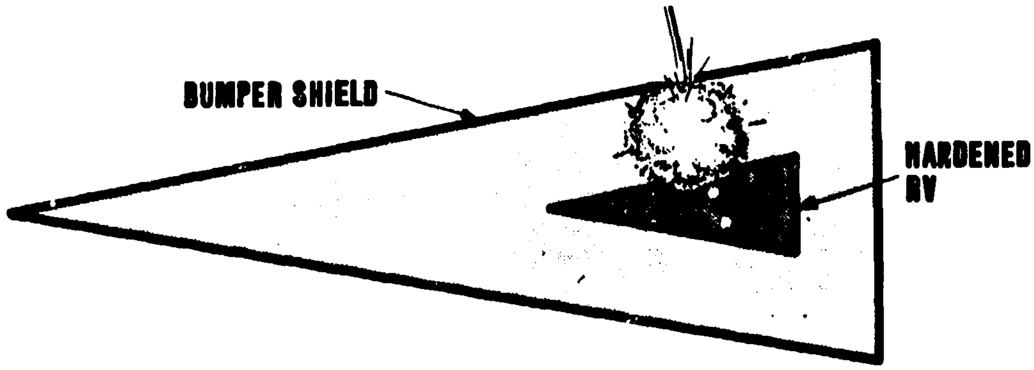

Fig. 1. The bumper shield concept.

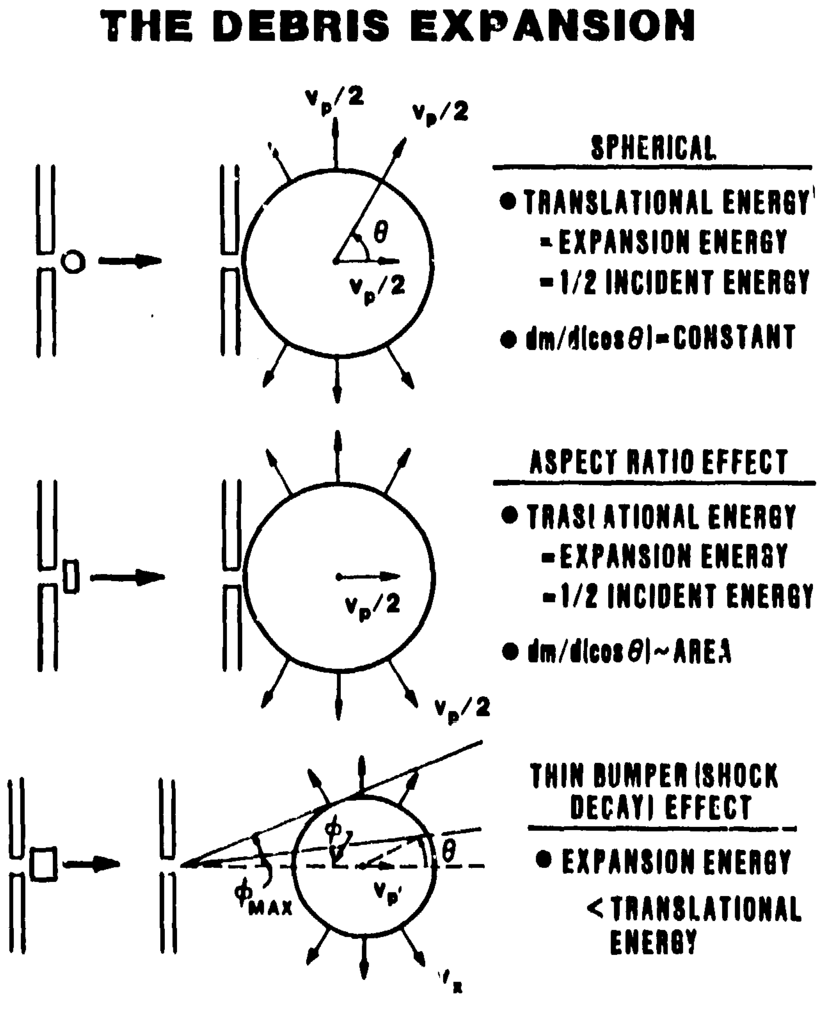

Fig. 2. The debris expansion.

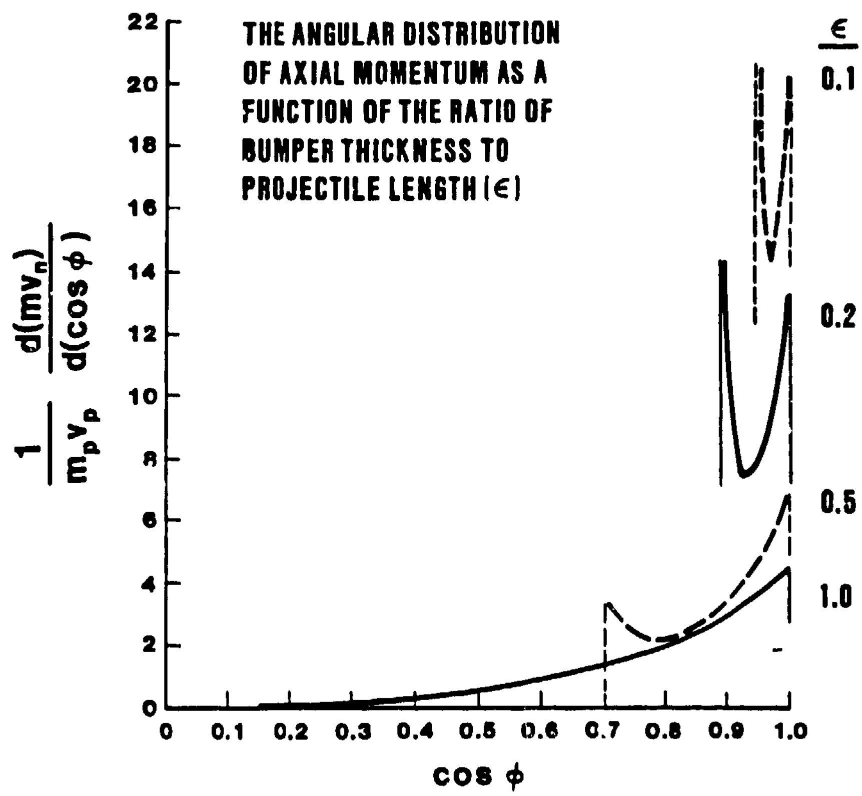

Fig. 3. The angular distribution of axial momentum as a function of the ratio of bumper thickness to projectile length (ε).

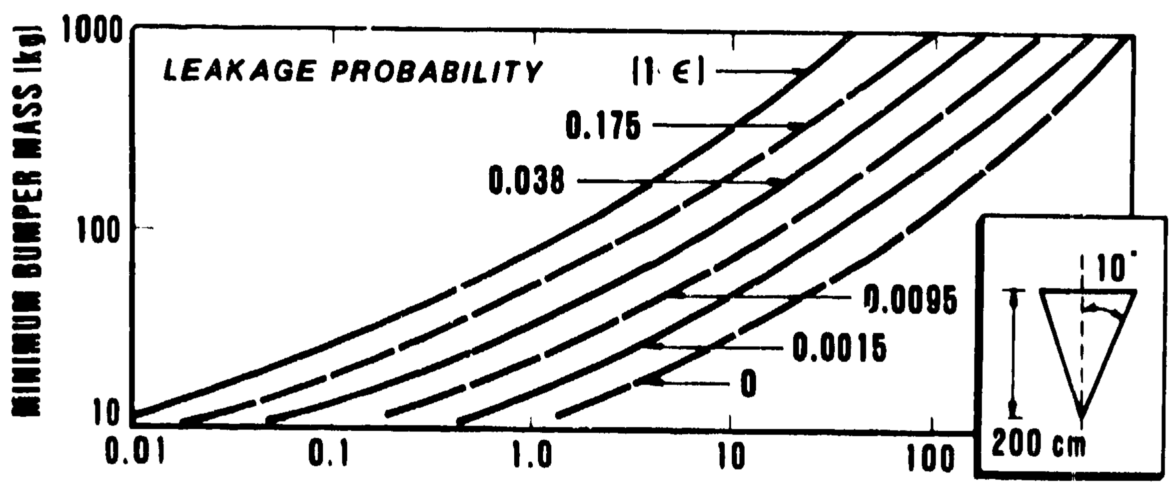

Fig. 4. Minimum required bumper mass to achieve specified survival (leakage) probability against random-direction hit of tungsten projectile with velocity of 50 km/s.