Hypervelocity Impact in Thin Sheets and Semi-Infinite Targets at 15 km/sec

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Pyrex spheres (0.15-mm diam) accelerated to a velocity of 15 km/sec by a plasma rail gun were used to produce holes in thin stainless steel and aluminum targets. The velocity was measured by time of flight, using a photomultiplier to detect the time at which a thin target was penetrated. The sphere diameter was measured by extrapolating the hole size in thin targets to a zero thickness target and arguing that that is the projectile diameter. The experimental hole diameters in thin targets were proportional to the velocity to the 0.2 power, and target thickness to the $\frac{2}{3}$ power. Also, the 15 km/sec spheres were used against 2014 T6 and 1100 aluminum semi-infinite targets to measure the crater size and obtain an indication of the effect of strength at the above velocity.

I. General Discussion

MUCH literature exists on the subject of many different types of hypervelocity accelerators. Two of the problems encountered with these accelerators are 1) to achieve a high velocity in a useful size projectile; and 2) to know the projectile conditions at impact.

The approach discussed in this paper makes use of a rail gun plasma accelerator to drag the projectile to high velocity, and is related to an approach developed by Scully,[1] and to some earlier work by the author.[2] The rail gun accelerator is shown in Fig. 1. It uses copper rails 1 cm in width, separated by 1 cm, and 20 cm in length. The pyrex projectiles are placed in the center of a 1-cm^3 block of styrafoam located 5 cm from the end of the rails. The arc begins at the flasher at the breech of the gun and proceeds down the rails such that the system is near peak current at the time the plasma front reaches the projectiles. The projectiles and plasma proceed out the gun into a vacuum chamber where the plasma is cooled by baffles and most of the debris is stopped by a detonator-driven shutter. The projectile velocity is measured by the time it takes for the projectiles to puncture holes in the target foils, as seen by photomultipliers. The time that the projectiles leave the gun is known from flash x-ray studies.

Some ablation of the projectiles is expected from the plasma stream. The projectile size at impact is measured by measuring the hole size in several thicknesses of target foils and extrapolating to zero thickness.

II. Discussion of Experimental Data

Thin Stainless Steel Penetration Data

Table 1 shows a summary of the stainless steel, thin-sheet experimental data. In every case the number shown is an average of the two largest holes found in the stainless steel target sheet. The pellets in all cases were initially 0.006-in.-diam pyrex. The velocities are about 15 km/sec. One final experiment was directed toward a velocity of 10 km/sec. Two values are shown for the hole diameter (H^* and H) where H^* is the diameter of the open area and H is the diameter at the peak of the crater lip (see Fig. 2). (For very thin targets, these values are essentially identical.) As the sheet thickness approaches the point of incipient penetration, these two numbers become increasingly different and, in fact, the open area of the hole can decrease. It is simpler to correlate the data concerning the hole diameter using the diameter of the crater lip since it joins smoothly with the infinite target data.

In the case of thin targets, craters which are within one-crater-diameter of the honeycomb edge which supported the sheet are not included in the data. Among the possible reasons is the fact that the support causes the sheet to appear thicker and results in holes which are larger than predicted.

Figure 3 shows the data plotted versus the target sheet thickness to the $\frac{2}{3}$ power ($T^{2/3}$).

Thin Aluminum Penetration Data

Table 2 shows a summary of the aluminum thin-sheet penetration data. The data shown are the average of the two largest holes, omitting those holes within a diameter of the honeycomb support. The pellets are initially 0.006 in. diam. Hole sizes include H^* which is the open area diameter and H which is the diameter across the crater lip. (For targets less than 0.005 in. thick these diameters are indistinguishable.) Figure 4 shows the data plotted vs $(T/D)^{2/3}$.

Several shots were done using 1100 and 2014 T-6 aluminum semi-infinite targets. The results are shown in Table 3 and Fig. 4. They fit existing correlations fairly well, although it would appear that at these higher velocities the difference between the 1100 and 2014 T-6 may be decreasing over that observed at lower velocities. As discussed in the theory section, the difference in strength of the two alloys is expected to cause a difference in crater size. This difference can be seen at 15 km/sec, but appears less than expected.

If anything, the slope of the curve of P/D (ratio of penetration to projectile diameter) appears to be less than proportional to $(v/C)^{2/3}$.

III. Theory of Hypervelocity Penetration

Several of the semi-infinite target penetration equations are discussed, including the importance of target strength.

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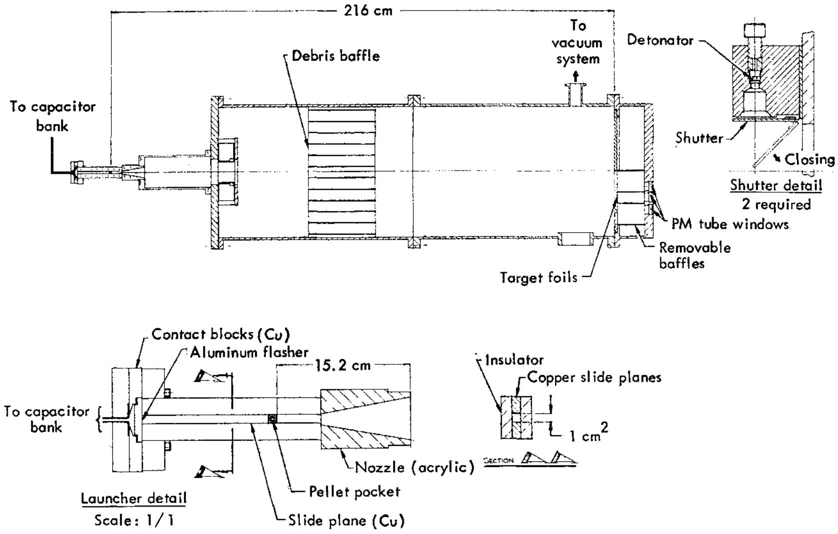

Fig. 1 Hypervelocity rail gun accelerator assembly.

An equation for predicting the hole size made in thin sheets was developed by requiring the equation to fit known end point conditions. This equation is compared with other equations which have been used.

Charters[3] has developed a simple model for penetration in which he argues that one-half of the energy of the incoming projectile is transferred to an expanding fluid shell whose expansion is resisted by the deformation stress S. Then,

$$\int_0^P S \times 2\pi P^2 dP = \frac{1}{4} mv^2 \quad (1)$$

or

$$S = 3/8\Pi(mv^2/P^3)$$

or this can be rewritten as

$$P/D = \tfrac{1}{2}(\rho_P v^2/2S)^{1/3} \quad (2)$$

where P = depth of penetration, ρ_P = density of the projectile, D = the projectile diameter, and v = projectile velocity.

One of the most commonly used empirical penetration equations is the Ames equation,[3]

$$P/D = 2.28(\rho_P/\rho_t \cdot v/c)^{2/3} \quad (3)$$

where c is the longitudinal sound velocity.

Equations (2) and (3) are similar. For similar targets and projectiles, they will be identical if

$$S = E/48 \quad (4)$$

where E is Young's modulus.

Since strength for pure materials is in general roughly proportional to E[4] this would appear reasonable for pure materials. (Dunn[5] has suggested a hypervelocity penetration correlation with the shear modulus.) A difficulty is that the strength required to make the equation fit the data is many times the values observed statically. Strength does decrease the hole diameter, as has been observed using 2014 T-6 aluminum versus 1100 aluminum (see Fig. 5).

Sorenson[6] has correlated much of the hypervelocity impact data to velocities of 0.7 cm/μsec including the effect of shear strength, using either

$$V/V_0 = 0.12(\rho_P/\rho_t)^{1/2}[\rho_P(v^2/S_t)]^{0.845} \quad (5)$$

or

$$P/D = 0.311(\rho_P/\rho_t)^{0.167}[\rho_P(v^2/S_t)]^{0.282} \quad (6)$$

where V = crater volume, V_0 = initial pellet volume, and S_t = shear strength of the target.

These equations are also illustrated in Fig. 5. The correlation is not as good with projectiles and targets of different materials. A number of other hypervelocity penetration equations for semi-infinite targets have been developed with

Table 1 Stainless target data[a]

	Target thickness, in.												
	0.0005		0.001		0.002		0.005			0.0105			
Shot no.	H	V, km/sec	H	V, km/sec	H	V, km/sec	H*	H	V, km/sec	H*	H	V, km/sec
48	6.83		10.1	16	13.81							
49	7.13		10.7	16	14.2							
51	8.37	13	8.88	15	13.07	15, 17	15.8	21.2	16			
54	7.65	13	10.5	14	14.8	15, 16						
56	7.71	13			14.46	15, 16						
58	8.5	15.6			14.62	15, 16	14.2	19.2	14.1			
59					12.65	15						
62			11.6		14.2					11.3	20.9	
66			9.2	16.5	13.2	16.0						
67										12.9	22.5	14.5
68										12.6	23.5	15.1
71			11.7	16.6			13.1	18.0	15.9	12.1	22.7	15.9
76			9.2	10.5			13.3	16.4	11			

[a] Note: All hole diameters are in mils.

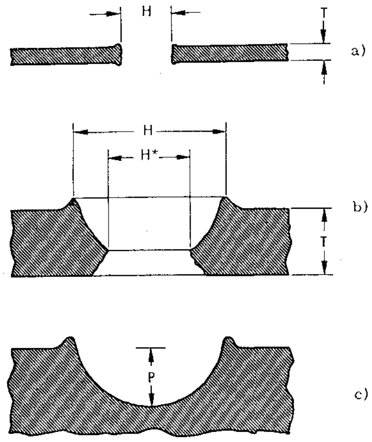

Fig. 2 Cutaway drawings showing typical craters. a) In "thin" target; b) near incipient penetration point; c) in semi-infinite medium.

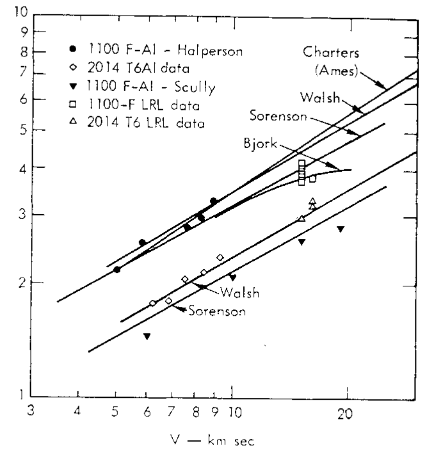

Fig. 3 Hypervelocity penetration in semi-infinite aluminum targets. LRL data and data of Scully multiplied by 1.07 to compensate for glass projectiles.

the assistance of computer calculations. The calculations of Walsh and those of Bjork, reported by Halperson[7] are shown on Fig. 5, together with some of Halperson's experimental values.

We have developed an equation to predict the hole diameters produced by hypervelocity pellets striking thin plates. The approach taken in developing this equation is to require the equation to fit the following limiting conditions:

1) For an infinitely thin plate, the hole diameter H is equal to the pellet diameter D.

2) For an infinitely thick plate (i.e., a semi-infinite solid), the craters produced are approximately hemispherical. At the point where thin plates become "semi-infinite" (i.e., where a thin plate is just barely perforated by a pellet), the crater diameter should equal twice the plate thickness T. Furthermore, the equation developed should agree at this point ($H - 2T$) with an equation used to predict hole diameters in semi-infinite solids.

Finally, the equation was required to fit existing hypervelocity data, which meant that H/D must be approximately proportional to $(T/D)^{2/3}$. This relation was also assumed true at higher velocities.

An equation developed by Charters and Summers[3] and often called the Ames equation was taken as the basic equation [Eq. (3)]. It gives the penetration depth P of a pellet striking a semi-infinite solid. For hemispherical craters with $H = 2P$, Eq. (3) becomes

$$H/D = 4.5(\rho_P/\rho_t)(v/c)^{2/3} \tag{7}$$

where ρ_P is the density of the pellet and ρ_t is the density of the target. Assume an equation of the form

$$H/D = A(\rho_P/\rho_t)^x(v/c)^x(T/D)^{2/3} + 1 \tag{8}$$

At the point of incipient penetration $H = 2T$, and neglecting the 1,

$$H/D = \mathbf{A}(\rho_P/\rho_t)^x(v/c)^x(\tfrac{1}{2})^{2/3}(H/D)^{2/3} \tag{9}$$

Since this must equal Eq. (7), $x = \frac{2}{9}$ or 0.22 and $A^3 = 2^2 \times 4.5$ or $A = 2.6$.

With the aforementioned limiting conditions, the following equation results for thin plate penetration:

$$H/D = 2.6[(\rho_P/\rho_t)(v/c)]^{0.2}(T/D)^{2.3} + 1 \tag{10}$$

The experimental data as shown in Figs. 6 and 7 fits this equation except that a coefficient of 3.2 rather than 2.7 would give a slightly better fit. A single experiment at a velocity of 1.1 cm/μsec also appears to fit the equation reasonably well.

An alternative equation can be developed using the Eq. (6) by Sorenson[6] as the starting point. The equation for thin sheet penetration then becomes

$$H/D = (\rho_P/\rho_t)^{0.055}[\rho_P(v^2/s_t)]^{0.01}(T/D)^{2/3} + 1 \tag{11}$$

This indicates that the hole diameter is not highly sensitive to the strength, but for materials of unusually high or low strength it should be considered.

IV. Experimental Technique

Some of the principles involved in the original design choices are discussed briefly.

The most convenient expression for the force on the arc in a rail gun is $F = \frac{1}{2}L'I^2$. The rate of change of the inductance (L') in a gun can be simply measured and, knowing the current, (I) the force on the arc is known. The peak current is $I^2 = V^2[C/(L_B + L_G)]$, where L_B is the bank inductance, L_G is the gun inductance and C is the bank capacitance. The pressure is then

$$P_{\text{peak}} = [L'/(L_B + L_G)](V^2C/2)(1/A) = [L_G/(L_B + L_G)](E_s/V)$$

In other words, the pressure times the volume of the gun equals the ratio of gun inductance to the total inductance

Table 2 Aluminum target data[a]

	Target thickness, in.													
	0.001		0.002		0.005			0.010			0.020			
Shot no.	H	V, km/sec	H	V, km/sec	H^*	H	V, km/sec	H^*	H	V, km/sec	H^*	H	V, km/sec	
55	11.55	16.2	14.02	15.0	19.7	27.5	15.0							
59			15.58	15	12.6	20.0	15							
73			15.1	15	11.8	20.0	15	20.8	35.2	15	17.8	32.8	15	
75			15.3					23.0	35.0					

[a] Note: All hole diameters are in mils.

Table 3 Semi-infinite target data

Shot no.	1100 Al: Hole sizes P_1	P_2	P_{av}	V, km/sec	2014 T-6 Al: Hole sizes P_1	P_2	P_{av}	V, km/sec
49					15.9	15.7	15.8	16
54	18.7	18.5	18.6	15				
57	19.84	15.54	17.7	16	15.56			16
58	19.76	19.58	19.7	15				
59	20.16	17.80	19.0	15				
67	18.53	16.29	17.4	15	14.19	13.61	13.9	15

times the total system energy (E_s). The rate of change of inductance with length, neglecting skin effects for a square gun, should be equal to μ, 12 nH/cm. For a 20-cm gun with a bore $\frac{3}{8} \times \frac{3}{8}$ in., the inductance was measured to be 145 nH, or 7.3 nH/cm. This gun was used with a capacitor bank having 1870 μH at 20 kv with 4.3-nH inductance. Peak pressure at the time the arc is exiting the gun is then about 0.2 Mbar.

The pellet acceleration process involves the drag acceleration of the pellets by the high-velocity plasma. Pellets accelerated in a freestream typically have a large dispersion, of the order of 100–200 mrad, so many pellets are required in order to have a few exit from the end. A mass of plasma many times that of the pellets is required since the size of the exit tube must be many times the diameter of the pellets. Thus the system efficiency is very low. The plasma can be derived from two sources 1) an exploding wire or foil which is used to initiate the arc, and 2) from ablation of the rails. In practice, the rail ablation is so enormous that any mass addition from an exploding foil is negligible. In general, the guns are designed so the peak current occurs at the time the arc reaches the pellets. In other words, the pellets are spaced some distance from the foil which initiates the arc. This permits the system to reach peak current when the arc has reached the pellets.

The ablation or erosion of rails in a rail accelerator is not thoroughly understood. Joule heating seems to contribute part of the effect, although ion bombardment of the surface may also contribute. Copper rails appear to work as well or better than anything else which has been tried. In addition, small diameter rail guns the skin friction of the plasma on the wall can have a large effect.

One approach for studying the velocity of an arc in a rail gun of the type used in these experiments is to write the equations for the arc in a rail gun and include both mass addition and a skin friction coefficient. The equation for the arc in a rail gun becomes

$$d(mv)/dt + 2(C_f/D)(mv^2) = F$$

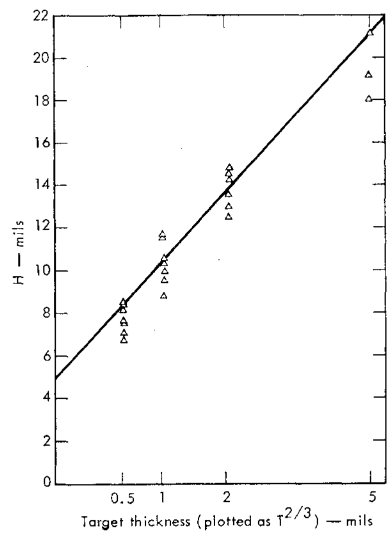

Fig. 4 Hole size in stainless steel targets (showing extrapolation to zero target thickness).

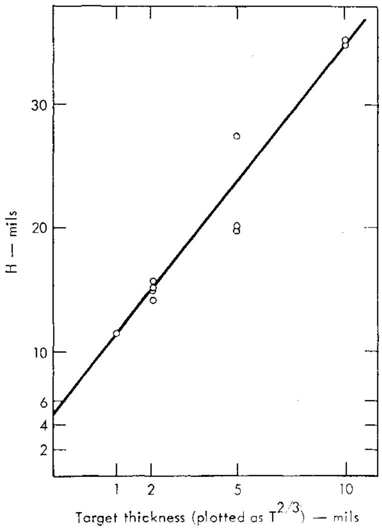

Fig. 5 Hole size in aluminum targets showing extrapolation to zero target thickness.

where m is the mass of the arc, D is the diameter of the channel, C_f is the skin-friction coefficient, and F is the force on the arc $= \frac{1}{2}L'I^2$ (where L' is the rate of change of inductance with length). If the current is assumed to be $I = I_p \sin\Pi t/2r_t$, then the solution is

$$v = \frac{D\Pi}{8r_t C_f}\left[\left(1 + \frac{8r_t L' I_p C_f}{m' D\Pi}\right)^{1/2} - 1\right]$$

where m' is atoms eroded per electron. Some typical values might be $L' = 7.3$ nH/cm $= 7.3 \times 10^{-7}$, $D = 1$ cm, $r_t = 2$ μsec, $C_f = 0.01$, $I_p = 1$ Ma, $m' = 10$ atoms/electron $= 7 \times 10^{-6}$ kg/coulomb, $v = 20[(1 + 0.53)^{1/2} - 1] = 4.8$ cm/μsec. A difficulty is that the velocity does not increase as rapidly as might be expected with any of the above parameters. An increase in both peak current and rise time is probably the simplest approach to still higher velocities. The value of m', the mass addition per electron, may not be a constant either. In actual practice the total plasma cloud does not proceed down the rails with this velocity, but rather has a wide distribution of velocities with a range of about 2–10 cm/μsec.

The actual quantity of material ejected appears to be many times this. The initial density of the first plasma to emerge from the gun is probably about the aforementioned value. The density would be expected to increase and velocity decrease with time. By using a nozzle on the end of the gun, the pellet would see more nearly constant density and constant velocity along its path in the gun. This is because as the pellet moves into the nozzle section, a later more dense part of the plasma column would have reached the nozzle.

The ablation problem is very similar to the re-entry heating problem. The technique used for calculating the thickness ablated is to estimate the heating rate and make a heat balance. Using estimated values for the parameters of the plasma stream, an ablation of the order of one thousandth of an inch is calculated. This would indicate that the pellet

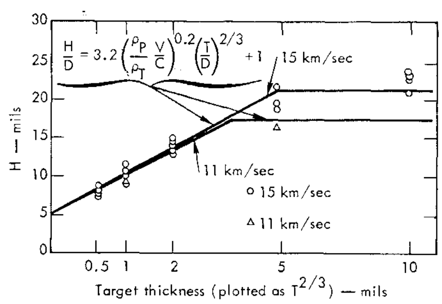

Fig. 6 Hole size in stainless steel targets.

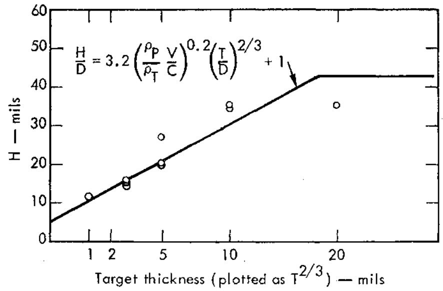

Fig. 7 Hole size in aluminum targets at 15 km/sec.

diameter must be measured at impact and cannot be assumed to be equal to the initial diameter.

A major problem is the measurement of the in-flight projectile size, and several techniques are conceivable for this measurement. Scully[1] has measured the in-flight diameter by the amount of light refracted by the bead. An interesting approach is to activate the beads, accelerate the beads into small containers, and measure the radioactivity of the debris. This was tried with little success. The approach which was finally used to arrive at the diameter of the pellet was to fire the beads through several thicknesses of thin targets and extrapolate the hole size to zero thickness sheet. The hole size in a zero thickness target is assumed to be the pellet diameter.

Two types of pellets have been used at various times, glass beads and pyrex beads. The glass beads gave fairly good results, but with considerable scatter in the data. A fairly large percentage (of the order of 20%) of the beads were misshapen or had air bubbles. One of the primary problems was believed to be that the glass beads broke badly under thermal shock conditions. Experiments to measure bead diameter indicated a mean diameter $\frac{1}{3}$ to $\frac{1}{2}$ the initial diameter, with wide scatter in the data. The LRL Chemistry Department succeeded in making some very uniform pyrex beads. They were made by feeding crushed and sieved pyrex through a plasma torch. The pyrex beads showed no indication of breakage.

The plasma gun output of 400 kjoules (equivalent to about 70 g of HE), a large fraction of which is hot plasma, requires some consideration or the target assembly will be melted. In these experiments, the early hot gases which travel with or ahead of the pellet cloud were cooled by placing an egg-crate type baffle system in the path between gun and target. This baffle system consisted of a square egg crate with openings 1-in. × 1-in. and 18 in. long. To stop the late time debris, a double door was closed by two detonators. The closing time was about 500 μsec. This prevented the late time debris from damaging the targets.

The largest source of error in this experiment is involved in estimating the projectile size. The hole measurements for small values of T/D involves errors like ±5%, while at high values of T/D it could be 10%. Including the extrapolation, it is estimated that the projectile size is known to ±20% or 5 ± 1 mil. Since the projectiles were originally 6 mils, it was not possible for the error to be greater than +1 mil unless particle agglomeration had occurred, and there was no evidence of that. Estimates of projectile velocities are good to better than 5%.

This same approach could probably be used with a larger plasma source to accelerate larger projectiles to similar or perhaps higher velocities. One such plasma source is the Voitenko compressor.[8,9]

References

[1] Scully, C. N. et al., "Electrothermal Guns for Hypervelocity Ballistics Research," *Proceedings of the Seventh Hypervelocity Impact Symposium*, Tampa, Fla., Vol. I, Nov. 1964, pp. 147–186.

[2] Brast, D. E. and Sawle, D. R., "Study of a Rail-type MHD Hypervelocity Projectile Accelerator," *Proceedings of the Seventh Hypervelocity Impact Symposium*, Tampa, Fla., Vol. I, Nov. 1964, p. 187.

[3] Charters, A. C. and Summers, J. L., "Some Comments on the Phenomena of High Speed Impact," *Proceedings of the Decimal Symposium*, U.S. Naval Ordnance Lab., White Oak, Md., 1959.

[4] Gilman, J. J., "Strength of Ceramic Crystals," Monograph 59, 1963, National Bureau of Standards.

[5] Dunn, W. P., "On Material Strength of the Hypervelocity Impact Problem," *AIAA Journal*, Vol. 4, No. 3, March 1966, pp. 535–536.

[6] Sorenson, N. R., "Systematic Investigation of Crater Formations in Metals," *Proceedings of the Seventh Hypervelocity Impact Symposium*, Tampa, Fla., Vol. VI, Nov. 1964, pp. 281–325.

[7] Halperson, S. M., "Comparisons between Hydrodynamic Theory and Impact Experiments," *Proceedings of the Seventh Hypervelocity Impact Symposium*, Tampa, Fla., Vol. V, pp. 235–258.

[8] Sawle, D. R., "Characteristics of the Voitenko High Explosive Driven Gas Compressor," *Astronautica Acta*, Vol. 14, 1964, pp. 393–397.

[9] Voitenko, A. E., "Generation of High Speed Gas Jets," *Soviet Physics Doklady*, Vol. 9, 1966, pp. 860–862.