AN EXPLODING WIRE HYPERVELOCITY PROJECTOR

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INTRODUCTION

In this paper we describe a novel method of accelerating projectiles to hypervelocities by using exploding wires. The hypervelocity projector described is based on ideas acquired and data obtained from exploding wire work carried out at the Naval Research Laboratory [1] in 1957 and from work carried out more recently at Technical Operations, Inc. For background purposes, we propose to describe briefly these early experiments and then to discuss our more recent results.

The primary objective of the early experiments at the Naval Research Laboratory was to heat wires to very high temperatures by depositing in them high electrical power. In the course of these experiments, one geometry was used in which the explosion was confined in solid material or water. A thin Mylar diaphragm was "burned out," and heated gases were permitted to propagate down a small evacuated tube. Very high velocities were observed for the heated wire material propagating down these small-diameter tubes. It was also noted that when the hot wire material impacted with solid surfaces, considerable energy was transferred.

DESCRIPTION OF THE EXPERIMENT

Two years ago at Technical Operations, Inc., we began using this exploding wire experiment to develop a novel hypervelocity gun for ultimately accelerating solid particles to velocities up to 30 km/sec (10^5 ft/sec). The "hypervelocity gun" used in these experiments consists essentially of an electrically exploded wire or foil as the "explosive charge," a water mass as the "breech," and a glass capillary tube as the "barrel." Not only are all parts of this gun cheap and therefore almost as expendable as the projectile itself, but the system has the added advantage of being able to attain very high temperatures through the efficient coupling of a fast-capacitor energy storage system to a metallic conducting wire (or foil) with small radiating surface.

A schematic diagram of the experimental arrangement is shown in Fig. 1. A fine wire (or foil) is mounted across the end of a plastic capillary tube and exploded by discharging the capacitor, C, through it. The capacitor used in this investigation stored 3500 joules at a potential of 120 kv.*

The confined electrical explosion is separated from the accelerator tube and vacuum chamber by a Mylar diaphragm, which contains the explosion for a time approximately equal to the electrical discharge time. The thickness of the Mylar diaphragm was varied according to the experiment being performed. Generally, in this experiment, the diaphragm was made rather thick (about 10 mils) so that it would tear out instead of burn out and would serve as a Sebot to seal the tube, thus preventing the propellant gas from leaking out past the projectile. In some cases, the Mylar disk was used as a projectile with no additional material in the gun. We have had our most spectacular success using this Mylar-disk projectile.

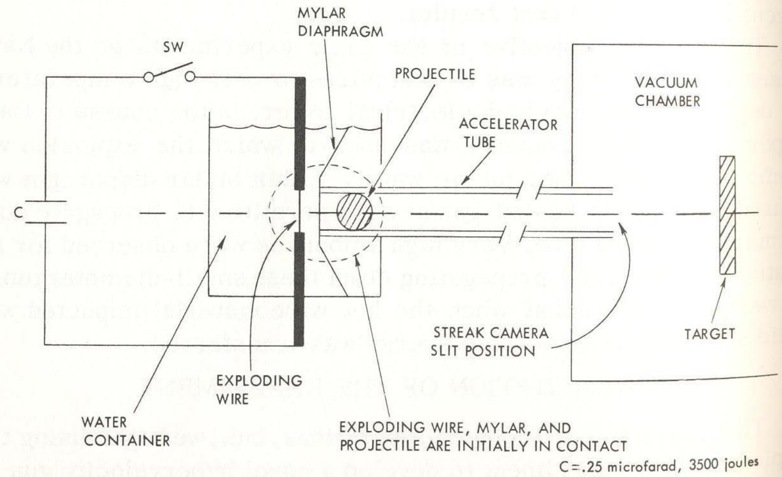

Fig. 1. Schematic diagram of the experimental arrangement.

When a thin Mylar diaphragm ($^1/_4$ to 1 mil thick) is used with no projectile in the gun, the explosion is contained by the Mylar until it burns out, allowing the hot propellant gases to flow down the tube

*Since the data presented in this paper were recorded, the hypervelocity research program at Technical Operations, Inc., has received official support from the U.S. Air Force, Aeronautical Systems Division, Wright-Patterson AFB, Ohio. Under this contract, a new laboratory facility with an electrical energy storage system somewhat larger than that described in this paper has been constructed. The results presented in this paper have been substantiated and extended.

at velocities up to 100,000 ft/sec. A paper cup filled with water has sufficient mass to localize the explosion to the exploding wire until after the projectile has been accelerated down the tube. Water is a good substance for this purpose, since it is an excellent insulator for microsecond times. The accelerator tube is mounted in a larger glass vacuum chamber that contains the target. The streak camera is used to measure the velocity of propagation of the projectiles down the tube to the target. The orientation of the streak camera slit relative to the image of the gun is indicated in Fig. 1.

The Beckman and Whitley Model 339-B Continuous-Writing Streak Camera, used in this experiment, is a research instrument employed in the study of high-speed events. The camera transcribes on 35-mm film a record of the variable density of the illumination that falls upon a slit pattern as a function of time. The film is stationary and is swept by the traveling slit image reflected by a turbine-driven rotating mirror. The image of the event is placed on the slit aperture by the objective lens. The internal relay optics are of first-surface mirror construction and give the highest resolution to the image reflected onto the curved film track by the rotating mirror in the evacuated body of the camera.

The internal optical system of the camera reduces the image by a factor of 2. We are presently using a 3-mil slit, which gives a 1.5-mil image at the film. For this slit, the time resolution at the maximum writing rate of 9.1 mm/μsec is $5 \cdot 10^{-9}$ sec. The energy storage system used in this study stored 3500 joules of energy at 170 kv. The discharge frequency was about 250 kc.

EXPERIMENTAL RESULTS

Figure 2 is a streak picture showing the propellant acceleration down the accelerator tube in the absence of a projectile or target.

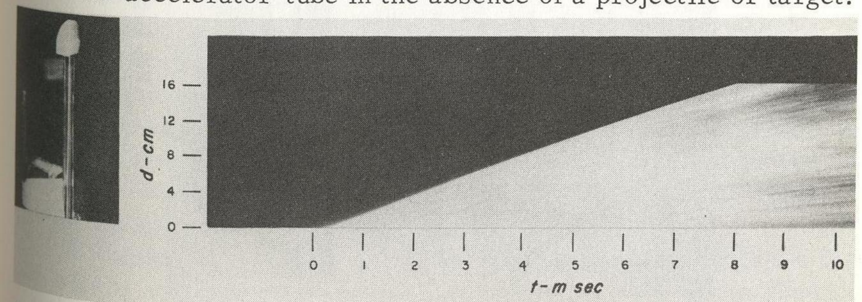

Fig. 2. Streak picture showing acceleration of propellant gas in the accelerator tube in the absence of a projectile.

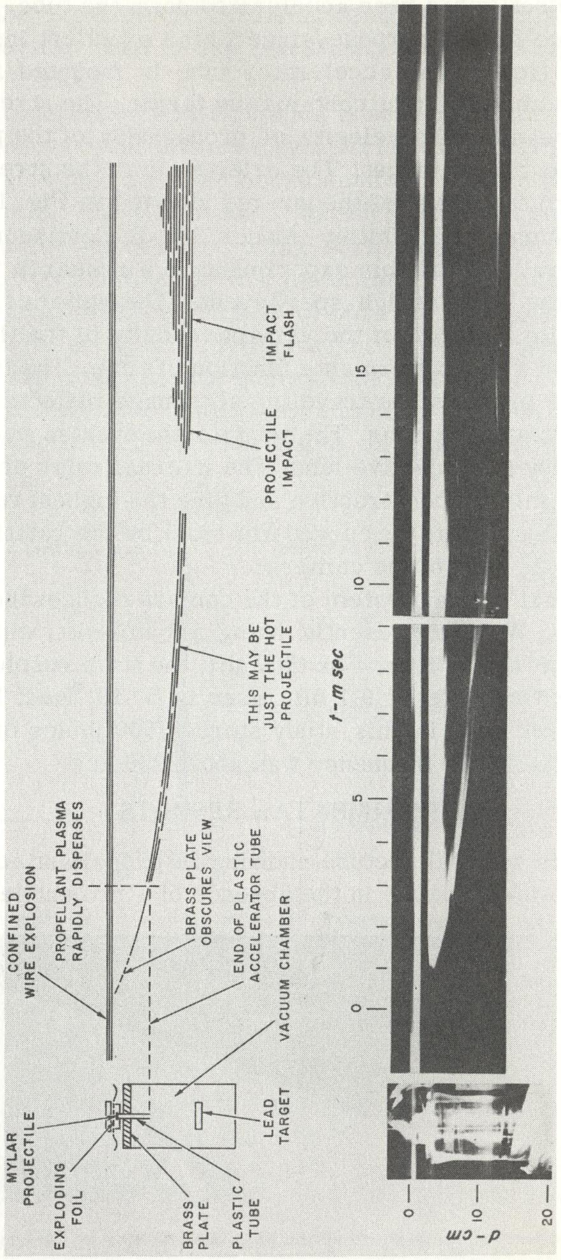

Fig. 3. Streak picture showing acceleration and impacting of an 11.1-mg projectile.

Here we see a still frame picture taken before the accelerator tube run, with an image of the slit superimposed. The streak picture itself illustrates the initial, confined explosion followed by a rapid expansion of the propellant gas down the tube. We estimate an initial propellant velocity of 60,000 ft/sec.

Figure 3 is a streak picture showing the acceleration of an 11.1-mg Mylar disk projectile and the resultant impact of the projectile upon the target. As an aid to understanding the streak picture, we present a schematic diagram indicating the various events that occur. As before, a still frame picture taken before the run is shown, indicating the streak camera slit position.

The streak picture points out the initial confined electrical explosion, the projectile acceleration, and the target impact. After the projectile enters the vacuum chamber, the propellant gases become dispersed. Then the hot projectile becomes visible in the streak picture, followed by its path to the target, and finally its impact on the target. The intense light and the expanding shock from the impact area indicate that the impact flash is quite energetic. Figure 4 is a time-integrating picture of the above test.

In Fig. 5 we show two targets after impacts. Figure 5a presents a target impact that resulted from the impact shown in Fig. 2 in which an 11.1-mg projectile with a speed of 53,000 ft/sec impacted a lead target. The target has been dissected to show the shape of the crater. The crater gives no evidence of projectile breakup.

Figure 5b presents the lead target after a similar shot in which no projectile was in the tube. In this case, only propellant gas and debris hit the target. The target surface was polished up a bit, but no significant damage resulted.

A summary of the experimental data is given in Table 1.* For each shot we have tabulated the projectile mass, projectile velocity, stored electrical energy, estimated projectile kinetic energy, the efficiency of energy coupling between the electrical energy storage system and the projectile, and the target material used. The projectile mass was varied from 0 to 177 mg. As the mass was decreased, the velocity increased from about 4000 ft/sec to 100,000 ft/sec in such a way that the energy coupling efficiency remained about the same (5-10%).

In Figure 6 we compare our data on target impacts with the data of others working in the field. The curve and data points shown in

*More preliminary results were given in an earlier paper [2].

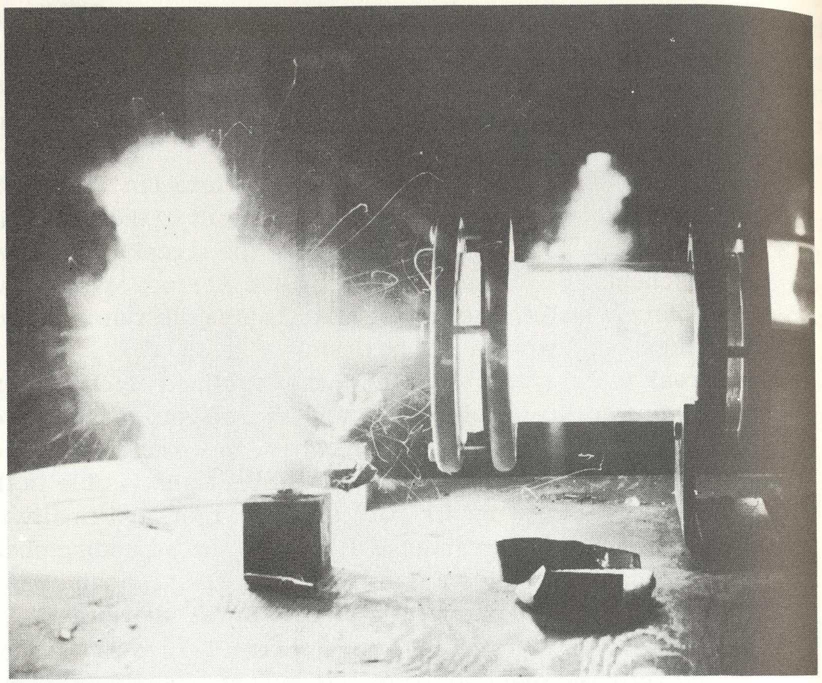

Fig. 4. A time-integrating photograph of the hypervelocity gun during firing.

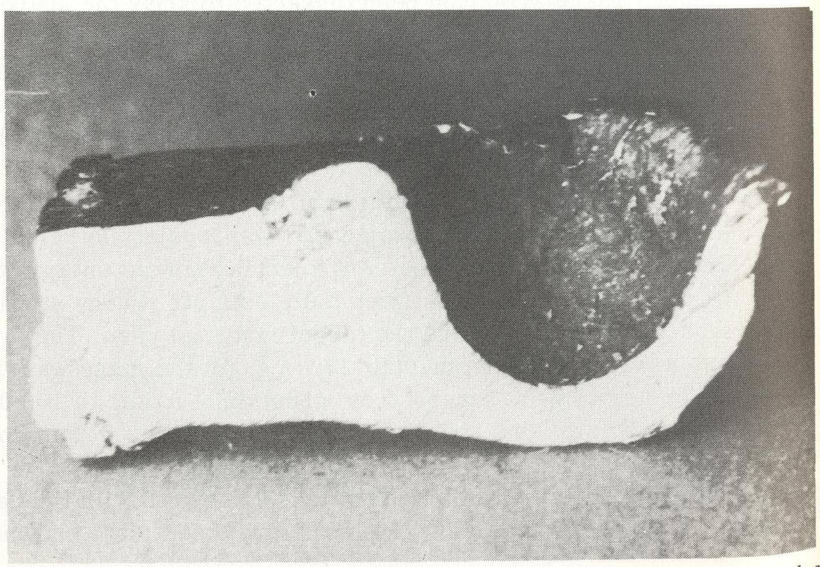

Fig. 5a. Lead target which has been impacted by a 10-mg Mylar projectile with a velocity of 53,000 ft/sec.

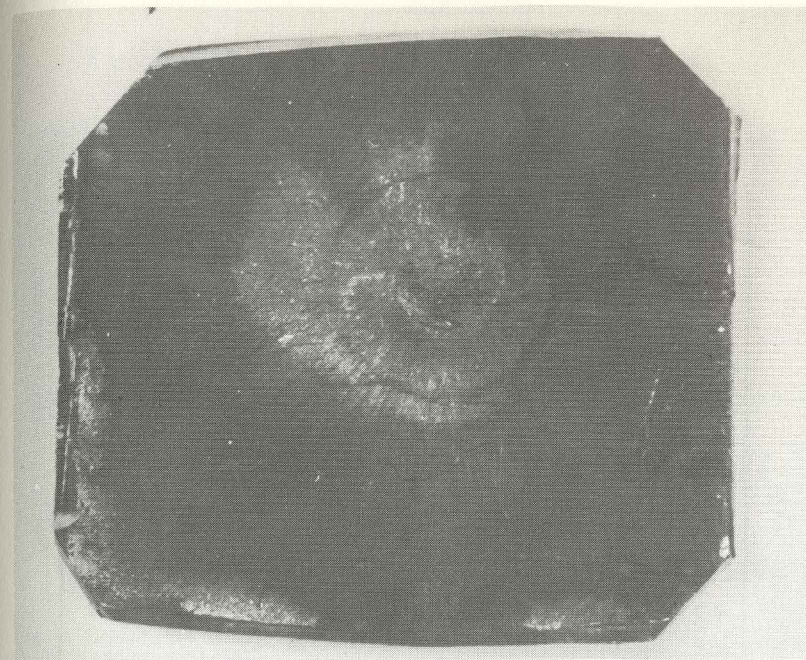

Fig. 5b. Lead target bombarded by propellant gas and debris only.

Fig. 6 (except those marked Tech/Ops) were copied from an article by J. William Gehring and L.G. Richards [3]. The "normalized crater diameter" (crater diameter divided by cube root of projectile mass) is plotted against the projectile velocity for a lead target. The solid curve represents low-velocity data. The dotted curve represents a straight-line extension of the curve. Shown near the curve extension are two data points reported by Gehring at the Third and Fourth Hypervelocity Conferences [3]. These data points were obtained in an experiment in which projectile breakup occurred and a statistical method was used to correlate projectile with craters. Shown as black dots in Fig. 6 are our recent data using Mylar projectiles. The data reported by Gehring were based on the use of steel projectiles. In order to place our data on the curve, we corrected the crater diameter for relative projectile effectiveness, using data by E. P. Palmer [4] in which $\frac{\text{crater volume}}{\text{projectile energy}}$ was plotted as a function of projectile density. We see that the craters resulting from our hypervelocity impacts agree with the data reported by Gehring.

Table I. Hypervelocity Summary

Projectile mass, mg	Projectile velocity cm/sec	Projectile velocity ft/sec	Stored electrical energy, joules	Projectile kinetic energy, joules	Eff. kinetic energy / Electrical energy, %	Target material
177	$1.2 \cdot 10^5$	4,000	2,000	128	6.5	no target
177	$1.2 \cdot 10^5$	4,000	2,000	128	6.5	no target
177	$1.0 \cdot 10^5$	3,300	2,000	90	4.5	no target
177	$1.4 \cdot 10^5$	4,600	3,500	176	5	no target
44.3	$2.1 \cdot 10^5$	7,000	3,500	100	4	no target
44.3	$3.0 \cdot 10^5$	10,000	3,500	205	6	no target
11.1	$8.0 \cdot 10^5$	27,000	3,500	360	10	paraffin
11.1	$7.5 \cdot 10^5$	25,000	3,500	317	9	lead
11.1	$7.0 \cdot 10^5$	23,000	3,500	262	7.5	lead
4.4	$1.6 \cdot 10^6$	53,000	3,500	565	16	lead
4.4	$1.3 \cdot 10^6$	43,000	3,500	372	11	lead
2.2	$1.0 \cdot 10^6$	33,000	3,500	110	4	lead
2.2	$1.3 \cdot 10^6$	43,000	3,500	186	5	lead
1.1	$1.45 \cdot 10^6$	49,000	3,500	115	3	—
0	$1.6 \cdot 10^6$	53,000	3,500	no projectile		—
0	$3.1 \cdot 10^6$	100,000	3,500	no projectile		—
0	$1.8 \cdot 10^6$	60,000	3,500	no projectile		lead

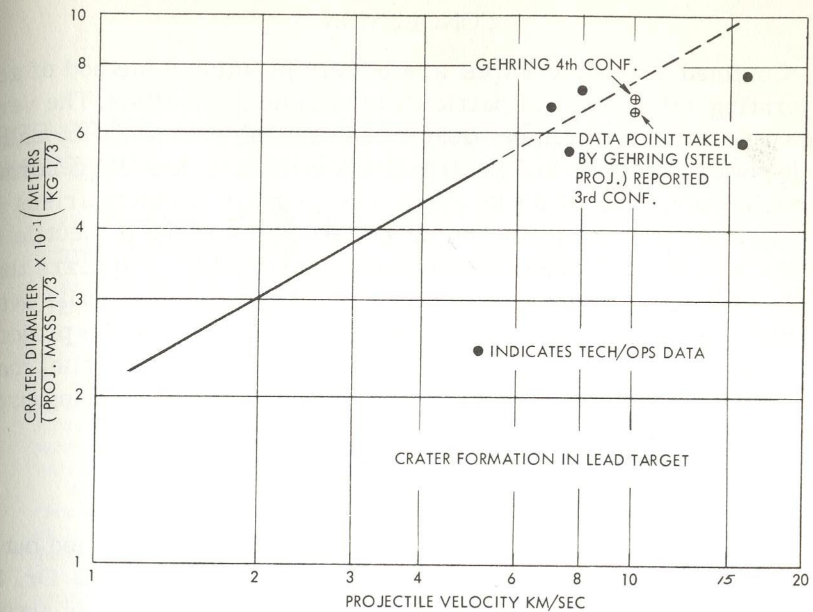

Fig. 6. Crater formation in lead target and comparison of results with those of Gehring and Richards [3].

MECHANISMS OF HYPERVELOCITY ACCELERATION

The data of the Technical Operations, Inc., hypervelocity experiments suggest that two primary mechanisms may be responsible for the attainment of 50,000-ft/sec particles which impact targets as single particles. From the electrical power developed in the explosion [5], we estimate the temperature of propellant gas to be about $1.5 \cdot 10^5\,°K$. This temperature has been confirmed [6] by an analysis of expansion velocity data similar to that shown in Fig. 2.

The high-temperature gas contains sufficient energy density to give an initial acceleration followed by additional acceleration as the hot gas expands and pushes the projectile down the tube. Additional acceleration of the projectile may arise from the vaporization of a thin layer on the rear surface of the projectile. This vaporized projectile material would then add to the propellant gases and provide both further acceleration and some shielding against further vaporization.

Although we need further data to estimate the recoil pressure exerted upon the projectile by the explosion of its rear surface, crude analysis shows that we can expect a substantial effect.

CONCLUSION

Confined exploding wires are a very promising method of accelerating solid material particles to very high velocities. The very high energies and temperatures that can be generated by using high-power, fast-discharge capacitors are sufficient to generate particle velocities of 30 km/sec. The primary problem arises in transferring energy from hot propellant gases to the projectile in such a way that the projectile does not disintegrate. It appears that very high-temperature gases which accelerate the projectile over a relatively long distance, while absorbed radiation on the projectile rear surface both protects and accelerates the projectile, may be the best way of achieving the desired goal of accelerating projectiles to hypervelocities.

ACKNOWLEDGMENTS

The author is indebted to Dr. Paul Richards, who carried out a theoretical analysis of the exploding wire "gun," and Dr. F. Henriques, President of Technical Operations, Inc., for his active support of this work. Mr. Fred Hauser aided in performing the experiments. Mr. Ihor Vitkovitsky of the Naval Research Laboratory worked very closely with the author in carrying out initial experiments at NRL in 1957 and 1958.

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HIGH-SPEED CINEMICROGRAPHIC STUDIES OF ELECTRICALLY EXPLODED METAL FILMS*

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Exploding metal films exhibit a striation phenomenon which has been previously reported [1]. Studies of exploding films of aluminum on a glass substrate indicate that these striations are essentially perpendicular to the apparent current path and become visible early in the discharge as bright transverse regions from which aluminum is rapidly evaporated.

More detailed studies of the formation of these striations have now been carried out with the cinemicroscopic technique [2]. At 25×magnification and at $1.2 \cdot 10^6$ frames/sec an unusual polarized structure can be seen forming during the current flow at the site of artificial scratches on the film. These structures appear essentially identical with those formed in the absence of artificial scratches. These observations will be shown, and the effects of voltage and film thickness upon the striations will be commented upon.

INTRODUCTION

The authors have previously reported studies [1] of the behavior of electrically exploded aluminum films on a glass substrate. In these studies they have described the sequential optical and electrical observations made on the exploding films. Since these experiments form a basis for the present work, they will be described and summarized briefly.

The experiments may be described as follows:

1. The metal films consisted of aluminum, which was vacuum-evaporated onto glass slides (Fig. 1).

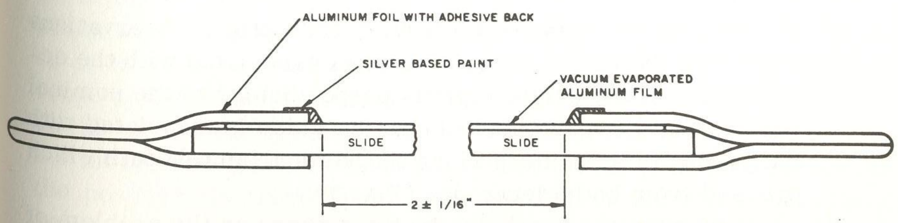

Fig. 1. Aluminum film on glass substrate.

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