AN EMPIRICAL PENETRATION EQUATION FOR THIN METALLIC FILMS USED IN CAPTURE CELL TECHNIQUES

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ABSTRACT. The problem in the determination of impact particle parameters from hypervelocity impact damage on a foil or multilayer structure is one which deserves close attention in the era of ready access to recovered space impact events. In the MFE experiment (McDonnell et al 1984), we chose metallic foils, and this paper addresses the decoding of perforations in metallic foils, primarily of aluminium of typical dimensions 5 μm (hard temper rolled). Data is examined to establish for the first time a penetration relationship which extends over:

1. marginal and thin sheet perforation;
2. velocities varying from some 2 to 69 kms^{-1};
3. particle densities varying from some 1 g cm^{-3} (ices?) to 7.8 g cm^{-3} (iron?)

1. INTRODUCTION

The mathematical description of hypervelocity impacts onto solid material commonly takes the form of empirical equations derived from experimental data. Such equations are typically of two types:

i) crater size equations for both thin foils and semi-infinite targets;

ii) marginal or perforation limit equations applied to impact on thin foils.

Another approach is to model the actual physical processes which take place in hypervelocity impact using a three-phase equation of state and a numerical computer code. This latter method has been successfully used to simulate impacts on the Giotto meteoroid shield (Arnadeau et al 1984) but requires accurate data, profound understanding of the physical phenomena and extensive computing power. The empirical method, then, continues to be used although the equations cannot always be reliably extrapolated beyond the experimental limits which are usually less than 20 kms^{-1} for micron dimensioned particles in a Van der Graaff

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dust accelerator and less than 10 kms^{-1} for millimetre-sized particles in a light gas gun.
A list of commonly-encountered crater size equations is shown in Table I and plotted against reliable experimental data for iron projectiles impacting aluminium foil (Figure 1). Most noticeable is the turn over in the experimental data particle diameter d decreases, preceding a perforation limit. These phenomena are not represented in any of the equations which have only limited regions of coincidence with the data.

Table I

Three empirical crater-size equations

Nysmith and Denardo	$\frac{D}{d} = 0.88\rho_m^{\frac{1}{2}}(\frac{f}{d})^{0.45} V^{\frac{1}{2}}$	(1)
Sawle	$\frac{D}{d} = 1.3.2 \ (\frac{\rho_m}{\rho_f}.\frac{v}{c})^{0.2} \ (\frac{f}{d})^{2/3}$	(2)
Maiden	$\frac{D}{d} = 0.45 \ (\frac{f}{d})^{2/3} V + 0.9$	(3)

A list of commonly-encountered crater-size equations relating final hole size D to target and incident particle parameters.

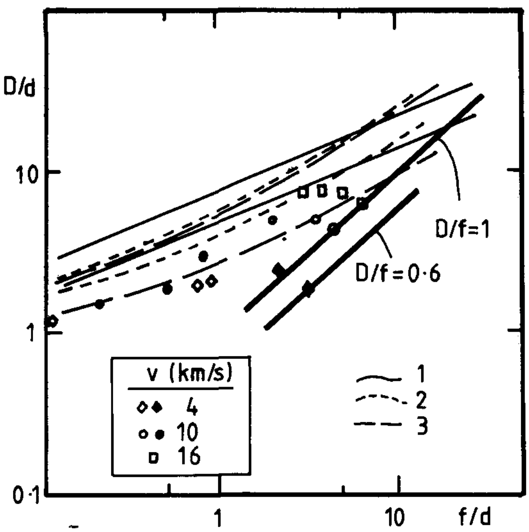

Figure 1. Experimental data points for iron projectiles impacting aluminium foil at 4, 10 and 16 km/s are shown. The plotted lines are given by the equations of Maiden et al, Sawle and Nysmith and Denardo for velocities of 4 and 10 kms^{-1}, scaled to iron on aluminium where appropriate.

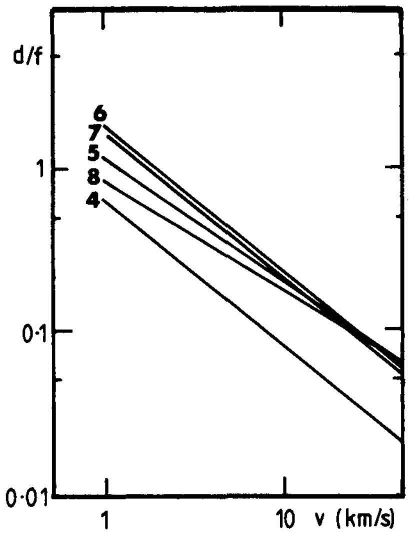

Figure 2. Perforation limit equations plotted for iron projectiles impacting 5 μm aluminium foil.

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2. EMPIRICAL EQUATION DERIVATION

It is therefore necessary to derive an equation which describes the regime near the perforation limit in which the perforation diameter, D, starts to decrease. There is already an equation (McDonnell 1979) which describes the perforation limit of iron particles on aluminium foil and this limit falls on the D/f = 1 curve shown in Figure 1, for high velocities.
For velocities of 4 kms^{-1} and below, the perforation limit lies on the D/f = 0.6 line, implying that the morphology of lower-velocity marginal perforations is different from that at higher velocities. A list of perforation limit equations is shown in Table II and plotted for iron on aluminium for 5 micron diameter particles in Figure 2.

Table II

Marginal or Perforation-Limit Equations

Nauman	$f/d = d^{0.056} V^{0.875} \rho^{0.52}$	(4)
McDonnell	$f = 0.79\, V^{0.763}\, d$	(5)
Pailer and Grün	$f = \dfrac{1}{\varepsilon^{0.006}\rho_f^{0.05}}\, m^{0.4}\rho_m^{0.33}(V\cos\alpha)^{0.88}$	(6)
Fish and Summers	$f/d = 0.57\left(\frac{1}{\varepsilon}\right)^{1/8}\left(\frac{\rho_m}{\rho_f}\right)^{\frac{1}{2}} V^{7/8}\, d^{1/18}$	(7)
Cour-Palais	$f = 3.56 \times 10^{-4}\rho^{0.148}\, m^{0.352}\, V^{0.67}$	(8)

A list of perforation limit equations relating foil thickness f to target and incident particle parameters.

List of symbols

v	=	velocity	d	=	projectile diameter
D	=	perforation diameter	D_t	=	perforation diameter at top of foil
f	=	foil thickness	D_l	=	perforation diameter at lower edge of foil
ρ_f	=	density of foil	ρ_m	=	density of projectile
ε	=	foil ductility	α	=	impact angle

Note: Units are not consistent throughout all the above equations.

As an important constituent of the cosmic dust population is likely to be low density material rather than iron, so a perforation limit for low velocity (ρ = 1) particles on aluminium has been calculated. Arnadeau et al (1984) have published results for a low density particle

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impacting an aluminium meteor shield at 68 kms^{-1} near marginality. Results of experiments using iron projectiles on gold foil (McDonnell, unpublished) may also be examined by assuming these are equivalent to unit-density particles impacting aluminium foil because the projectile-target density ratios are very similar (Fish and Summers 1965). The limits are found to lie on D/f = 2 for low velocities but are expected to extend (as for iron projectiles) to D/f = 1 for higher velocities where the perforation diameters are relatively large. The limit equation for low density (ρ = 1) particles impacting aluminium foil is thus:

$$f/d = 0.46\ V^{0.64} \qquad (9)$$

where v is in kms^{-1}. This is plotted in Figure 3 with other perforation-limit equations scaled (when necessary) for low density particles.

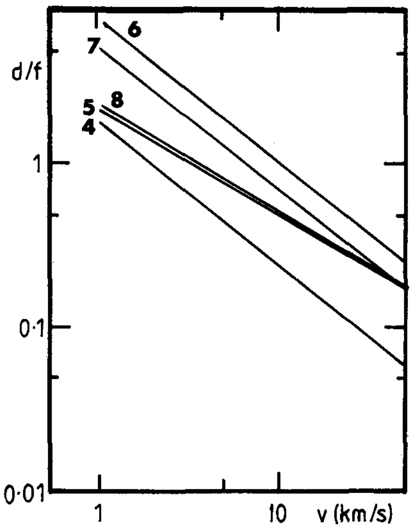

Figure 3. Perforation limit equations plotted for particles with ρ_m = 1 impacting alumium foil.

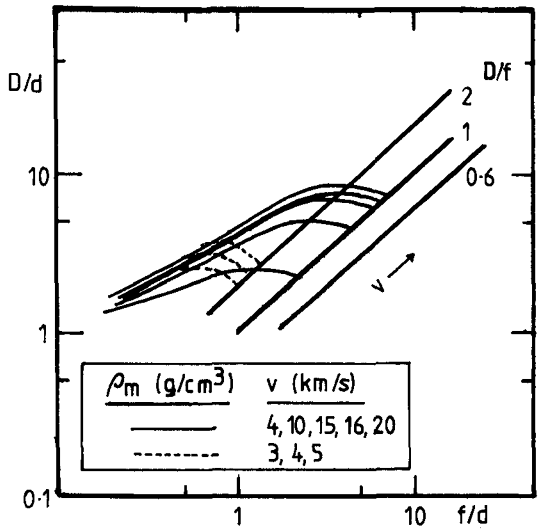

Figure 4. The empirical crater-size equation for iron on aluminium plotted against experimental data. Data for low density particles is also shown.

Taking the D/f = 1 as the marginal perforation limit for iron on aluminium and using the data points shown in Figure 1, a crater size equation has been derived for velocities of 4 to 20 kms^{-1}. The equation takes the form:

$$\frac{D}{d} = 1 + 1.5(f/d)\ V^{0.3} \left[\frac{1}{1 + (f/d)^2\ V^{-n}}\right] \qquad (10)$$

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where, for $2 < V < 20$, where

$$n = 1.02 - 4 \exp(-0.9\, V^{0.9}) - 0.003(20 - V) \qquad (11)$$

The term outside the square brackets is fitted to the data points where D is increasing and is modified by the term inside the brackets. The factor n fits the curve through the perforation limits. This equation is shown plotted in Figure 4, with the experimental data for iron on aluminium to which it is fitted and the data for low density ($\rho_m = 1$) particles on aluminium for comparison.

For Fe-Al at $V > 20$ kms^{-1} we have:

$$\frac{D}{d} = 1 + 1.5(f/d)\, V^{0.3} . \left[\frac{1}{1 + (f/d)^2 . V^{-1.02}}\right] \qquad (12)$$

3. CONCLUSIONS

We have developed a single equation covering the marginal and very thin foil perforation properties which fits the available data for iron particles impacting aluminium foil at velocities up to 20 kms^{-1}. This situation undoubtedly is not the most common of impact events in space, and hence we have commenced the scaling of this to lower density projectile data, e.g. cometary particles of density ~ 1 g cm^{-3}. A marginal perforation limit is derived which will be extended to cover non-marginal perforations in the future.

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