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CRATERING IN LOW-DENSITY TARGETS

by Emerson T. Cannon and Gerry H. Turner

Prepared by
UTAH RESEARCH & DEVELOPMENT CO., INC.
Salt Lake City, Utah
for

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ABSTRACT

Craters were formed with aluminum, steel, nylon, and magnesium projectiles in targets made of rigid and flexible polyurethane foams, foamed glass, and natural pumice. The velocity range involved was 4.7 to 6.9 km/sec. Crater dimensions and volumes were determined. Values of shear strength and shearing energy were determined for all target materials. Some comparison was done among different projectile-target combinations to better understand the reasons for differences in crater shape. Values were determined for target mass displaced in a crater per unit of energy involved. It was found that projectiles of some materials are much more efficient in cratering than are others; steel projectiles being less efficient than the other types used by as much as a factor of one-half. Plots were made showing V/V_o and p/d being equal to $c\left[(\rho_p/\rho_t)(\rho_p v^2/S_t)\right]^b$ where c and b are constants, V is crater volume, V_o is projectile volume, p is crater depth, d is projectile diameter, ρ is density, v is projectile velocity, s is shear strength, and the subscripts p and t denote projectile and target. It was found that in the volume relationship, b remains constant at 1/2 for each target material, but c varies from 0.2 to 1.0. In the depth relationship, b is 1/3 for rigid targets and 1/2 for flexible ones, with c varying from 0.025 to 0.3.

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SUMMARY

Craters were formed with aluminum, steel, nylon, and magnesium projectiles in targets made of rigid and flexible polyurethane foams, foamed glass, and natural pumice. The velocity range involved was 4.7 to 6.9 km/sec. Crater dimensions and volumes were determined. Values of shear strength and shearing energy were determined for all target materials. Some comparison was done among different projectile-target combinations to better understand the reasons for differences in crater shape. Values were determined for target mass displaced in a crater per unit of energy involved. It was found that projectiles of some materials are much more efficient in cratering than are others; steel projectiles being less efficient than the other types used by as much as a factor of one-half. Plots were made showing V/V_o and p/d being equal to $c\left[(\rho_p/\rho_t)(\rho_p v^2/S_t)\right]^b$ where c and b are constants, V is crater volume, V_o is projectile volume, p is crater depth, d is projectile diameter, ρ is density, v is projectile velocity, S is shear strength, and the subscripts p and t denote projectile and target. It was found that in the volume relationship, b remains constant at 1/2 for each target material, but c varies from 0.2 to 1.0. In the depth relationship, b is 1/3 for rigid targets and 1/2 for flexible ones, with c varying from 0.025 to 0.3.

INTRODUCTION

A limited amount of investigation has been done concerning cratering in materials having a specific gravity of less than one. Considerable interest is currently being shown in the formation of craters by high-velocity projectiles in low-density materials. This interest arises because of consideration being given to materials for shielding spacecraft, and because of a desire to determine lunar-surface properties. To better understand cratering processes in low-density materials, an experimental program has been carried out to determine the effect of various target properties on the observed crater. The results of that investigation are presented in this report.

EXPERIMENTAL METHODS

Spherical projectiles were accelerated by a light-gas gun to velocities between 4.7 and 6.9 km/sec. The high-speed projectiles were allowed to hit a specified target in an evacuated range at room temperature. The projectiles which were used in the experimental program were stainless steel (1/16 inch, 3/32 inch and 1/8 inch in diameter), aluminum (1/16 inch and 1/8 inch in diameter), nylon and magnesium (both 1/8 inch in diameter). The size of the projectile used for a particular shot was mainly based on the "stopping power" of the target. The target materials were chosen by their density (less than one gm/cm^3) and their availability. A series of rigid polyurethane foams having densities of 0.034, 0.065, 0.072, 0.082, 0.16, 0.27, 0.32 and 0.62 gm/cm^3 was supplied by Goodyear at no cost. Flexible polyurethane (density 0.080 gm/cm^3), foamed glass (0.15 gm/cm^3) and natural pumice (0.51 and 0.65 gm/cm^3) were obtained locally. All types of the above-mentioned projectiles were fired into each type of target where it was practical.

Crater dimensions were determined by cross-sectioning the targets. Crater volumes were calculated from the measurement of these cross-sections at intervals along the axis of the crater. Because the diameter of each crater was not constant, it was necessary to consider average values for a number of segments in each crater when calculating its volume. Target material densities were calculated from the volumes and weights of uniformly shaped specimens.

The shear strength of each target material was determined. This was done by measuring, with a Universal testing machine, the maximum force necessary to shear a one-inch diameter plug from a specimen. Figure 1 is a sketch of the testing apparatus. The energy used in shearing the specimen was calculated for each test by plotting force as a function of distance traveled by the die, and then calculating the area under the curve. A typical force-distance diagram is shown in Figure 2. Two or more tests were made with each material and the specimen thickness was varied by a factor of two. Good agreement was shown in most instances. The results of these tests are presented in Table I. The numbers given are either averages or represent, in our opinion, the most reliable value. Values are given for two different energy relationships; energy per unit area used in shear up to the point of maximum stress, which we define as the yield point, and energy per unit area used in shear during the entire punching operation. As examples of actual values obtained, the data concerning the rigid polyurethane foams are shown in Figures 3 and 4. Figure 3 shows shear strength as a function of material density, and Figure 4 shows energy used in shear as a function of material density.

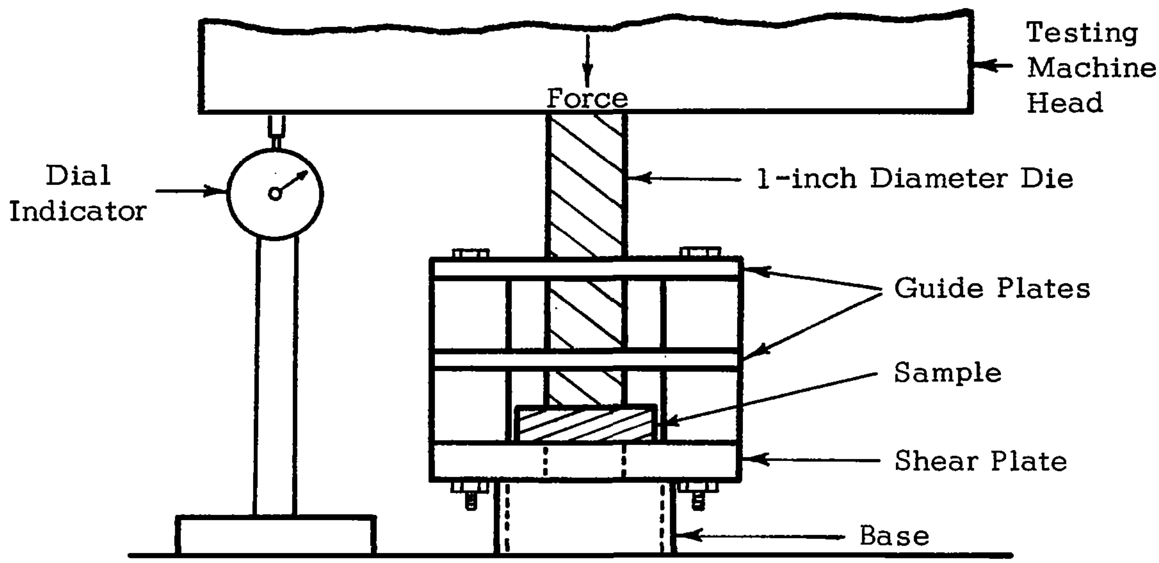


Figure 1. Diagram of the apparatus used in shear testing low-density materials.

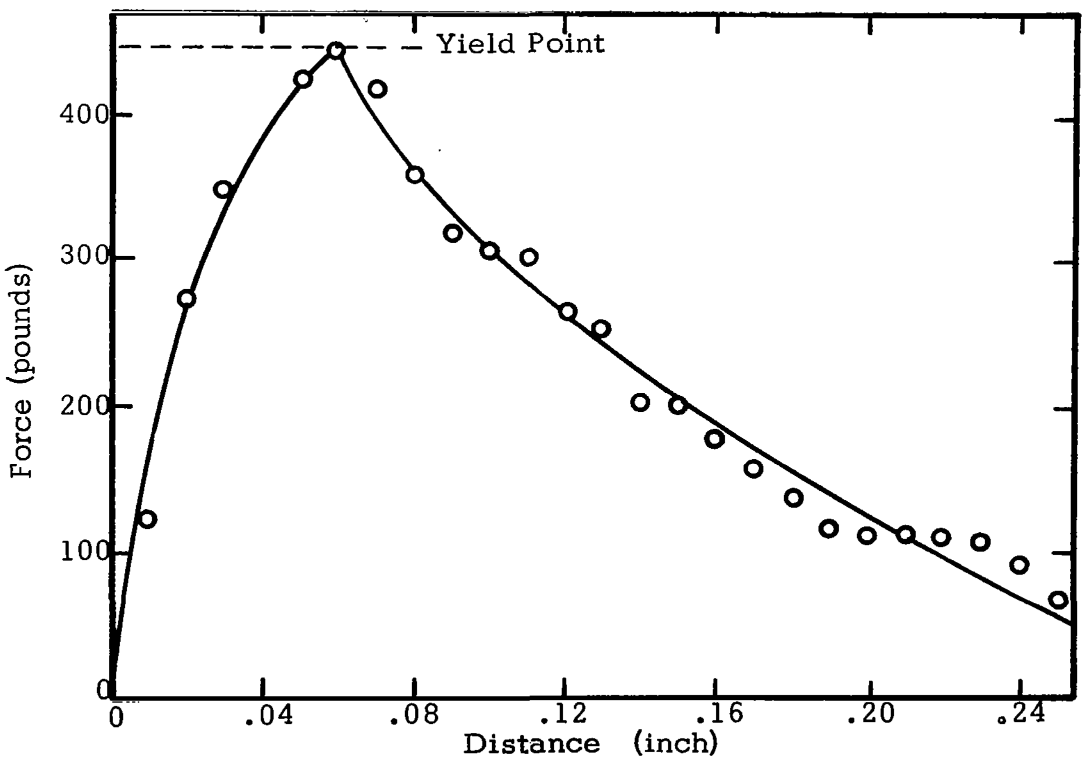


Figure 2. Plot of force applied as a function of distance moved by the die in testing a 0.256-inch thick rigid polyurethane foam of density 0.27 g/cm^3.

TABLE I

SHEAR STRENGTH AND SHEARING-ENERGY DATA FOR LOW-DENSITY TARGET MATERIALS

Target Material	Density (g/cm^3)	Shear Strength ($dyne/cm^2$)	Shearing Energy to Yield Point ($Joule/cm^2$)	Total Shearing Energy ($Joule/cm^2$)
Rigid Polyurethane Foam	0.034	4.2×10^6	0.081	0.20
" " "	0.065	5.7	0.092	0.41
" " "	0.072	5.9	0.10	0.46
" " "	0.082	6.4	0.11	0.53
" " "	0.16	13	0.20	0.99
" " "	0.27	35	0.32	1.45
" " "	0.32	52	0.53	1.56
" " "	0.62	200	1.39	1.41
Flexible " "	0.080	11	0.12	0.16
Foamed Glass	0.15	1.8	0.045	0.14
Natural Pumice	0.51	3.3	0.015	0.077
" "	0.65	3.9	0.090	0.21

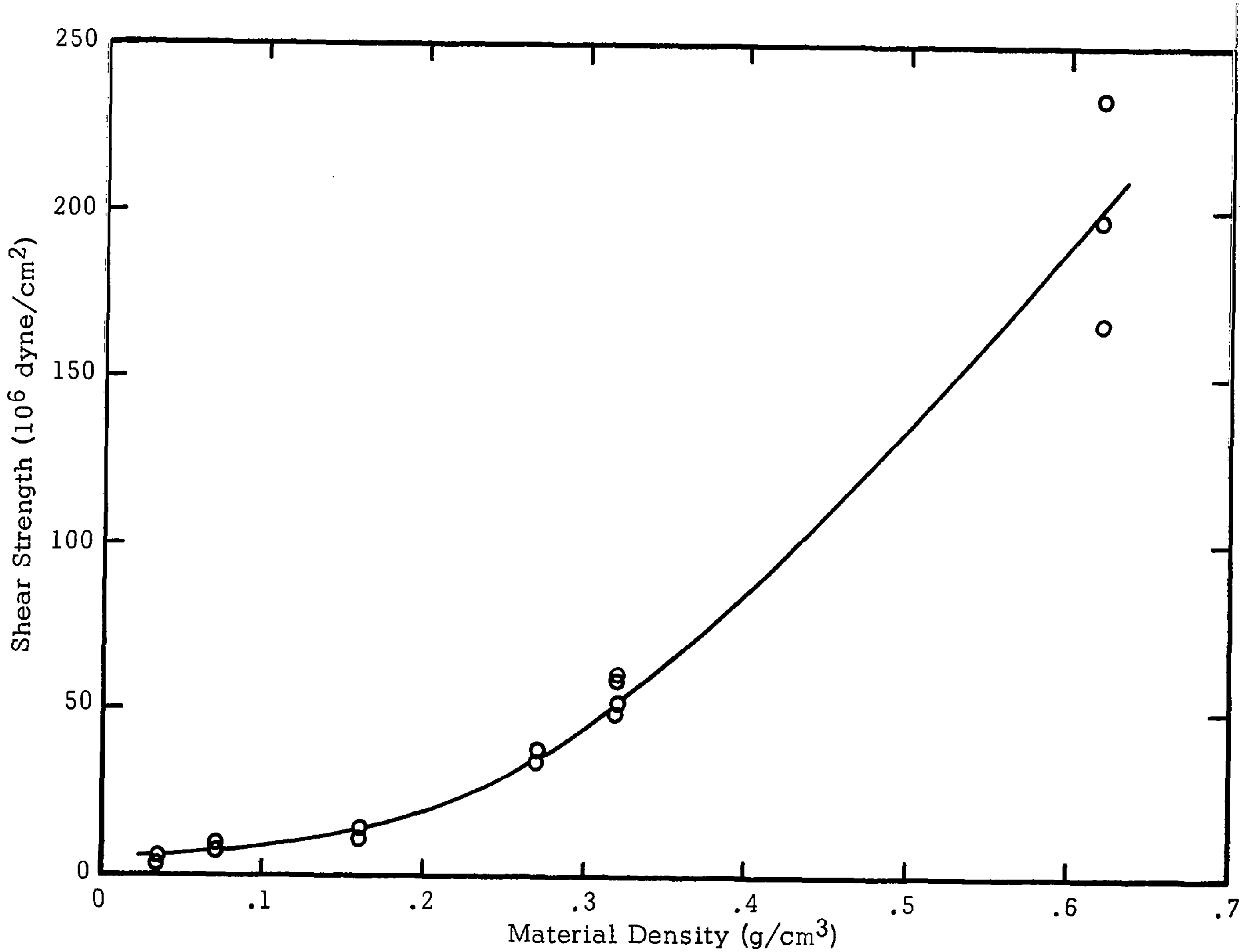


Figure 3. Shear strength as a function of material density for rigid polyurethane foams.

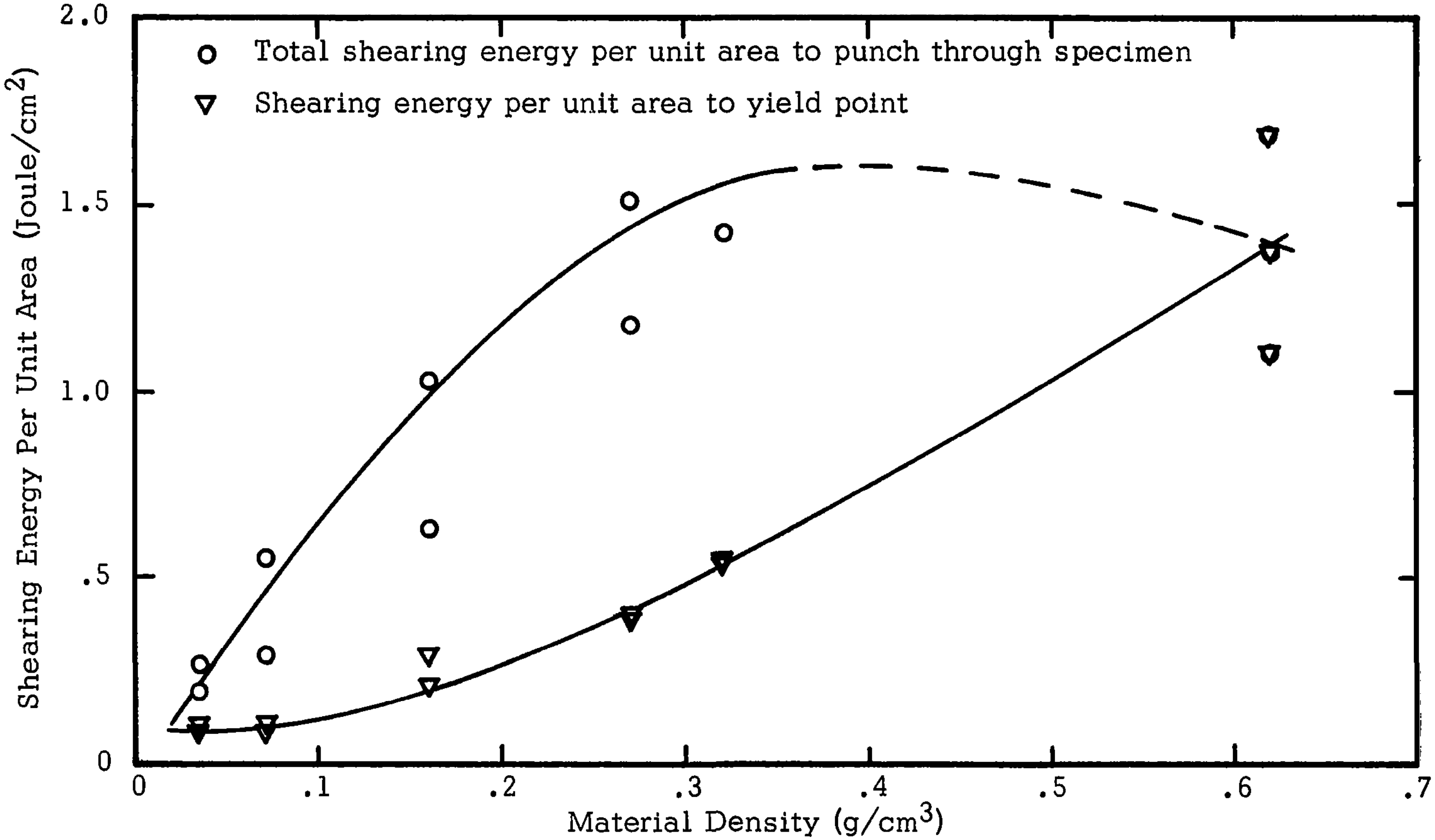


Figure 4. Total shearing energy per unit area required to punch through a specimen and shearing energy per unit area used to the specimen yield point, as functions of material density for rigid polyurethane foams.

RESULTS

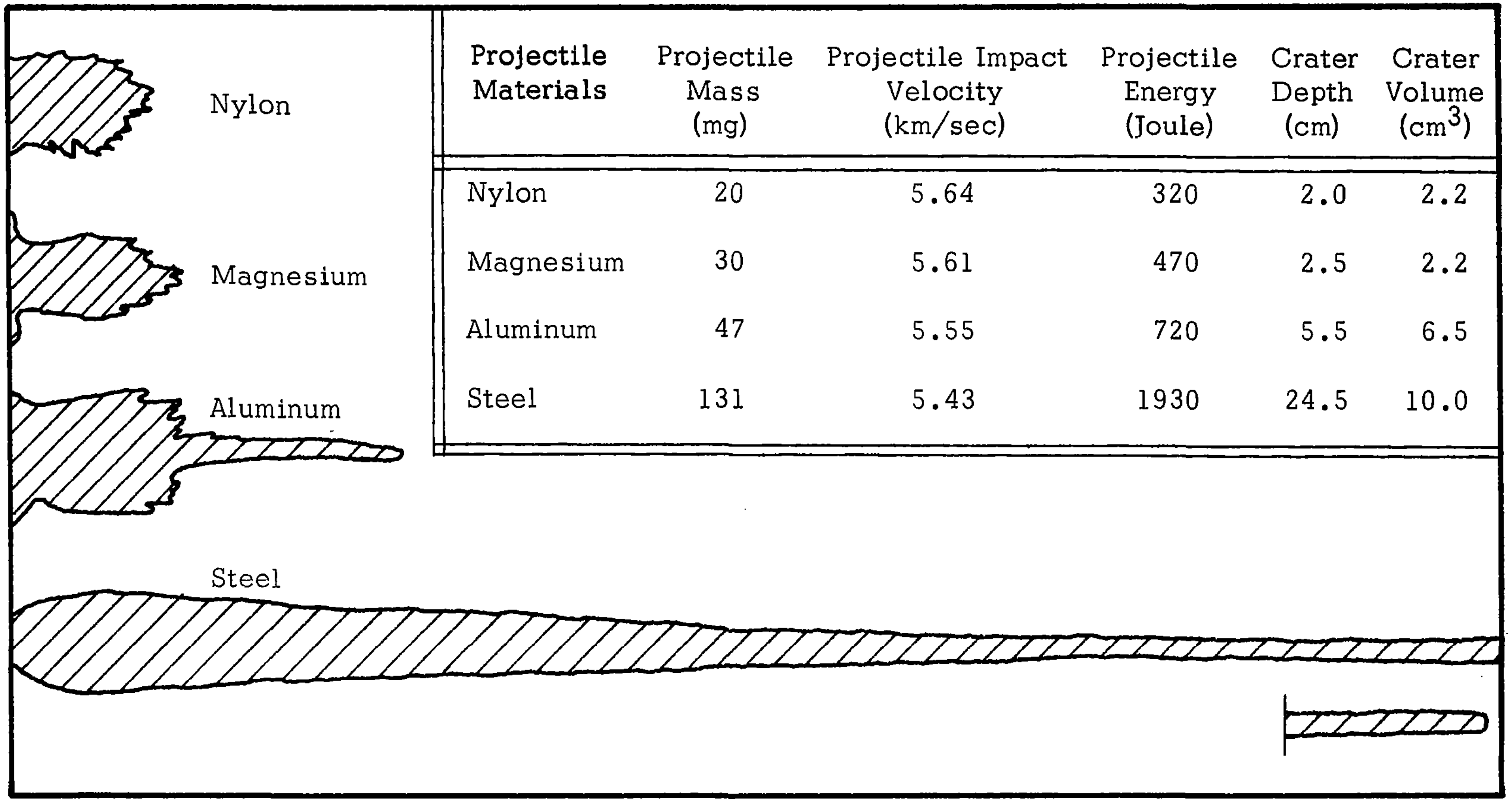
Crater Shape

General variations in crater shape are illustrated by comparing cross-sections of craters formed in rigid polyurethane foams of various densities and craters formed with projectiles of different materials. Figure 5 compares the shapes of craters formed in a foam of density 0.32 g/cm^3 by 1/8-inch diameter projectiles of nylon, magnesium, aluminum and steel. This sketch shows that crater depth is approximately proportional to projectile mass and thus to projectile momentum. The jagged crater walls with nylon, magnesium, and aluminum projectiles seem to indicate that the projectiles were fragmented. The smooth walls of the crater formed by the steel projectile seem to indicate that the projectile remained intact. Figure 6 compares the shapes of craters formed in foams of densities 0.16, 0.27, 0.32, and 0.62 g/cm^3 by 1/16-inch diameter steel projectiles. Of interest in this sketch is the change in crater depth between targets of densities 0.16 and 0.27. This difference in shape suggests a possible change in cratering mechanism. Data concerning projectile velocity, mass and energy; and crater depth and volume, are tabulated in Figures 5 and 6.

Crater Size

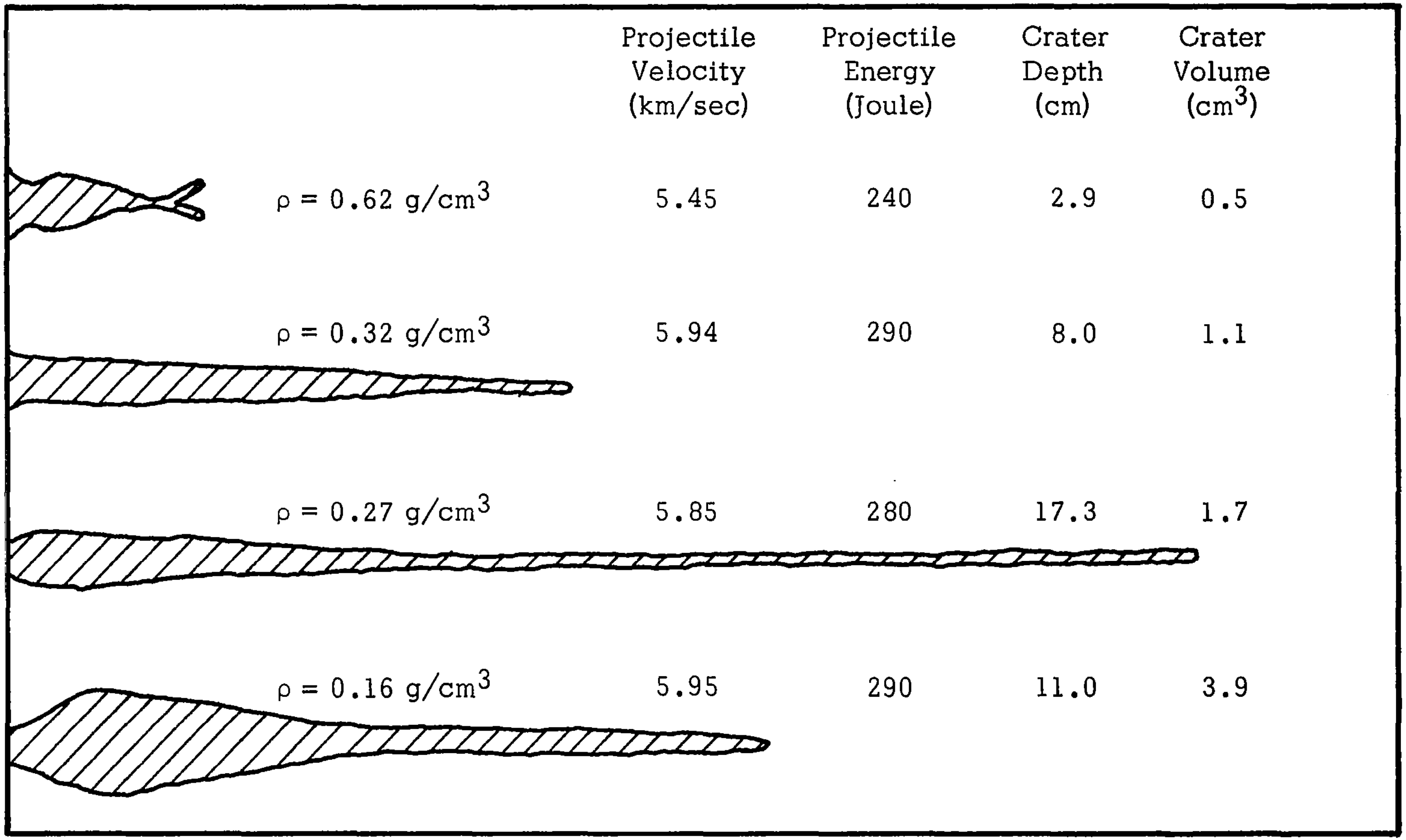
The size, or volume, of a crater is naturally dependent upon the density of the target material. As a more consistent method of comparing size with other factors, the target mass displaced by the crater (the product of target density and crater volume) is considered. Figure 7 shows target mass displaced per unit of energy as a function of target density for the impact of aluminum, steel, nylon and magnesium projectiles into rigid polyurethane foams. Best-fit straight lines, obtained by the least-squares method, are drawn through the data points. The vertical positions of the lines might be considered as a measure of the cratering efficiency of the projectile material; aluminum projectiles are thus most efficient, and steel projectiles are least efficient. The slopes of the lines are governed by changes in target material properties which change as the density changes. Shear strength is considered to be important in this regard and, as shown in Figure 3, it increases non-linearly with target density.

Values of target mass displaced per unit of energy, or cratering efficiency, were calculated for craters formed by aluminum, nylon, magnesium, and steel projectiles into foamed-glass and flexible polyurethane



Projectile Materials	Projectile Mass (mg)	Projectile Impact Velocity (km/sec)	Projectile Energy (Joule)	Crater Depth (cm)	Crater Volume (cm^3)
Nylon	20	5.64	320	2.0	2.2
Magnesium	30	5.61	470	2.5	2.2
Aluminum	47	5.55	720	5.5	6.5
Steel	131	5.43	1930	24.5	10.0

Figure 5. Sketch showing the actual shapes and sizes of craters formed in rigid polyurethane foam of density 0.32 g/cm^3 by 1/8-inch diameter projectiles of different materials.



	Projectile Velocity (km/sec)	Projectile Energy (Joule)	Crater Depth (cm)	Crater Volume (cm^3)
$\rho = 0.62\ g/cm^3$	5.45	240	2.9	0.5
$\rho = 0.32\ g/cm^3$	5.94	290	8.0	1.1
$\rho = 0.27\ g/cm^3$	5.85	280	17.3	1.7
$\rho = 0.16\ g/cm^3$	5.95	290	11.0	3.9

Figure 6. Sketch showing the actual shapes and sizes of craters formed in rigid polyurethane foams of various densities by 1/16-inch diameter steel projectiles having a mass of 16.3 mg.

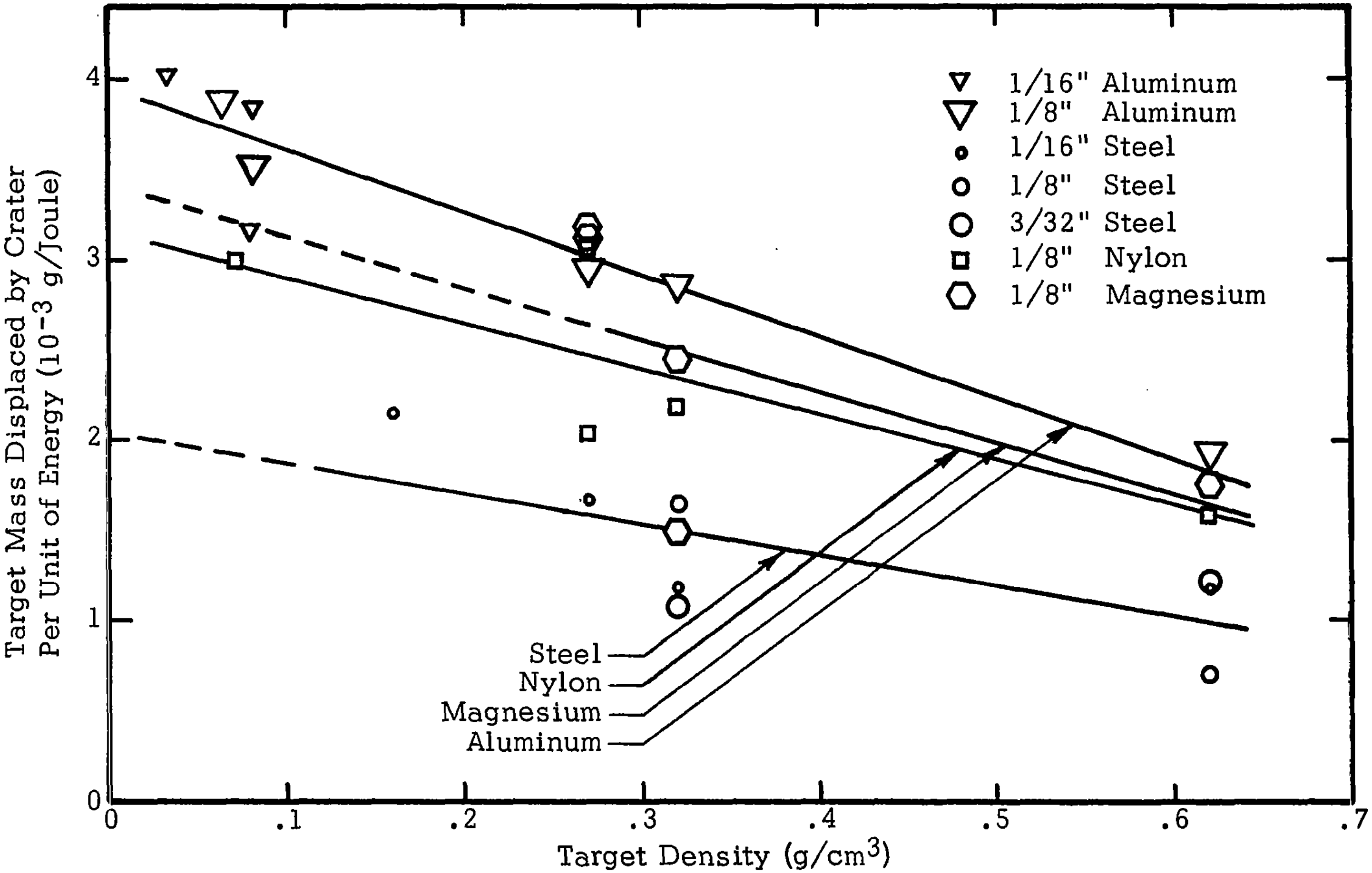


Figure 7. Target mass displaced per unit of energy as a function of target density for the impact of aluminum, steel, nylon and magnesium projectiles into rigid polyurethane foams.

foam targets. These values are given in Table II. They are averages of at least four craters with each projectile and target combination.

TABLE II

AVERAGE VALUES OF CRATERING EFFICIENCY FOR SEVERAL PROJECTILE-TARGET COMBINATIONS

Projectile	Cratering Efficiency (g/Joule)	
Material	Foamed-Glass Targets	Flexible Polyurethane Foam Targets
Nylon	5.2×10^{-3}	0.57×10^{-3}
Aluminum	4.3	0.59
Magnesium	3.6	0.60
Steel	3.0	0.76

Cratering efficiency has been related to the energy used in shearing. It was found that for targets of rigid polyurethane foam and foamed glass, target mass displaced by the crater per unit of energy is a linear function of total shearing energy; the relationship being approximated by the equation

$$CE = d - 1.0\, E_{total} \qquad (1)$$

where CE = Cratering efficiency
E_{total} = Total energy to shear
d = A constant for each projectile material.

It was also found that cratering efficiency is a non-linear function of the shearing energy required to yield; this relationship being

$$CE = \frac{e}{1 + 2.0\, E_{yield}} \qquad (2)$$

where CE = Cratering efficiency
E_{yield} = Shear energy to yield
e = A constant for each projectile material.

Target Shear Strength Considerations

Sorensen* established, by dimensional analysis methods, relationships correlating target and projectile properties and parameters. These relationships concern craters formed in metals by projectiles of the same or different metals.

$$\frac{V}{V_o} = 0.12 \left(\frac{\rho_p}{\rho_t}\right)^{1/2} \left(\frac{\rho_p v^2}{S_t}\right)^{0.845} \quad (3)$$

and

$$\frac{p}{d} = 0.311 \left(\frac{\rho_p}{\rho_t}\right)^{1/6} \left(\frac{\rho_p v^2}{S_t}\right)^{0.282} \quad (4)$$

where

V	=	Crater volume
V_o	=	Projectile volume
ρ_p	=	Projectile density
ρ_t	=	Target density
v	=	Impact velocity
S_t	=	Target shear strength.

On the basis of these relationships, the data concerning cratering in low-density materials were reduced and plotted with V/V_o and p/d on the ordinate as functions of $\left[(\rho_p/\rho_t)(\rho_p v^2/S_t)\right]$ on the abscissa. Data for the ratio V/V_o are shown in Figure 8, and those for p/d are shown in Figure 9. Individual data points are shown in Figures 8 and 9 for rigid polyurethane foams, but are omitted for flexible polyurethane foam, foamed glass and natural pumice.

For the volume relationship, it was found that

$$\frac{V}{V_o} = c\left[\left(\frac{\rho_p}{\rho_t}\right)\left(\frac{\rho_p v^2}{S_t}\right)\right]^{1/2} \quad (5)$$

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* Sorensen, N. R., "Systematic Investigation of Crater Formation in Metals," Seventh Hypervelocity Impact Symposium Proceedings, Vol. VI, p 281, 1965

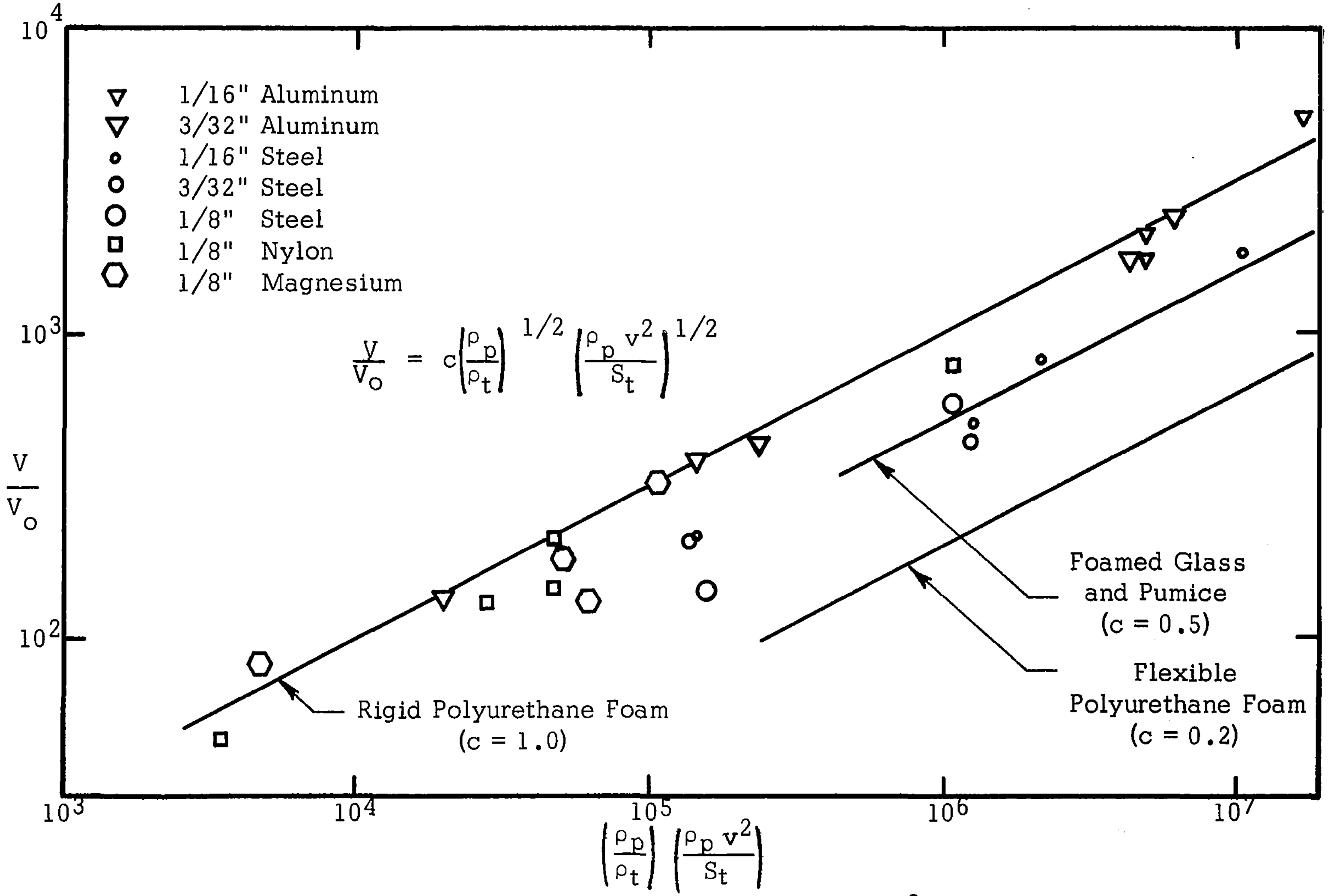

Figure 8. Log-log plot showing V/V_o as a function of $(\rho_p/\rho_t)(\rho_p v^2/S_t)$ for craters formed in rigid and flexible polyurethane foams, foamed glass, and pumice by aluminum, steel, nylon and magnesium projectiles. Individual data points are shown only for rigid polyurethane foam.

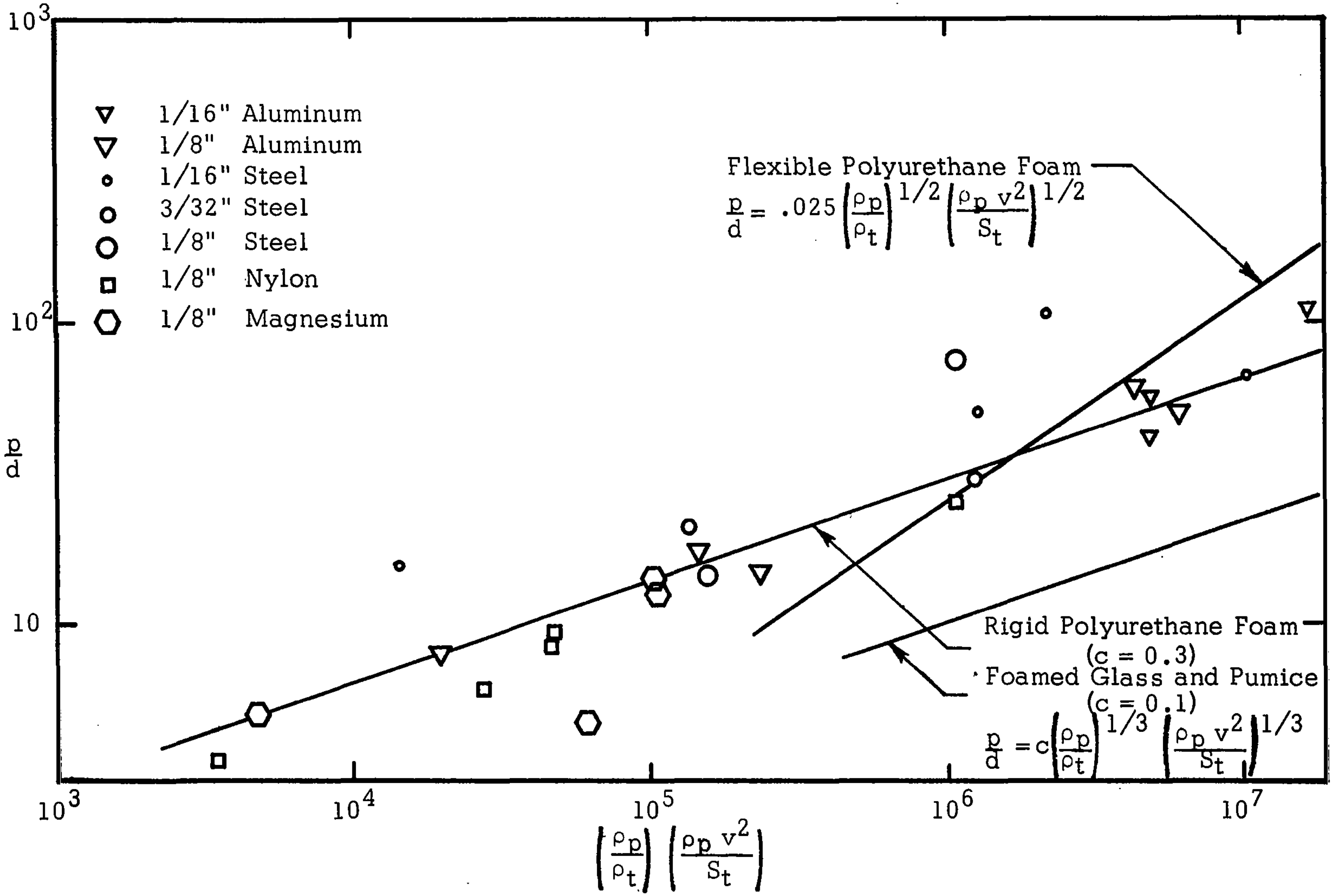

Figure 9. Log-log plot showing p/d as a function of $(\rho_p/\rho_t)(\rho_p v^2/S_t)$ for craters formed in rigid and flexible polyurethane foams, foamed glass, and pumice by aluminum, steel, nylon, and magnesium projectiles. Individual data points are shown only for rigid polyurethane foam.

where

c = a constant for each target material.

Values for c are 1.0 for rigid polyurethane foam, 0.2 for flexible polyurethane foam, and 0.5 for foamed glass and natural pumice. The data agree well with these equations with the steel data showing the most scatter. This relationship indicates that crater volume is proportional to projectile momentum and to $(1/\rho_t S_t)^{1/2}$.

For the depth relationship, it was found that for rigid polyurethane foam, foamed glass, and natural pumice targets

$$\frac{p}{d} = c\left[\left(\frac{\rho_p}{\rho_t}\right)\left(\frac{\rho_p v^2}{S_t}\right)\right]^{1/3} \qquad (6)$$

c being 0.3 for rigid polyurethane and 0.1 for foamed glass and natural pumice. For flexible polyurethane

$$\frac{p}{d} = 0.025\left[\left(\frac{\rho_p}{\rho_t}\right)\left(\frac{\rho_p v^2}{S_t}\right)\right]^{1/2} \qquad (7)$$

CONCLUSIONS

The shape and size of a crater formed in a low-density material vary considerably with different projectile-target combinations. In rigid polyurethane foams, the cratering data which compare target mass displaced per unit of energy with target density show that steel projectiles are less efficient (by a factor as low as one-half) than aluminum, magnesium, or nylon projectiles. With foamed-glass targets, approximately the same results are obtained. This suggests that projectile properties, perhaps strength, are important in this regard.

Target shear strength is seen to be a factor in correlating data from the various target and projectile combinations investigated. Plots of dimensionless relationships showing V/V_o and p/d as being equal to

$c\left[(\rho_p/\rho_t)(\rho_p v^2/S_t)\right]^b$ show consistency in the data from each type of target material. However, for the volume relationships, different coefficients were found for the different targets. Different coefficients and exponents were found for the penetration data. This does not agree with similar relationships with cratering in metals in which c and b remain constant for all projectile-target combinations.

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