METEORETICS AND HYPERVELOCITY STUDIES

Alan K. Hopkins

Directorate of Materials and Processes, ASD

Introduction

Space vehicle missions of long-duration, perhaps years, make the probability of significant collision along the way with one or more meteoroids or micrometeoroids of grave consequence. The potential loss of a multimillion dollar vehicle because of this little understood hazard is sufficient justification for more extensive research.

The probability of a significant impact, one which might cause failure of a vehicle, can be determined only with data from two different sources: (1) Distribution of number, mass, and velocity of natural meteoroids over the orbit of the earth, and (2) Degree of impact damage to be expected from a wide range of particle masses, compositions, and velocities. The first can only be acquired through observations of natural bodies in space, but studies of hypervelocity impact can be performed in the laboratory.

Although knowledge concerning the environment is increasing, and it becomes possible to compute the probability of encounter with particles of various masses, the designer is still faced with the problem of determining an optimum vehicle structure to provide both mission capability and reasonable probability of survival throughout the mission. This can be solved by increased knowledge of hypervelocity impact effects of simulated meteoroids and micrometeoroids at meteoritic velocities. This paper has a two-fold purpose: one, to survey briefly the present knowledge and research completed to date of the environment as it affects the techniques employed in the acceleration of particulate matter to hypervelocities; the other, to survey the areas of significant need for continued research. Our purpose is not to concern ourselves with the specific potential materials to be used in space vehicles, but rather to gain first a complete understanding of the dynamics of hypervelocity or meteoritic impact. Once this is known, materials selection can be made logically and intelligently.

Nature of the Environment

Definition of Terminology

It is evident from the widely differing information issued by authorities concerning the number, size, density, distribution, configuration, and penetrability of meteoric materials that this field of study is new. The problem is further confused by nonuniformity in defining terms. A firm foundation for the study of the simulation of meteoric material impact effects requires a common ground for describing the space environment. The following list of definitions are those which we have accepted and will use throughout this report.

Meteoric Particle - A relatively small intrasolar system body or particle of any size and speed generally of cometary or asteroidal origin.

Meteoroid	-	A meteoric particle, generally of cometary origin, of any size greater than 10^{-4} gms.
Micrometeoroid	-	A meteoric particle of less than 10^{-4} gms.
Cosmic Dust	-	Minute meteoric particles smaller than most micrometeoroids.
Meteor	-	The phenomenon resulting from the entrance into the atmosphere of a meteoric particle of sufficient mass at high speed.
Meteorite	-	A meteoric body, generally of asteroidal origin found on the earth's surface.
Micrometeorite	-	A meteorite of the approximate size of cosmic dust.
Hypervelocity	-	That velocity exceeding the speed of sound in the target material or the speed of the dilatational wave in the target.

Composition of Meteoric Material

Having defined the particulate matter found in space, we can proceed to a discussion of the relative numbers and velocity distributions of these particles as well as their composition. Meteoric particles are stony, iron or metallic masses which are smaller than many of the small planets (asteroids). Apparently they are concentrated in the ecliptic plane and move around the sun in the same direction as the planets. Large meteoric particles may be concentrated in streams irregularly placed in space. Meteorites are hard, high density materials and are the remainder of meteoric particles of large mass which have not vaporized or burned, and vary in mass from milligrams to several tons. There are three types of meteorites: siderites or metallic bodies, consisting of iron or nickel alloys; aerolites, consisting of stony materials primarily composed of silicates and oxides; and siderolites, which are iron-stone bodies. Of the three types, the metallic meteorites constitute less than 10 percent of the total.

In this paper, we shall not attempt to cover the origin of meteoric materials; however, some of the potential research outlined later will cover the determination of their origin. Most authorities agree that the bulk density of particles of cometary origin ranges from 0.05 to 0.3 gms/cc; whereas the meteoroids of asteroidal origin are as large as 8 gms/cc.

Velocity Distribution

Because of the earth's gravitational effects, material entering the earth's atmosphere cannot have a velocity of less than 11.2 km/second. Since the velocity of the earth about the sun is about 30 km/second and the maximum velocity of a meteoric particle is about 42 km/second, the maximum combined relative velocity is about 72 km/second. Secondly, in this velocity range of 11 to 72 km/second, there appears to be a distribution of velocities which varies with particle size. In addition, meteoric particle velocities vary because of time of day and month, their mean observed speed in the earth's atmosphere being highest in early morning and lowest in late afternoon.

If particles of a diameter of less than one micron tend to be blown out of the solar system by solar radiation pressure, and the ejection mechanism also depends on particle density, then to stay in the system those particles with a density of 0.05 gms/cc must have a diameter of 23 to 46μ. However, particles .01μ in diameter may not be affected by radiation pressure if their scattering power is low. The interplay of the gravitational effects and radiation pressure of the sun determine whether these minute particles will be spiraled onto the sun or blown out of the system. Figure 1 shows a distribution of meteor velocities as determined by radio methods during a 15-month study during 1948-1950. (1, 2) The smallest particles observable by radio methods have a mass ranging from 10^{-4} to 10^{-5} gms and their average velocity appears to be 37.5 km/sec. We account for the zodiacal light by assuming that many smaller particles must exist having lower velocities. Therefore, the average of 37.5 km/sec is probably high and should be reduced to between 28 and 35 km/sec.

Particle Distribution

The frequency of particles in the vicinity of the earth can be determined from the intensity of zodiacal light reflected by minute dust particles. A flux density of 10^{-6} particles/cm^2/sec of particle radii between 1 and 10μ (10^{-11} gms) is necessary (3) to produce zodiacal light. The frequency of particles having mass greater than "m" entering the vicinity of the earth/sq m/sec is, according to Broyles, $F_{>m} = \alpha\ m^{-\beta}$, where α and β are constant (4). Figure 2 depicts this mass distribution and from this curve one may infer the relative probability of impacts on a space vehicle.

The amount of satellite and rocket data taken to date tend to substantiate the mass distribution curve of Broyles. There exists a large concentration of meteoric particles in the vicinity of the sun. Zodiacal light measurements indicate that a maximum particle density between the earth and the sun occurs in the ecliptic plane. In addition, dust concentrations are expected to occur within the gravitational fields of the planets and moon and vary inversely with the 1.5 power of their distance from planet centers.

Meteoric Impact

The hazard from meteoric material impact to space vehicles can be divided into two problems: (1) surface erosion by dust particles, and (2) penetration and puncture of skins by more massive bodies.

Surface erosion has as a major consequence the reduction of thermal control since the physico-optical properties of the surface may be changed by erosion. Another consequence is that of increased drag from air friction on the roughened surface and the resultant overheating of the vehicle skin upon re-entry into the earth's atmosphere.

The consequence of puncture to a manned vehicle is obvious in view of its required pressurization, but damage may also be disastrous to internal components either from puncture by the primary impacting particle or by spalled skin material.

The problems to be solved are similar in that they both involve impact at velocities in excess of those presently obtainable in the laboratory. Two mechanisms are responsible for changing the character of the impact process at high velocity vs that occurring at low velocities.

Since momentum effects are linearly dependent upon velocity, they will dominate the low velocity experiments. Energy depends upon the square of the velocity and therefore energy effects will be predominant at high velocities. At high velocity, target materials are more resistant to momentum effects since the greater inertial stress of the target atoms dominate the common static stress of the target material at high rates of strain (5). At the maximum laboratory velocities presently obtainable, the shape of the crater in the target, resulting from impact, bears small relation to the incident particle momentum of the impacting body. We know, however, that the shape of the crater becomes slightly elliptical and that the penetration decreases as the incident particle deviates from the target's head on impact.

Impact Effects

1. Low Bulk Density Projectiles -- The probability of impact by low bulk density projectiles will be greatest because of their relative numbers, and will include predominately particles of cometary origin. Since the low density (0.05 gms/cc) particles have low cohesive strength, the major concern is the surface erosion caused by the impact of these particles on skins, mirrors, reflectors, windows, radar and infrared gear, energy collectors, thermal protection and heat balance systems.

Because of its low mass and resulting low kinetic energy, such a particle will probably fly apart upon impact and transmit only a very small portion of its original kinetic energy into the target. The most probable effects would be many small holes of slight penetration and deposition of material on the surface of the target. A dust particle 10 μ in diameter with density of 0.05 gms/cc and velocity of 30 km/sec has an incident kinetic energy of about 2 by 10^{-5} joules, which will be dissipated in the outer layers of the target.

2. High Density Meteoroids -- Meteoroids of asteroidal origin are generally high density materials. Impacts from these particles will occur with less frequency than those from dust particles but will produce catastrophic effects due to their high kinetic energy. A particle weighing 0.5 gms traveling with a velocity of 30 km/sec possesses a kinetic energy of about 2 x 10^{5} joules. This amount of energy cannot be dissipated completely in the outer shell of the vehicle. Let us analyze the energy partition in the target. Figure 3 shows a representative cross section of a particle impacting on the target and gives an idea of the manner in which the energy is partitioned in the target material.

3. Phenomena Associated with High Energy Hypervelocity Impact

a. Light Emission -- Upon impact, the initial effect is the explosive removal of both target surface material and a portion of the particle material. This matter is partially vaporized, liquified, and removed as solid material. A major portion of this energy is converted into radiant energy and can be seen as the luminosity associated with the impact. The matter which does not completely leave the target surface forms the crater lip.

b. Penetration -- The kinetic energy of the impacting particle is higher than the sublimation energy of most metals. Consequently, a meteoroid with high velocity penetrates into a metal as if it were a liquid and continues until the meteoroid atoms lose enough energy to be in the range of the binding energy of the metal lattice. There are several theories at present which attempt to predict the depth a particle will penetrate a given material as well as the volume of the resultant crater. Perhaps the most widely quoted equations for making these predictions are those set forth by Kornhauser (6). Changes are reflected in the curve of figure 4 as crater volume per unit energy becomes a function of target parameters as given by Partridge (7). The slope of the line in a graph of crater volume vs energy of the projectile will be different for different target materials depending on the modulus of elasticity or strength modulus of the material. All of the theories that have thus far been developed have dealt with velocities below 7.5 km/sec and therefore say nothing about the effects at expected meteoroid velocities.

c. Spallation -- Meteoric material penetrates a surface at hypervelocities and the Macl number at which this is done is determined by the acoustical properties of the target. The meteoric particle is preceded by a shock wave of high strength. As the energy of the shock wave is transferred to the target atoms within the shock cone, the atoms participate in the bulk motion and attain extremely high temperatures and vaporize. The vaporized atoms in the shock cone then attain velocities in the sonic region. The lattice energy of the target may be neglected and the energy of the vaporized atoms is carried forward into the skin by a compressional wave to an extent dependent upon the elastic properties of the target material. These compressional waves will be reflected as tension waves from the discontinuity at the reverse side of the structure.

At this point the analysis becomes somewhat complex and uncertain since the breakup at the surface, or spallation, depends upon the tensile strength, the existence of faults, cleavage planes, and in general the crystalline properties of the material. The spalled material will have a certain kinetic energy imparted to it which depends upon the strength of the compression wave as well as upon the other factors mentioned above which also contribute to the production of spallation. If the kinetic energy of the spalled material is sufficiently high, these secondary particles may produce damage upon impact with internal components in the vehicle.

d. Vibration -- The impact of massive meteoric particles can induce vibrations within the target materials. The amplitude of these vibrations may be sufficiently large to spall or flake off thermal coatings or may even crack open welded joints in the structure.

At present there are experimental and theoretical programs in progress to study existing laws and establish new laws of hypervelocity impact. A considerable variation exists in the equations proposed to describe these phenomena. Henderson and Stanley (8) attribute this to the following two factors:

(1). The processes which occur are extremely complex. Under low velocity conditions a small particle penetrates the target as a projectile and produces a deep hole. As the particle velocity approaches the speed of sound in the target material, something similar to transonic aerodynamic conditions occur. Penetration under these conditions depends on the rate at which the compression wave moves into the target, how efficiently the heat produced is conducted away from or melts the target-projectile combination, and some other factors not clearly understood.

(2). Experimental data, while available at relatively low speeds for large solid projectiles, are completely lacking in the range of velocities, particle size, and particle materials involved in meteoric damage. At the present time there exists essentially no data above 7.5 km/sec, which for most materials is between Mach 1 and 2. Particle sizes down to 10^{-11} gms and densities around 0.05 gms/cc are about an order of magnitude below that currently attainable in the laboratory. Therefore, the equations relating material properties, velocities, and energies have taken a variety of forms.

Experimental Observations

Despite the fact that, almost without exception, the experimental research on hypervelocity impact to date has been in the region below 7.5 km/sec, considerable work has been conducted which has resulted in large amounts of data especially in the studies of crater formations, penetrations of high density (> 2 gms/cc) projectiles, surface glancing effects, and target surface erosion from gases and shattered particulate materials. Let us now briefly review some of the work accomplished in these areas.

Crater Formation

The two primary studies of hypervelocity impact have been in the area of cratering and penetrations. Gehring (9) has analyzed the dynamics of crater formation using high speed photography to watch the qualitative features of the impact. From the data obtained from these photographs, he postulated equations for the impact dynamics and determined the portion of energy partitioned from the particle to form the crater. Others who have conducted research in this specific area include those listed in references 10 through 13.

Penetration Studies

Penetration studies have constituted the principal work in hypervelocity. Research has run the gamut from qualitative studies of observing just what occurs upon impact to those of quantitative determinations of crater volume and particle penetration depth both as a function of particle energy and material and of target material and configuration. Nearly all of the work has been conducted using Metal projectiles impacting on metal or lucite targets. Only recently has tentative data been disclosed in which borosilicate glass beads were employed as projectiles (14). These projectiles more closely approximate the stony meteoritic materials in density. Data is essentially nonexistent on the effects of "puff-ball" impacts.

The one bright spot in all the research conducted to date is that most crater volume-energy relationships agree, i.e., that the volume exhibits a linear dependence upon the kinetic energy of the projectile. The exact dependence is not firm but appears to be related to the modulus of elasticity or strength modulus of the target material.

Characteristics of penetration of particulate matter into a target are not so readily defined. Summers and Charters (15) have shown that the penetration of metal particles into metal targets can be expressed in terms of the densities of the particle and target, the particle velocity, and the speed of sound in the target. Atkins (16) indicates that as craters become hemispherical and energy/volume becomes constant, the penetration is proportional to the 2/3 power of impact velocity. James and Buchanan (17) show a linear dependence of penetration on the root reciprocal of target density. Investigators have been proving the dependence of penetration of a projectile on various physical properties of the target and of the projectile itself, but there appears to be a need for correlation of data to arrive at a unified penetration equation.

Surface Erosion

Aside from the examination of surfaces of recovered vehicles, research in the area of surface erosion has been scarce. Other than the data presented by Kornhauser (18) which is experimental data on surface roughening, and that of Beard (19) which is a theroetical treatment of the problem, the reports in the open literature are essentially nonexistent. Probably the greatest single obstacle to achieving hypervelocities for experimental purposes is that of particulate shattering prior to impact. The cohesive forces on a particle in most cases cannot withstand the extremely high acceleration rates required to obtain hypervelocity within a reasonable distance. However, in surface erosion studies, this problem of shattering may be ignored if by utilizing modern high speed photography we identify the particles prior to impact and associate a given crater with a known fragment of the projectile. Very recent velocities in excess of 11 km/sec attained in the laboratory promise that the dynamics of surface erosion may soon be analyzed.

Spallation

Although most experimenters employing thin targets have seen spallation occur, there is a complete lack of data relative to the characteristics of the spalled material. Prior to developing a mathematical representation of the phenomenon of spallation, Maiden, et al. (20), are presently studying, quantitatively, the compressional wave propagation in target materials.

Oblique Impact

Depth of penetration and the shape of the crater produced by a particle impacting on a target can vary with the angle of incidence of the particle, as well as with its velocity. As velocity of the impacting particle increases, dependence upon the angle of incidence decreases, within small angles, because of the predominance of energy over momentum. However, the more nearly parallel the direction of the projectile is with the surface of the target, the less likely there is to be any impact effect, regardless of the speed of the projectile. The results of Culp's experiments (21) show that eccentricity decreases with increasing velocity at fixed angles of incidence. Bryan (22) has attempted to set up a model of oblique impact which can be used as a starting point in describing the phenomen associated with this type of impact. Figure 5 shows the difference between head on and oblique impact.

Experimental Techniques

In all the research that has been conducted to date on hypervelocity, nearly as many methods for projecting particles have evolved as the number of experiments themselves. The light gas gun and "shaped" charges comprise the vast majority of those methods of projecting particles used to date. Rather than list all the different types of equipment used, we classify them into four basic groups and briefly describe each.

Light Gas Guns

The most common type of light gas gun consists of a breech, a pump piston, a pump tube filled with a low atomic weight gas, and a launch tube extending forward from the pump tube (figure 6). The gun functions by compressing the gas in the pump tube to a very high pressure by driving the pump tube piston down the tube; the piston is actuated by an explosive charge at the breech. A diaphragm placed between the pump tube and the launch tube is then sheared and drives a projectile down the launch tube at a hypervelocity. The upper velocity limit for present light gas guns is approximately 20,000 feet/sec.

Shaped Charges

By properly shaping the explosive charge, the projectile may retain the total energy imparted to it, thereby attaining its highest potential velocity. Figure 7 indicates a basic idea for the shaped charge. The shapes range from conical and paraboloidal to cylindrical, where portions of the lining of the cylinder are used as the projectiles. This method may be used in conjunction with the light gas gun described earlier. Fogg and Fleischer (23) outline a method of exploding charges sequentially to impart additional velocity to the particle. A projectile passes through the axial hole in the first charge. At a given point, the charge is detonated forming a high velocity jet which boosts the velocity of the particle by Δ V. This process is repeated until the highest attainable gas jet velocity is reached, whereupon the projectile impacts on a target.

Accelerator or Drift Tube Experiments

A potential method for projecting micron diameter metallic particles to hypervelocities creates an electrostatic charge on the particles and accelerates them to high velocities by a machine of either a linear accelerator or an electrostatic type. Hendricks, et al. (24) indicate a method for projecting 0.5 micron (10^{-12} gms of iron or copper) spheres to velocities on the order of 10 km/sec employing a 10 Mev Van de Graff electrostatic generator. There are three attendant problems associated with this method: first, we must accept a multiple particle bombardment of the target; second, the machine used for this purpose must be frequently and thoroughly cleaned because deposition of metallic particles throughout the equipment causes potential shorts; third, we must use metallic particles to eliminate the possibility of simulating the major portion of meteoric materials.

Electrical Discharge

Several workers (14, 25, and 26), in a novel approach to the problem of achieving hypervelocities, employ high energy fast discharge capacitor banks which generate large electric currents for microsecond pulses. Scherrer (25) describes a system employing an expendable barrel type gun. Figure 8 shows a basic setup for this procedure. The capacitor bank is discharged through a fine wire located at the breech of the gun. The wire is vaporized and creates high gas pressures behind the projectile which forces the particle down the barrel at hypervelocities. Scherrer has indicated a potential particle velocity in excess of 15 km/sec. Webb, et al. (26), have been working on a hypervelocity projector of much the same design as Scherrer's except that theirs uses dense agglomerations of materials rather than a single particle to impact on a target. Scully and Cowan (14) generate a high density, high temperature gas by capacitor discharge into a partially confined lithium metal cylinder; the resulting plasma pulls borosilicate spheres down an evacuated tube by aerodynamic drag. These systems are anticipated to achieve, or have been successful in achieving, particle velocities on the order of 10 km/sec or better.

Needs for the Future

Using the foregoing sections and the report of Whipple (27) as a foundation, let us explore some of the directions that future work in hypervelocity should take:

Extension and Correlation of Present Work

Probably the most urgent single objective is the extension of present research to velocities well in excess of 10 km/sec, perhaps to 50 km/sec. Granted, this is no small task especially with the forces imposed on a particle being accelerated to above 10 km/sec in one step. However, these forces can be minimized if the ultimate velocity is achieved in steps using a series of shape charges or a series of capacitor discharges. Velocities must be extended to:

1. Confirm the theory that increases in velocities, decrease the importance of the angle of incidence on crater shape.

2. Prove that scaling laws can be used to predict behavior of particle impact, essentially, to prove that particles with identical kinetic energy, but with differing mass and velocity produce identical effects at speeds above the speed of sound when impacting in the target material.

In view of the fact that no research has been reported using projectile materials of densities or sizes comparable to that of micrometeorites, this is one area which needs exploration. The program may include impact studies of materials having a range in bulk density of 0.05 through 8 gms/cc, and for which kinetic energy is kept constant (assuming scaling laws are valid again).

We have seen that there are many differing theories concerning crater formation, depth of penetration, volume of craters, etc. These theories need to be collected, analyzed and consolidated.

Spallation

At present, there are no data concerning the dynamics of spalled material. There may exist a problem area resulting from spallation in which high kinetic energy material may cause further damage to interior components of a vehicle. Experimentation in this area may include measuring variation of the mass and velocity of spalled material as related to impacting particle kinetic energy, target thickness, and material.

Erosion Effects

Although a small amount of research has been conducted on effects of erosion more work is needed in which fine particles are used at hypervelocities to impact on potential materials for space vehicles.

Satellite-Based Observations

Despite all that may be said in favor of ground-based observations, the fact remains that to study meteoritics properly, observations must be made of the natural particles in the natural environment, i.e., space observations. Although we may not be ready to make full use of the numerous satellites being placed into orbit at present, they may be invaluable in future meteoritic studies. Potential programs include:

1. Mass and Composition of Particles -- Prior to the development of systems to prevent catastrophic puncture of vehicles, it is imperative that a determination of mass and composition of meteoric material be made. This would necessitate catching the particle and recovering the entire system--a task of monumental proportions. The alternate approach would be to combine the "catching" substance or artificial atmosphere with an optical spectrometer to analyze the particle's constituents, thus eliminating the need for recovery.

2. Total Velocity Vectors -- If the velocities of particles, both direction and magnitude, can be determined, then this information combined with the mass distribution will assist in yielding data for the total distribution of matter within at least one astronomical unit of the sun. Whipple (27) lists several potential methods, which can be used with vehicles for obtaining these velocity vectors.

3. Charge on Space Particles -- Determinations of the electrical charge on solid space initiated particles would be useful in studying sun-earth relationships, conditions of the interplanetary gas, and studies of the corpuscular radiation from the sun. Perhaps we could also derive the temperature of the interplanetary gas from measurements of electrical charge on space particles.

In the study of hypervelocity and meteoritics, we have just scratched the surface. There remains a tremendous amount of research to be completed, research that is urgently needed for the proper design both of space vehicles and space experiments. The work yet to be accomplished may also yield answers to questions about motion patterns of particles in space.

I am indebted to Dr. Robert Rolsten of Convair, San Diego, for the sections of his report "Meteor Bumpers" ZS-Mt-014 covering the nature of the environment and analyses of effects of hypervelocity impact, the bulk of which yielded information for the first two sections of this paper.

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DISTRIBUTION of VELOCITIES for SOME 11000 METEORS

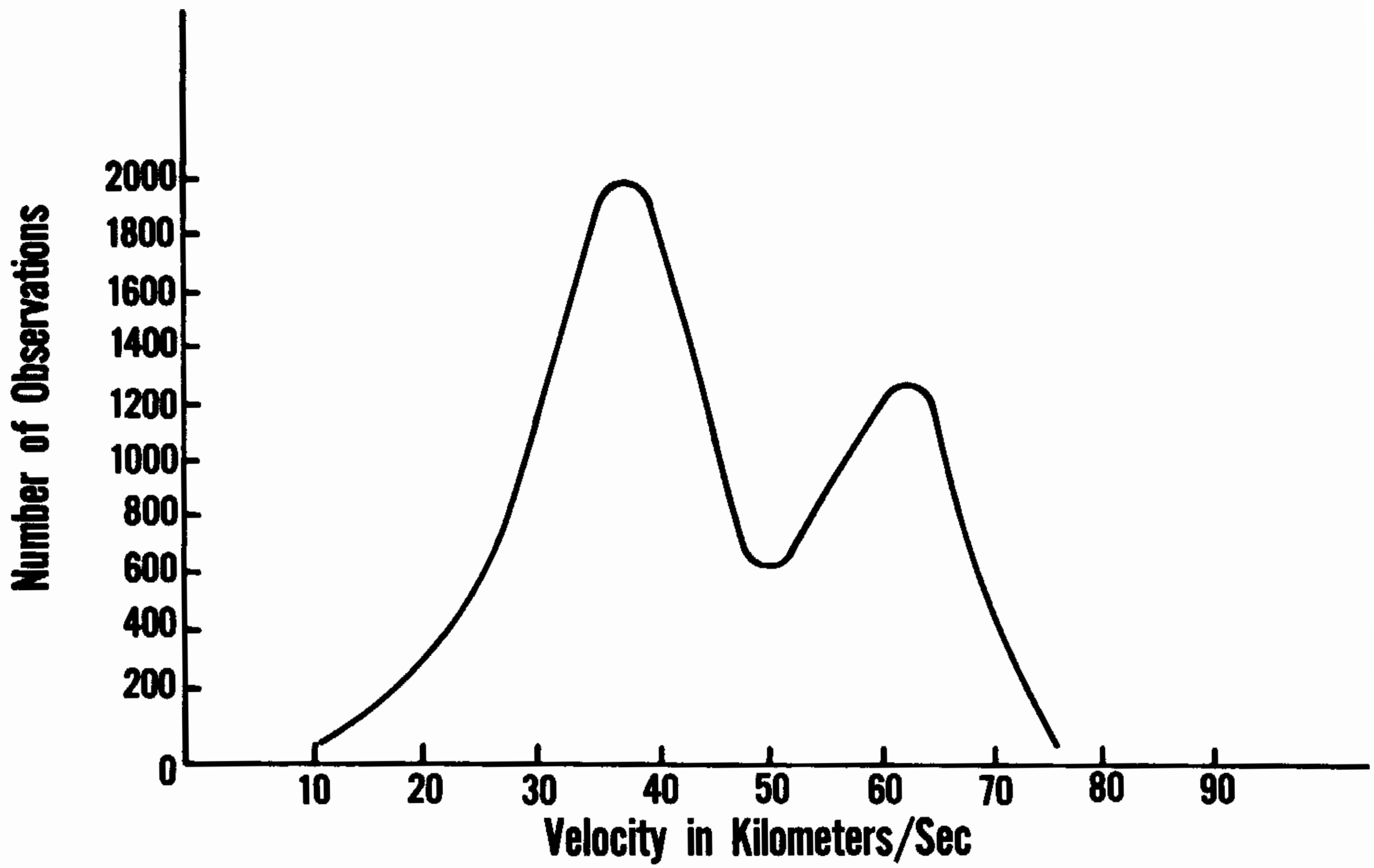


Figure 1.

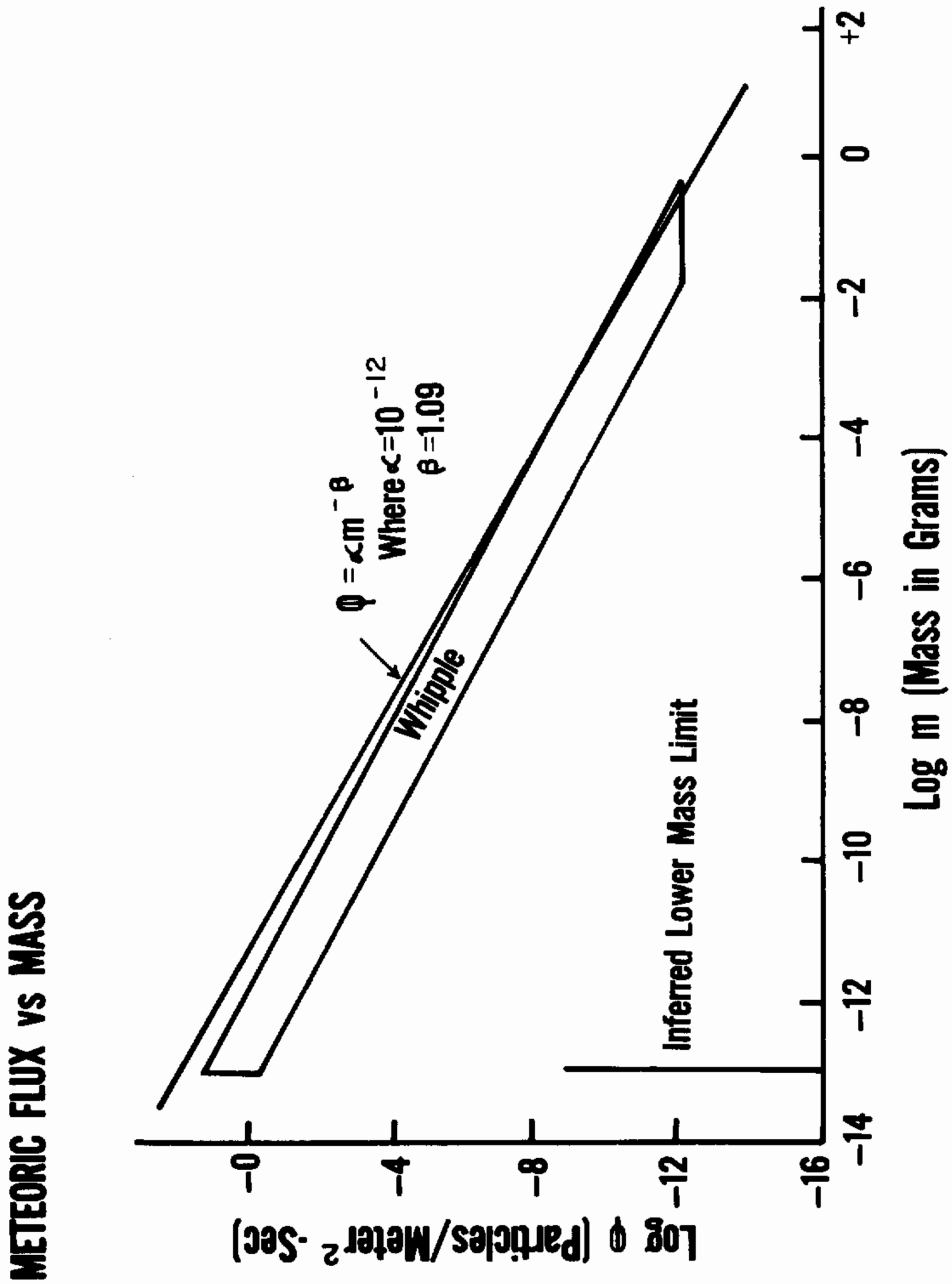

METEORIC FLUX vs MASS
Log φ (Particles/Meter² -Sec)
-0
-4
-8
-12
-16
-14
-12
-10
-8
-6
-4
-2
0
+2
Log m (Mass in Grams)
φ = αm^-β
Where α=10^-12
β=1.09
Whipple
Inferred Lower Mass Limit

Figure 2.

VOLUME/UNIT KINETIC ENERGY vs PARAMETER $\frac{1}{C^2 \rho}$

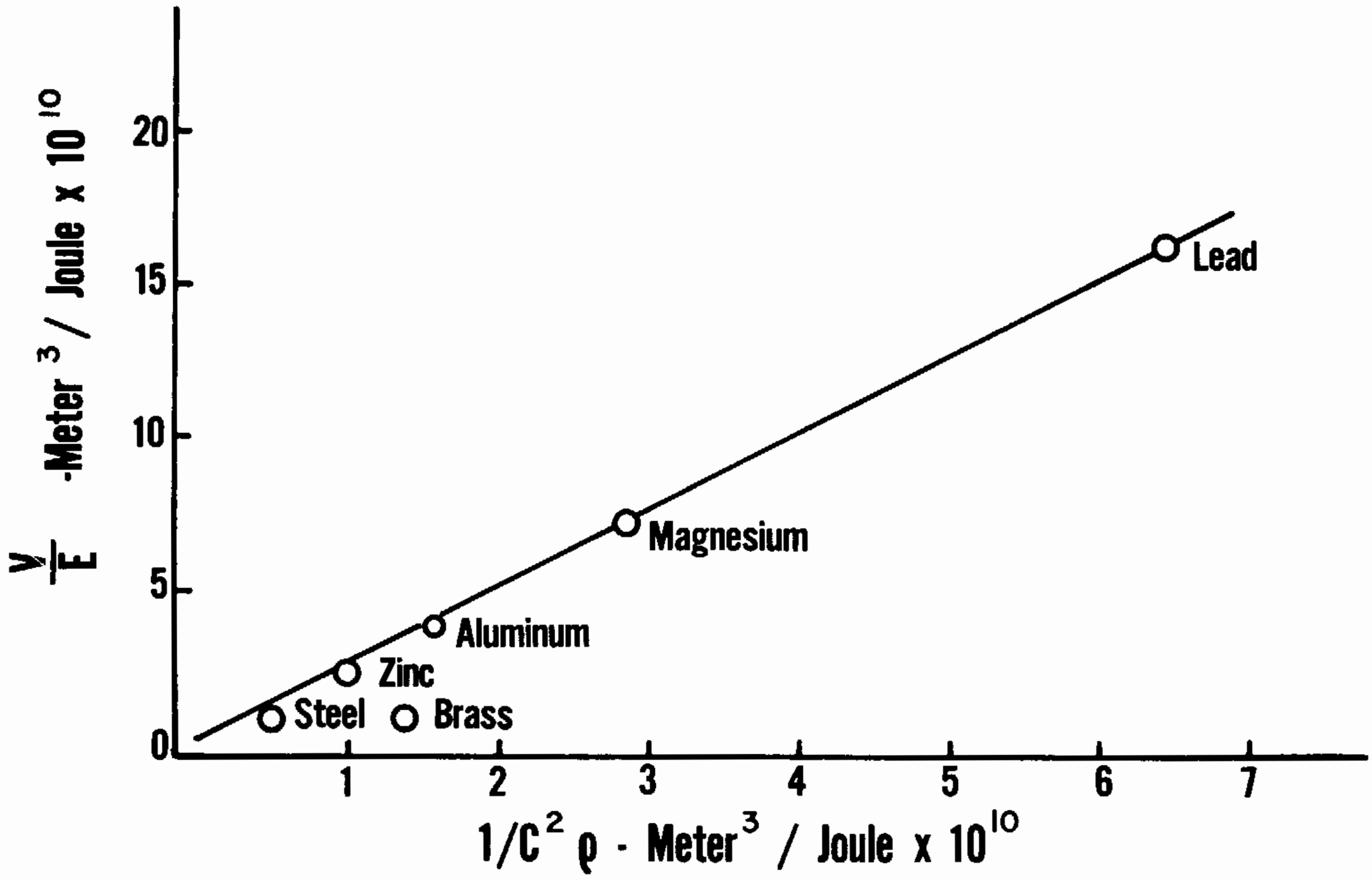


Figure 3.

CROSS SECTION of METEROID IMPACT

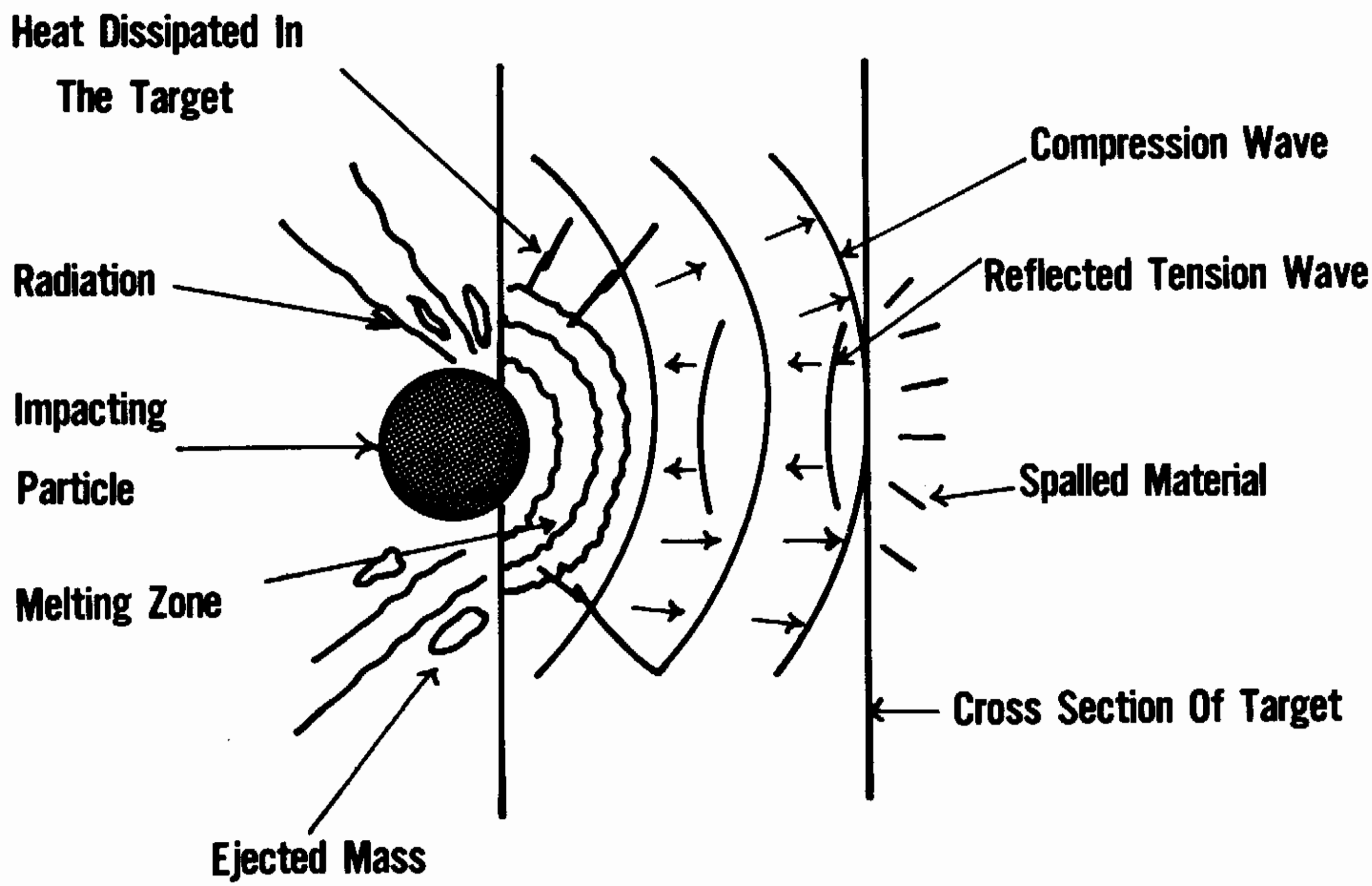


Figure 4.

CRATER SHAPE vs ANGLE of IMPACT

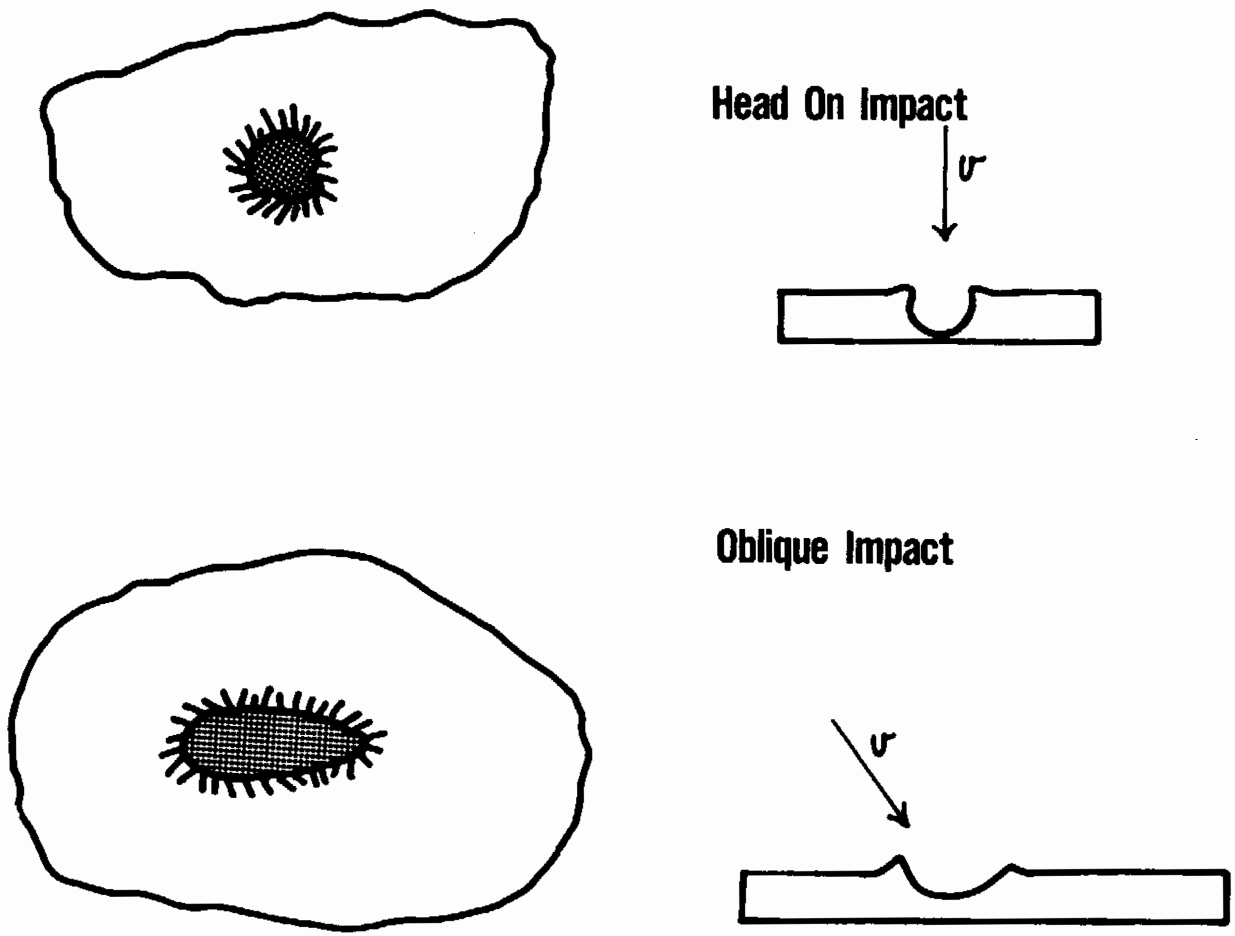


Figure 5.

BASIC LIGHT GAS GUN

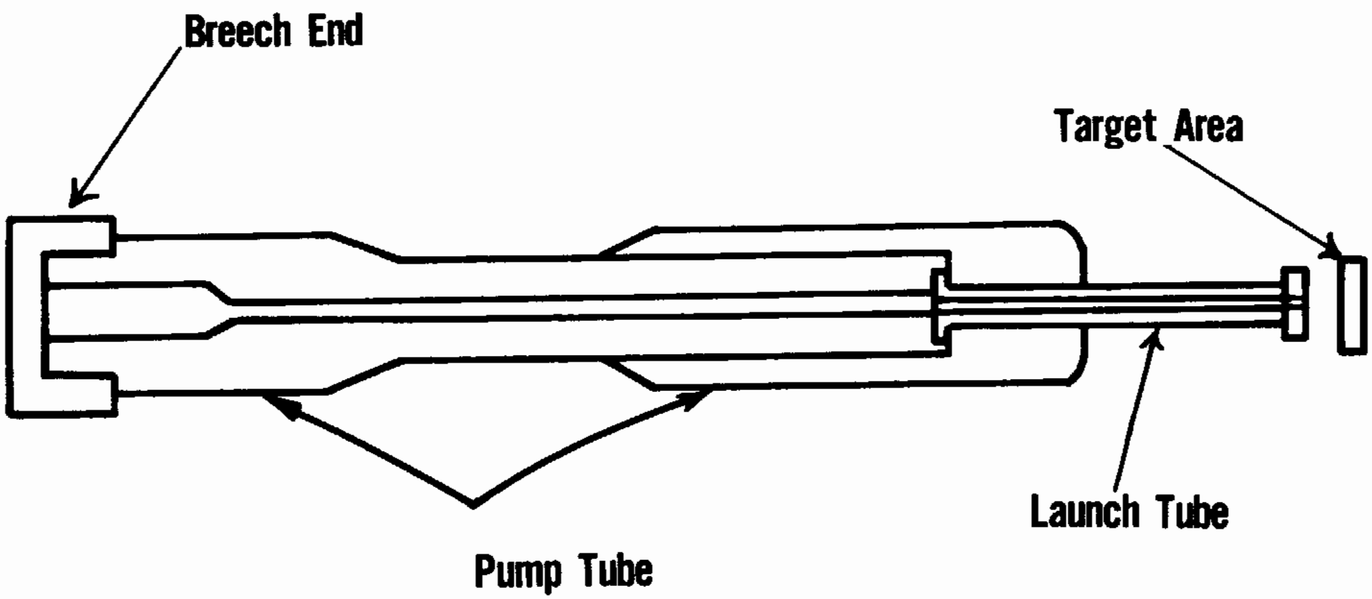
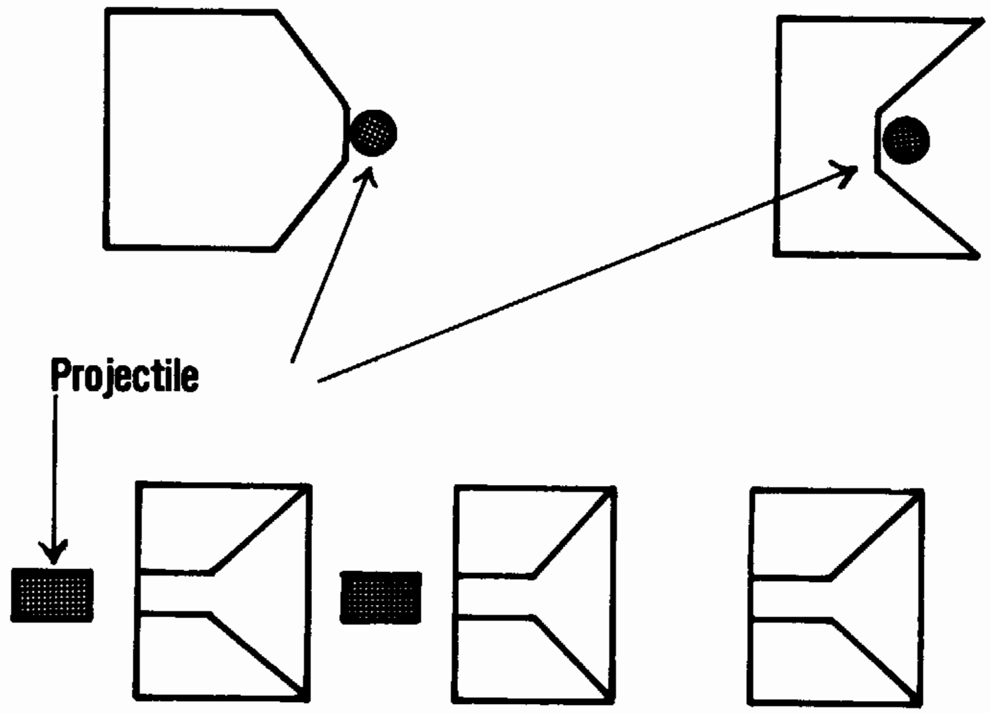


Figure 6.

TWO BASIC SHAPE CHARGES



POSSIBLE SEQUENTIAL VELOCITY BOOSTER

Figure 7.

CAPACITOR DISCHARGE PROJECTOR

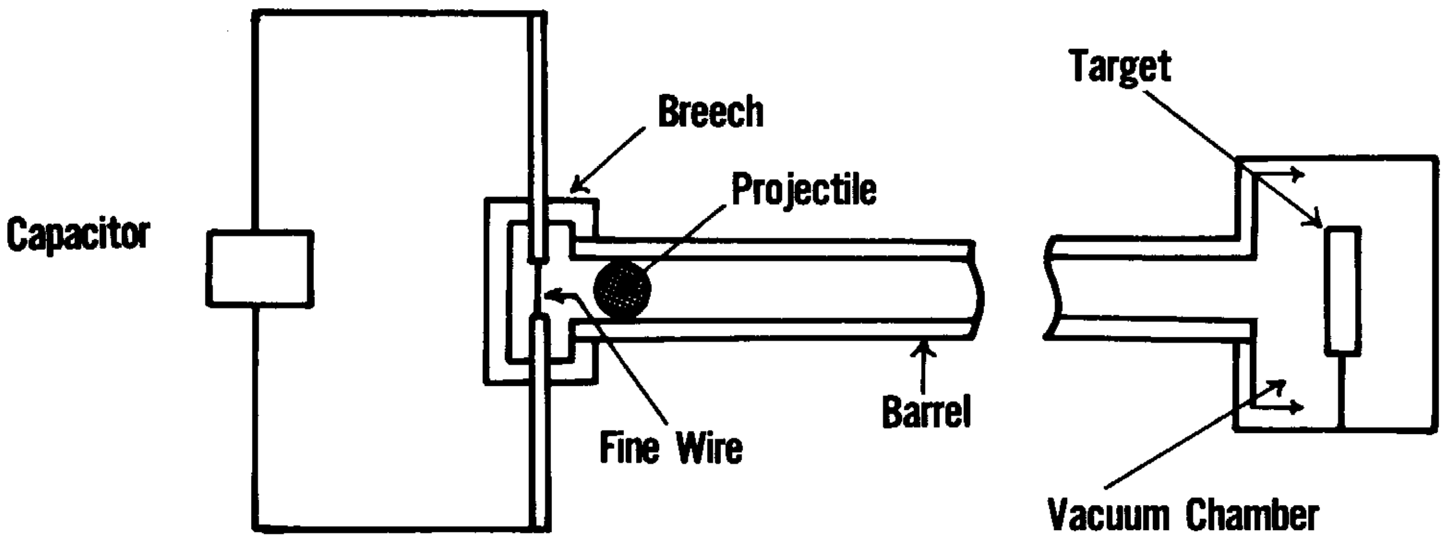


Figure 8.