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TECHNICAL REPORT 3485

RESPONSE OF EXPLOSIVE TO FRAGMENT IMPACT

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DECEMBER 1966

PICATINNY ARSENAL
DOVER, NEW JERSEY

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BY

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AMMUNITION ENGINEERING DIRECTORATE
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SUMMARY

This phase of the Safety Design Criteria Program conducted by the Ammunition Engineering Directorate's Process Engineering Laboratory deals with the analytical and experimental determination of the sensitivity of high explosives and high energy propellants to impact by primary and secondary fragments.

This material was the subject of a presentation made at the New York Academy of Sciences "Conference on Prevention of and Protection Against Accidental Explosion of Munitions, Fuels and other Hazardous Mixtures" held in New York City 10-13 October 1966.

RESPONSE OF EXPLOSIVE TO FRAGMENT IMPACT

This phase of the overall Safety Design Criteria Program conducted by Picatinny Arsenal deals with the analytical and experimental determination of the sensitivity of high explosives and high energy propellants to impact by primary and secondary fragments.

By definition, primary fragments are those fragments which result from break-up of explosive casing at detonation. Usually these fragments are characterized by having high velocity (in the order of several thousands fps) and being comparatively small in size.

The analytical work performed at Picatinny Arsenal resulted in the establishment of:

1. A method of predicting the vulnerability to high order detonation of an explosive system in terms of geometry of the system and explosive properties.

2. A method for calculation of safe distances for any assumed degree of risk.

These methods are based on a correlation of various relationships developed by British and American investigators as a result of theoretical studies, confirmatory tests and actual experience (Reference 1 and 2).

The general relationships are in Figure 1. These equations permit prediction of the gross mass detonability characteristics of explosive systems. Shown are the factors which must be considered for any explosive system in either donor or acceptor role. Values of the output constant (E') Equation (1) for several explosives are in Reference 3. For other explosives the values (E') could be established experimentally by conducting small-scale tests in which cased samples of various explosive-to-casing (E/C) ratios are detonated and corresponding fragment velocities measured. The output constant is then obtained from a plot of (Vo) vs. (E/C) in accordance with Equation (1).

Equation (2) was developed for calculation of the number of fragments in any particular weight range produced by detonation of a cased charge (Reference 3).

A relationship between fragment weight, the casing thickness and boundary velocity (the minimum velocity at which a fragment of a given mass and acceptor casing thickness will cause detonation for a given explosive) is shown in Equation (3). Sensitivity constant (K_f) included in this equation must be established for the acceptor explosive. Values of this constant are available for some well-known explosives such as TNT and Composition B (Reference 4). For other explosives this constant could be established from a plot of V_b vs $\frac{e^{5.37ta/m^{1/3}}}{m^{2/3}(1+3.3ta/m^{1/3})}$ in accordance with Equation (3).

Once the sensitivity of an explosive to fragment impact is established, the next step is the establishment of relationships for calculation of safe distance in terms of probability of high order detonation occurrence or risk of propagation of detonation by fragment impact at these distances. For the sake of simplicity and convenience, a graphical representation of these relationships is in Figures 2-5.

The plot in Figure 2 (based on Equation (4)) relates fragment striking velocity (Vs) with fragment mass at any distance from the detonation source (d) for a single value of initial velocity (Vo). Constant (k) which is a part of Equation (4) is a function of the presented area to fragment mass ratio, density of air and air drag coefficient (Reference 5 and 6). The plot shown in Figure 3 (for Composition B) -- a typical representation of Equation (3) -- relates the boundary velocity (V_b) with fragment mass (m) and acceptor casing thickness (ta).

When the plots from Figure 2 and 3 are combined as in Figure 4, a relationship is obtained for the striking velocity (or boundary velocity) of a fragment with fragment mass at various distances (d) and acceptor casing thicknesses (ta). If boundary velocity of a fragment is now equated to its striking velocity, it becomes possible to find the minimum effective mass of a fragment produced by the donor explosive causing a high order detonation in the acceptor under the prevailing conditions. The number of such effective fragments produced at any distance from the donor charge can then be calculated from Equation (2) in Figure 1.

As expressed by Equation (5), Figure 5 is a plot relating the probability of detonation occurrence as a function of distance (between donor and acceptor charges) or shielding.

This plot relates the distance between the donor and acceptor charges (d), shielding (ta) and probability of high order detonation occurrence (E). The zero probability curve (Po) indicates a relationship between the distance (d) and shielding (ta) beyond which no high order detonation is possible.

The higher the probability level tolerated, the lower the distance/shielding combination necessary. This relationship permits a prediction of the necessary separation or shielding between two explosive systems at any degree of probability of high order detonation occurrence. To compose such a relationship for a specific situation all that is necessary is knowledge of the geometry of the system and the explosive properties relating the sensitivity and output.

A limited test program for experimental determination of the boundary velocities for bare pentolite and cyclotol charges was conducted at the A.D. Little Test Facility in Hinsdale, New Hampshire (Reference 7).

The experimental work in this program utilized an explosive technique for projecting rectangular fragment against explosive charges. Non-spinning rectangular fragments of 0.2 to 3.0 ozs. were projected at the acceptor charges at velocities both above and below required for detonation. Fragment velocities were measured by screens and high-speed photography.

The explosive launching technique consists of the placement of a fragment, its metallic surround and an attenuating or buffer sheet of lucite on the forward flat face of cylindrical explosive donor. The lucite spacer or buffer plate provides the means for controlling the launch velocity. The fragment is surrounded by four pieces of steel of equal thickness that prevent deformation at the edges of the fragment during the early stages of launch (Figure 6).

The cylindrical charge is initiated on the rear flat face of the explosive donor. On detonation, the fragment is propelled along predictable path and impacts the target (acceptor charge) at a distance of about six feet. The velocity of the impacting fragments is measured by accurately positioned timing sensors and in most cases confirmed by high-speed photographs of its flight. Fragment velocity is controlled by the size and composition of the donor charge and the buffer plate thickness. The maximum velocities attained in these tests with fragments intact were 5,200, 3,500 and 2,500 fps for 0.2, 0.9 and 2.85 oz. fragments, respectively.

The instrumentation consisted of time-measuring devices (recorded on Model 7260 Beckman Time Interval Meters) and Dynafax Drum Cameras with a framing rate to 25,000 frames per second which photographed the fragment in flight. A typical film series is in Figure 7. The timing devices were an ionization probe taped to the donor charge and a pair of thin aluminum screens separated by a thin piece of polyethylene film. Two of these screens -- one located on the forward face of the acceptor charge and the other located at a specified distance above the acceptor charge -- were used in most firings. Fragment travel time between each of these sensors was recorded in microseconds. The Dynafax camera (located about 20 feet from the flight path) viewed about the last four feet of travel including target impact. Figure 8 shows schematically the camera layout.

The fragment aiming procedure is depicted in Figure 9 which assured that the fragment would impact the center of the acceptor charge. The donor charge assembly was placed at the top of the seven-foot-high stand and the acceptor charge was centered vertically below. The telescope and 45° angle mirror assembly were then located with the mirror over the desired impact point and the brass plate perpendicular to the axis of the acceptor charge. While sighting through the scope, the donor charge assembly was positioned so that the fragment could be clearly seen. Another mirror was then placed on the fragment (held by a magnet) parallel to the surface of the fragment. While sighting through the scope, the donor charge was shimmed until the reflected image of the telescope end was centered in the eyepiece.

It was demonstrated in subsequent tests that this aiming procedure is reliable and can be carried out in a relatively short time. Once the aiming was completed, the mirror and scope assembly were removed, velocity screens located and all final electrical connections made, the test set-up was ready to fire. Figure 10 shows the test set-up assembly before firing.

Results of the firings against the bare cyclotol and pentolite charges are presented graphically in Figures 11 and 12. Predicted boundary velocity curves developed analytically (and discussed previously) also are shown for both explosives.

In general, the data conforms to relationships developed analytically for small and intermediate fragments while the detonation velocity for heavy fragments fired into the bare cyclotol charges was higher than predicted. This would indicate that the mass-velocity relationship may have to be adjusted for a more accurate prediction of sensitivity to impact by heavy fragments. However, the current predicted values for the boundary velocity tend to be conservative and hence are satisfactory for design purposes where safety is the prime consideration.

More tests must be conducted to establish a definite trend with increase in fragment size as well as to investigate the effect of other variables (such as degree of casing, sensitivity of explosives) on the detonation velocity.

As noted, the large-scale cubicle tests conducted under the auspices of the Armed Services Explosive Safety Board clearly indicate -- after careful investigation of the high speed film records -- that the secondary fragments are the main cause of propagation of explosion into the acceptor charge (Reference 8). By definition, secondary fragments are those fragments other than primary fragments which result from the detonation of explosive charges, such as wall break-up, pieces of equipment, etc. These secondary fragments are usually characterized by having lower velocity than the primary fragments (seldom exceeding 1,000 fps) and being fairly large.

Since there was no analytical data on the quantitative behavior of these fragments, an extensive experimental program was initiated to determine threshold velocity of fragment (or fragments) that would cause detonation in the explosive charge.

Two experimental methods were chosen among several investigated. The first method consisted of a rocket-powered sled (track method) designed to throw a collection of concrete and aggregate fragments (usually produced from concrete wall break-up caused by a detonation) at an explosive charge at velocities within the range of those occurring in full-scale cubicle tests (Reference 9 and 10).

The main feature of the rocket-powered sled was a test vehicle and fragment container attached to the top of the motor (Figure 13). Water-breaking action was supplied by partially filled polyethylene water bags fastened to the last 10 to 15 feet of track. Sled deceleration was accomplished when the wedge on the front of the sled hit the water-filled bags fastened to the track. A standard two-inch steel deflector plate placed six feet from the end of the track at a 5° angle from the track center line was used to deflect the test vehicle to keep it from striking the target (Figure 14). Fragment specimens used weighed a total of about 70 lbs. and contained about 50 lbs. of broken-up concrete and 20 lbs of aggregate.

The target, placed on a wooden stand about 30 feet from the track, consisted of 100 lbs. Composition B charge in light aluminum casing.

The operation of the test vehicle consisted of acceleration of the rocket-propelled vehicle to a predicted velocity followed by release of the fragments through the frangible cover of the container by water-brake deceleration of the vehicle. The velocity of the vehicle was controlled by the number of rocket motors used by changing the distance of the ignition point from the point of water-brake activation and by varying the weight of the sled. The track method -- although reliable for generating and measuring fragment velocities -- proved to be expensive. Its velocity range could be extended above 1,000 fps but as the test results indicated (at least for Composition B) this was unnecessary in most cases.

The second method, the ground mortar facility, was developed to provide a less expensive and less complex test set-up to produce a large quantity of fragment data (Reference 11).

The fragment mortar was a muzzle loading shotgun developed by the U.S. Naval Ordnance Test Station, China Lake, California, and manufactured from standard thick-walled seamless steel tubing (Figure 15). A thick breech plate was welded to the tube at the breech sealing that end. A saucer-shaped steel recoil plate was fastened near the muzzle to transfer recoil energy to the ground. Running down the length of the tube was an air hose that ported air (or nitrogen) through the plate to the bottom side of a breech cup. The elevator mechanism or breech cup was a heavy steel cup containing propellant. It is raised by air pressure for loading and then lowered into firing position by bleeding air from under it. The fast-burning 4.2-inch mortar shell double-base propellant was stocked in 20-sheet packs and was suited for variation of loading to provide desired velocities. The follower and sabot were designed to ride down on top of the elevator. The follower, an inverted cup-shaped unit made of vermiculite-filled resin-epoxy for optimum strength and flexibility, carried the ignition charge. The flexible skirt of the cup acted as a chamber sealant at the instant of propellant ignition. The sabot was a bucket made of cardboard or polyurethane foam and contained the payload (rubble) that was propelled from the mortar (Figure 16). After the propellant, follower and sabot were lowered to the bottom of the mortar tube, firing was initiated from a remote firing point by an electrical squib in the ignition charge.

The fragments used in this test series, in addition to the 70 lbs. rubble used in the track tests, consisted of dry plaster sand and gravel (aggregate) of the same weight. This was done to compare the detonation velocities using different fragments against identical explosive charges.

The test procedure consisted of suspending the acceptor charge above the mortar muzzle and firing the fragment at selected velocities vertically at the charge by varying the amount of the propellant in the steel cup at the breech end of mortar (Figure 17).

To measure fragment velocities (in both the track and ground mortar method) high-speed cameras as well as carbon rods were used. Using the camera technique, velocity measurements were made by counts of time of frames and reference distances of mass travel.

The carbon rod technique used two sets of carbon rods placed five feet apart above the muzzle of the ground mortar. The projected fragment broke both sets of carbon rods giving a measurement of its velocity (Figure 18).

For the track method, the rods were installed across the track 30 feet apart. A bolt projecting down from the center of water-brake edge on the steel broke the rods when the sled passed. The pulse was then transmitted to the telemetering station and recorded on calibration tape -- providing a record of sled travel time between the two points.

The two systems (camera and rod technique) provided a check and back-up for each other.

More than 100 tests were performed using both methods. All track tests were conducted using 70 lbs. concrete rubble as an impacting fragment. The ground mortar, in addition to the 70 lbs. rubble, used 70 lbs. of gravel (concrete aggregate), 70 lbs. dry plaster sand and 35 lbs. rubble. The fragment velocities chosen for investigation corresponded to those that were recorded during the destruction of walls in full-scale propagation tests.

A tabulation of selected test results is in Table 1. The fragment velocities indicate the highest velocities at which detonation did not occur and the lowest velocities at which detonation occurred for both track and ground mortar tests and for different types of fragments. In the tests conducted by track method, the spread amounted to only 44 fps (Table 1). In the tests conducted with the ground mortar the spread between the highest and lowest velocities of occurrence and non-occurrence of detonation was appreciably greater. The difference in this spread can be attributed to such factors as greater variety of acceptor types used, larger number of tests conducted by ground mortar, different methods of firing fragment. Included in the table are selected velocities from

TABLE 1

SELECTED TEST RESULTS

Method of Testing	Fragment Velocities		Fragment Type	Acceptor Reaction
	Carbon Rod	Fastax Camera		
Track	--	416	70 lb. rubble	X
Track	--	460	70 lb. rubble	O
Ground Mortar	462	401	70 lb. rubble	X
Ground Mortar	670	703	70 lb. rubble	O
Ground Mortar	--	913	Gravel	X
Ground Mortar	381	498	Sand	X
Ground Mortar	433	406	Sand	O
Ground Mortar	280	302	35 lb. Gravel	O
Full Scale Tests	--	430	Concrete	X
Full Scale Tests	--	700	Concrete	O

the film records of large-scale cubicle tests for the purpose of comparing the fragment detonation velocities recorded in large-scale tests. The lowest recorded velocity in those tests was 430 fps which compares favorably with the threshold velocities in the track and ground mortar tests.

The tests to date positively point to secondary fragments as the main cause of detonation propagation. The threshold detonation velocity for conditions investigated was approximately 400 fps. Because of insufficient number of rounds fired, the effect of varying fragment mass and shape on threshold detonation velocity has not yet been established.

Tests conducted to date have been limited in scope since their purpose was to develop a useful and inexpensive method of firing fragments at velocities that could cause detonation in the acceptor and to establish the threshold detonation velocity for standard explosive for both primary and secondary fragments. This has been to a large extent accomplished.

An extensive experimental program for a quantitative determination of various parameters (such as acceptor sensitivity, casing and size, rigidity of support, fragment size and shape) on the threshold detonation velocity will be the next step in our overall program of establishment of Safety Design Criteria for storage and processing of explosive materials.

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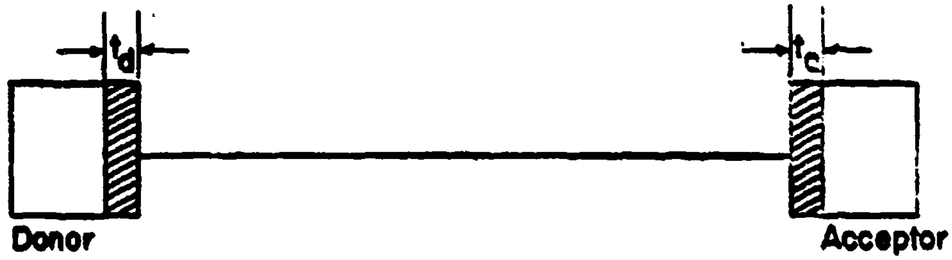
APPENDIX

APPENDIX A

Figures



(1) $V_o = \sqrt{2E'} \left[\frac{E/C}{1 + E/2C} \right]^{1/2}$

Where V_o – Initial Fragment Velocity

$\sqrt{2E'}$ – Gurney's Energy Constant

E/C – Explosive To Casing Weight Ratio

(2) $N_{(x)} = \ln (C' M_a) \frac{\sqrt{m}}{M_a}$

Where $N_{(x)}$ – Number Of Fragment Greater Than (m)

C' – Fragment Distribution Constant $= \frac{C}{2 M_a^3}$

C – Total Weight Of Metal Casing In oz.

m – Fragment Weight (oz.)

M_a – Fragment Distribution Parameter $= B t_d^{5/6} d_i^{1/3} (1 + \frac{t_d}{d_i})$

d_i – Average Inside Diameter Of The Casing (in.)

t_d – Donor Casing Thickness (in.)

B – Constant Depending On Donor Explosive And Casing Material

(3) $V_b = \left[\frac{K_f e^{(5.37 t_a / m^{1/3})}}{m^{2/3} (1 + 3.3 t_a / m^{1/3})} \right]^{1/2}$

Where V_b – Boundary Velocity (ft./sec.)

K_f – Explosive Sensitivity Constant

t_a – Acceptor Casing Thickness (in.)

Figure 1. Donor-Acceptor Relationships Governing Propaga[tion] By Fragment Impact.

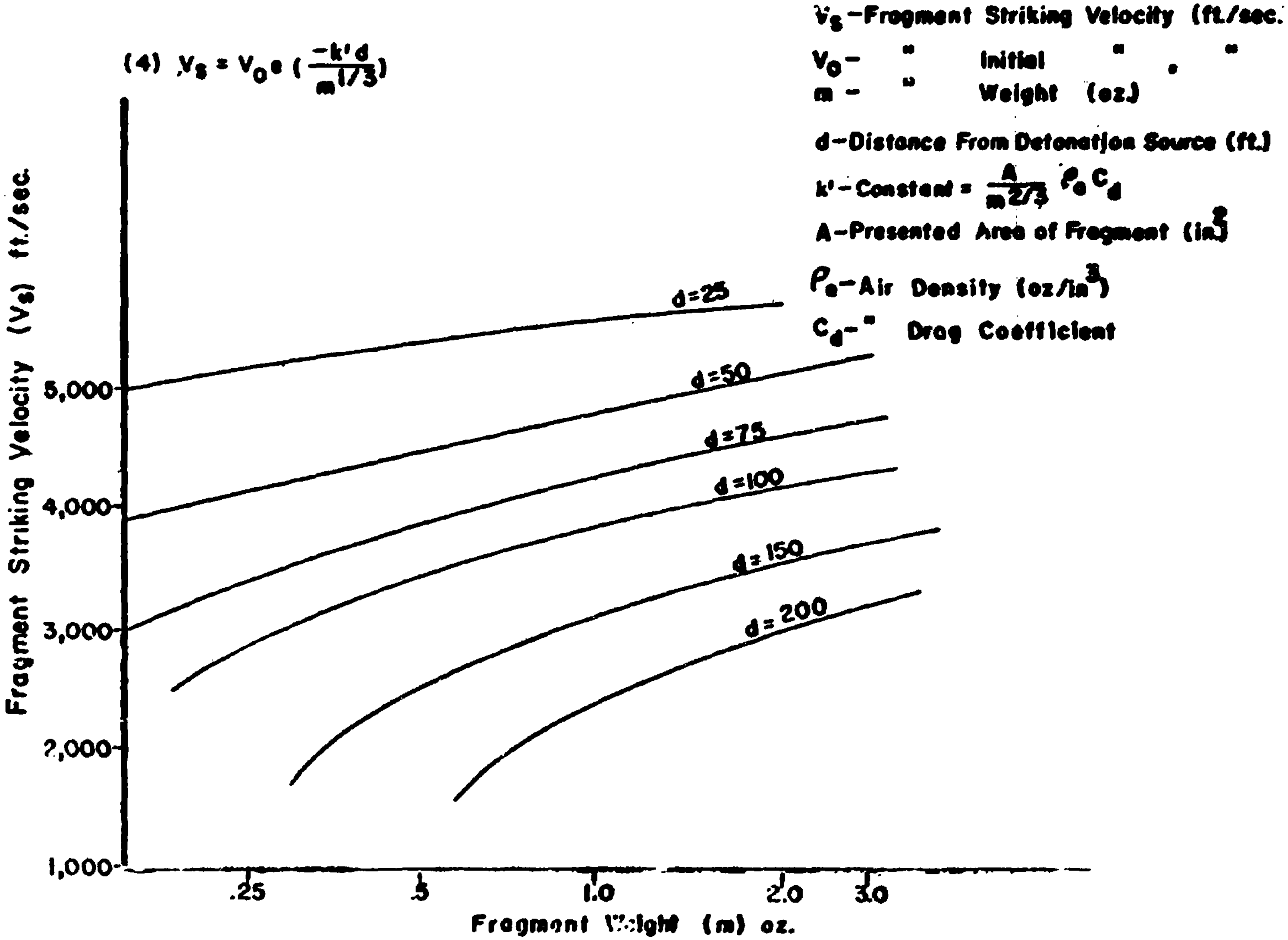
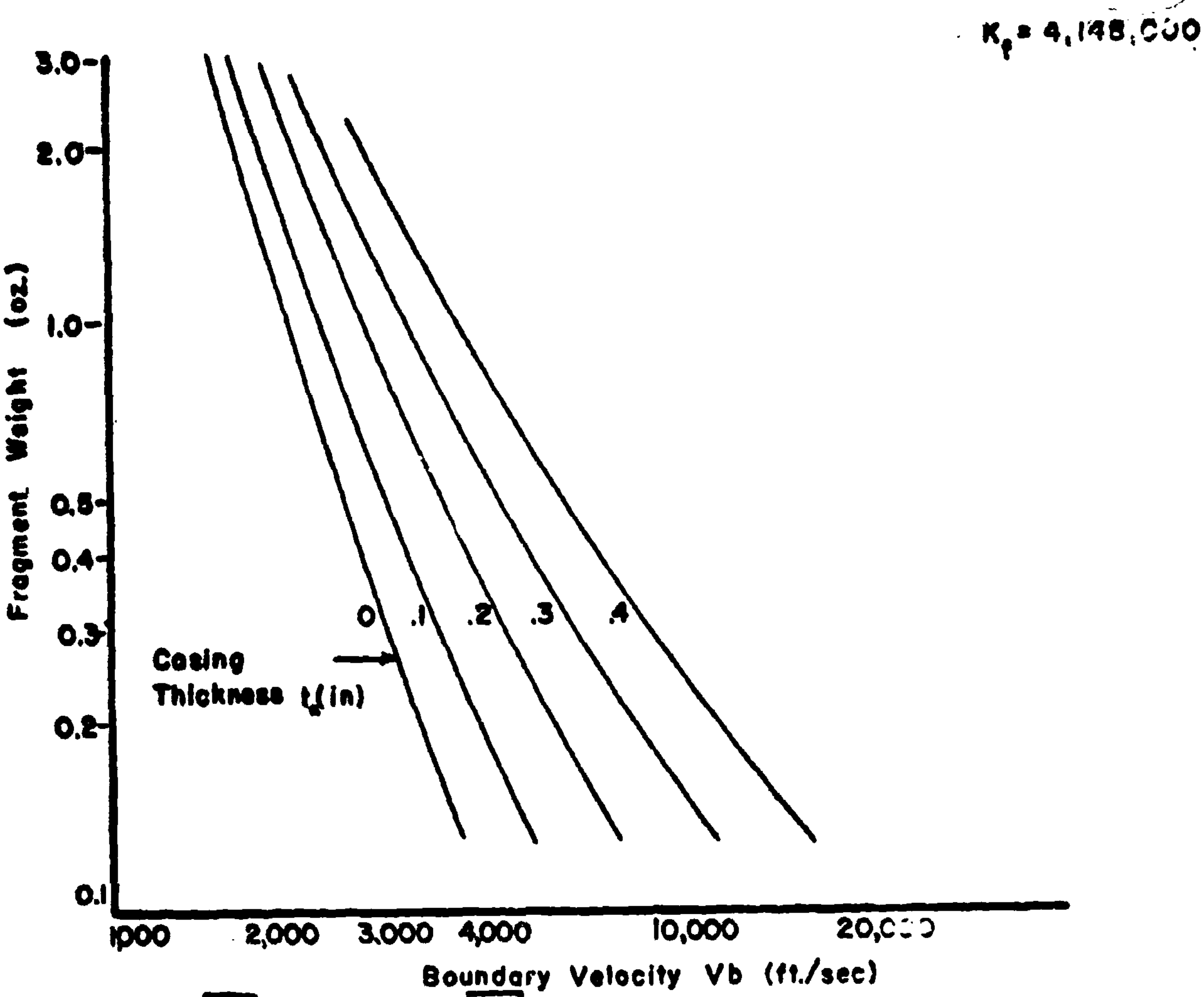


Figure 2. Striking Velocity Of A Fragment As A Function Of Fragment Weight And Distance For Cyclotol 60/40 And Initial Fragment Velocity "V_o" Of 6,000 ft./sec.



$$(3) \quad Vb = \left[\frac{K_f \, 5.37 ta/m^{1/3}}{m^{2/3}(1+3.3ta/m^{1/3})} \right]^{1/2}$$

Vb – Boundary Velocity (ft./sec.)

K_f – Sensitivity Constant for 60/40 Cyclotol

m – Fragment Weight (oz.)

ta – Acceptor Casing Thickness (in.)

Figure 3. Boundary Velocity as a Function of Fragment Weight and Acceptor Shielding for 60/40 Cyclotol.

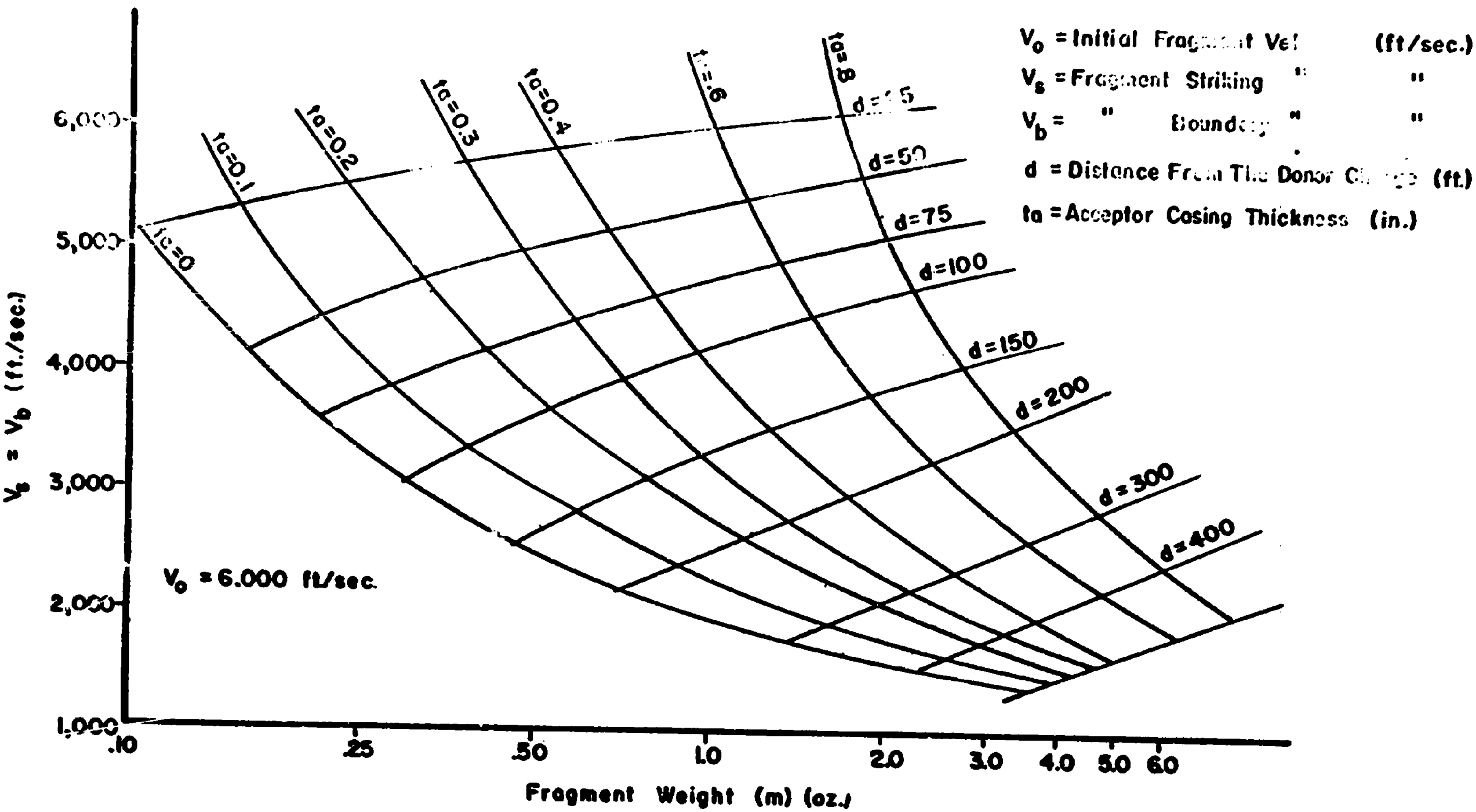


Figure 4. Minimum Effective Fragment Weight And Corresponding Velocity As A Function Of Distance And Shielding For 60/40 Cyclotol.

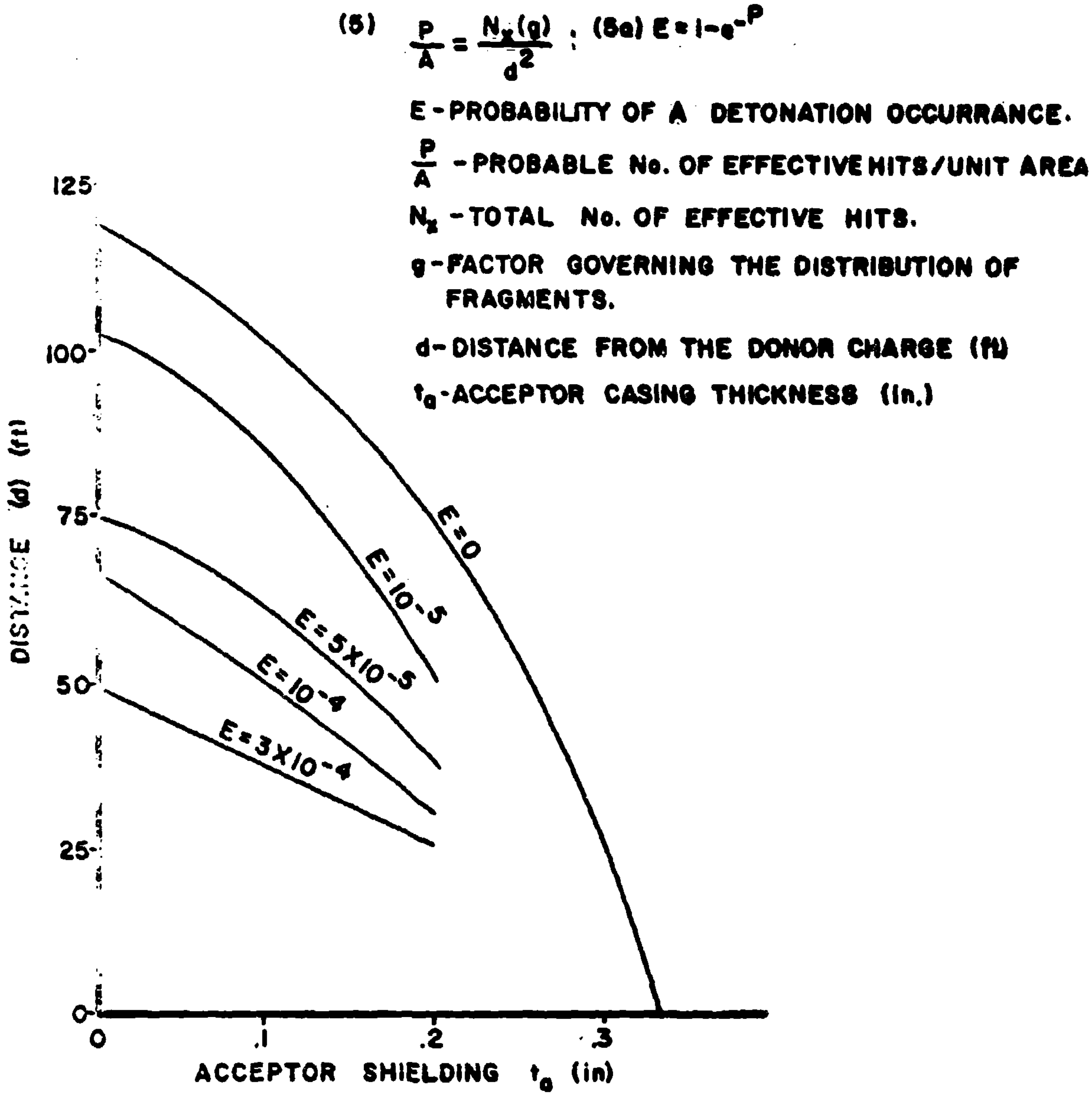


Figure 5. Probability of Detonation Occurrance as a Function of Distance and Shielding for 4.5in Rocket Head M32.

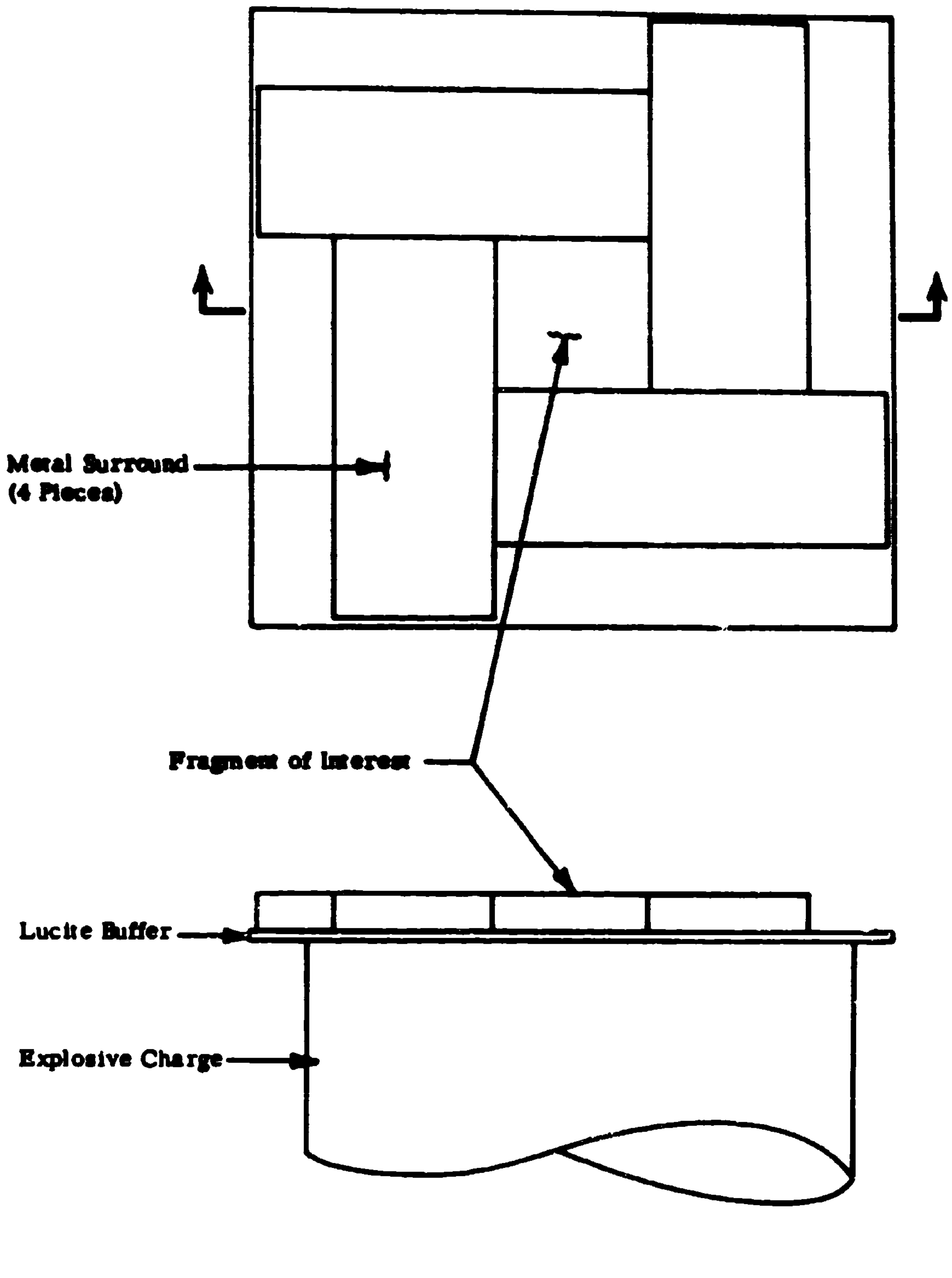


FIGURE 6 FRAGMENT ARRANGEMENT WITH METAL SURROUND

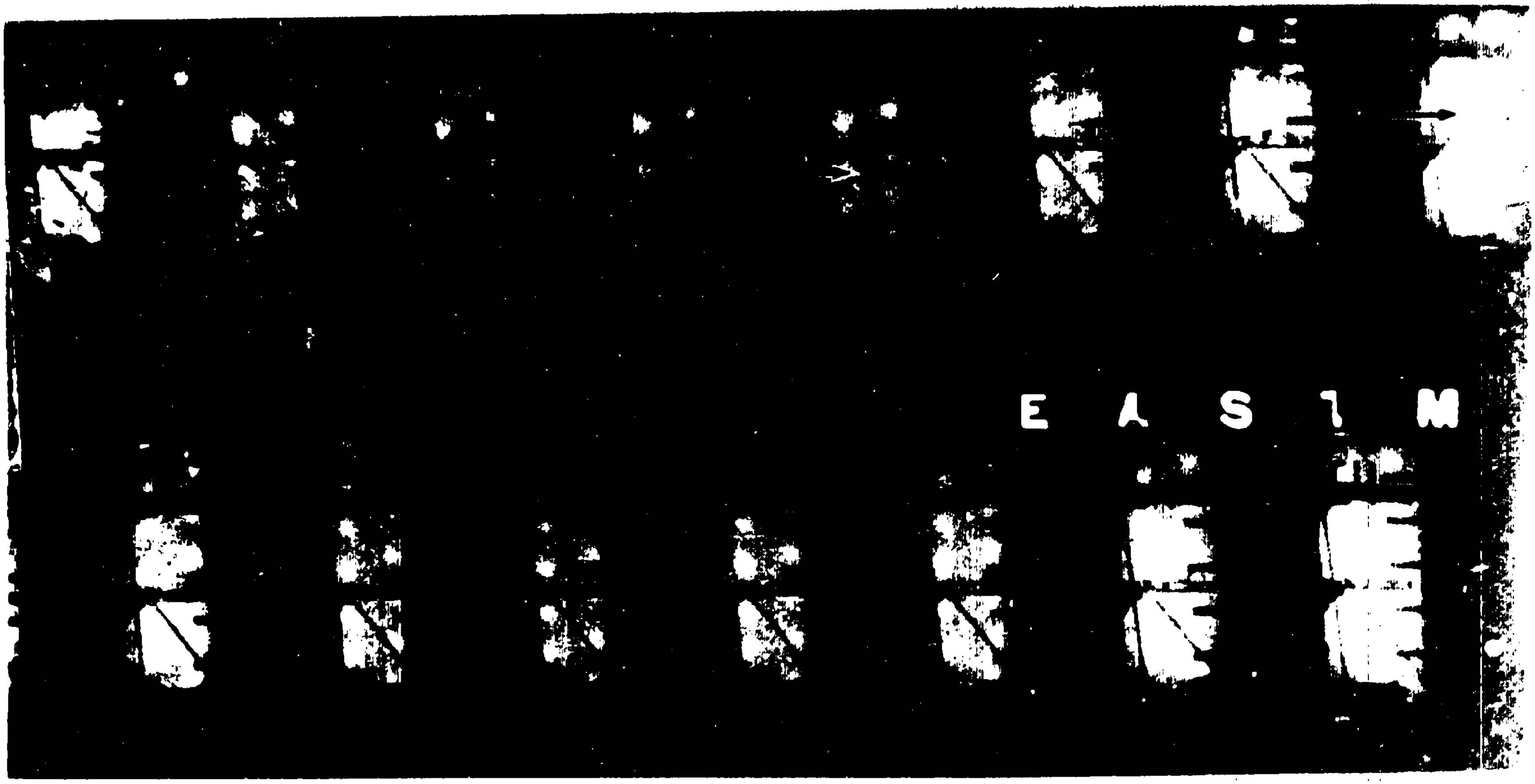


FIGURE 7 - HIGH SPEED PHOTOGRAPH FRAGMENT IN FLIGHT

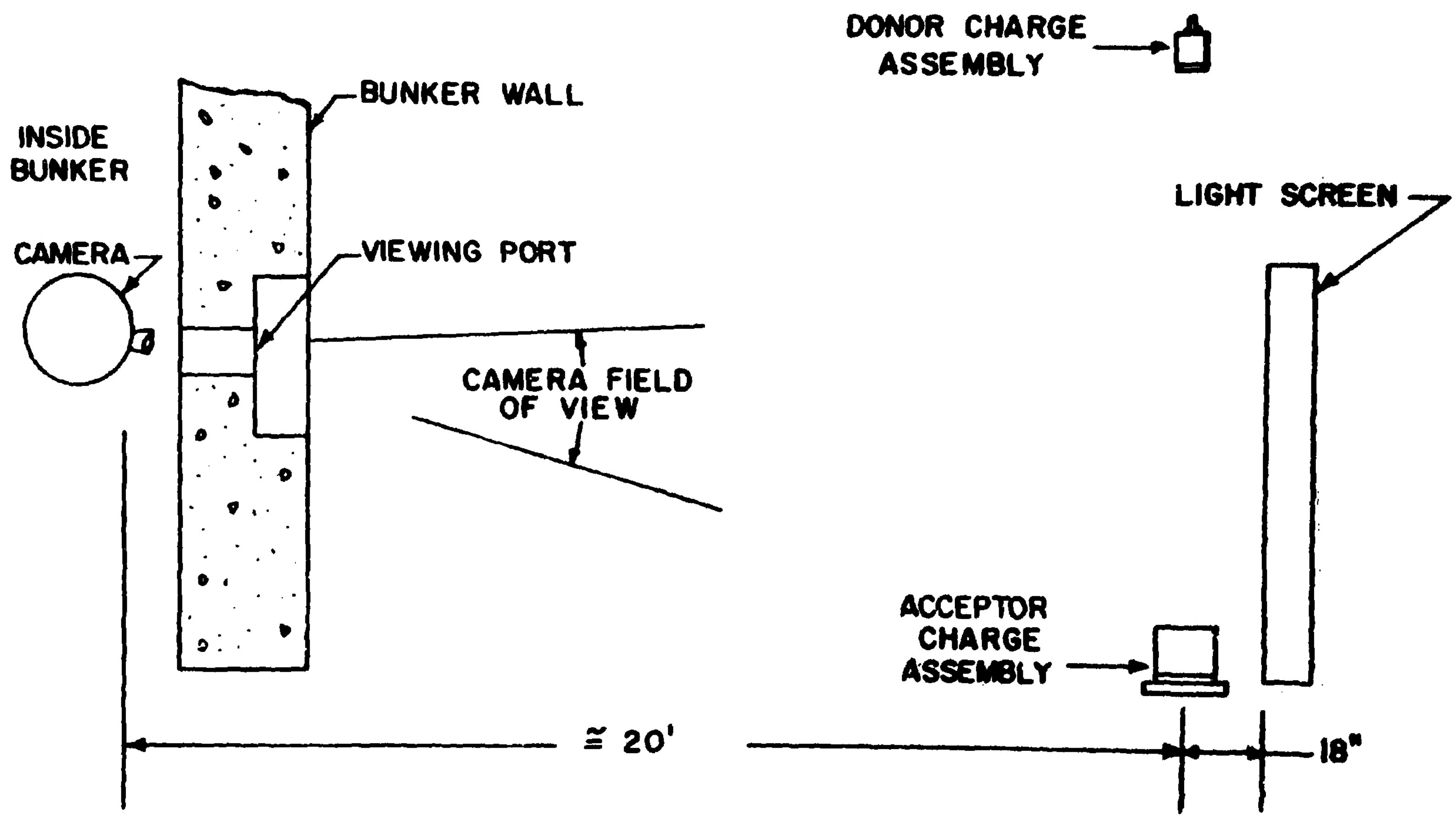


FIGURE 8 - CAMERA LAYOUT SCHEMATIC

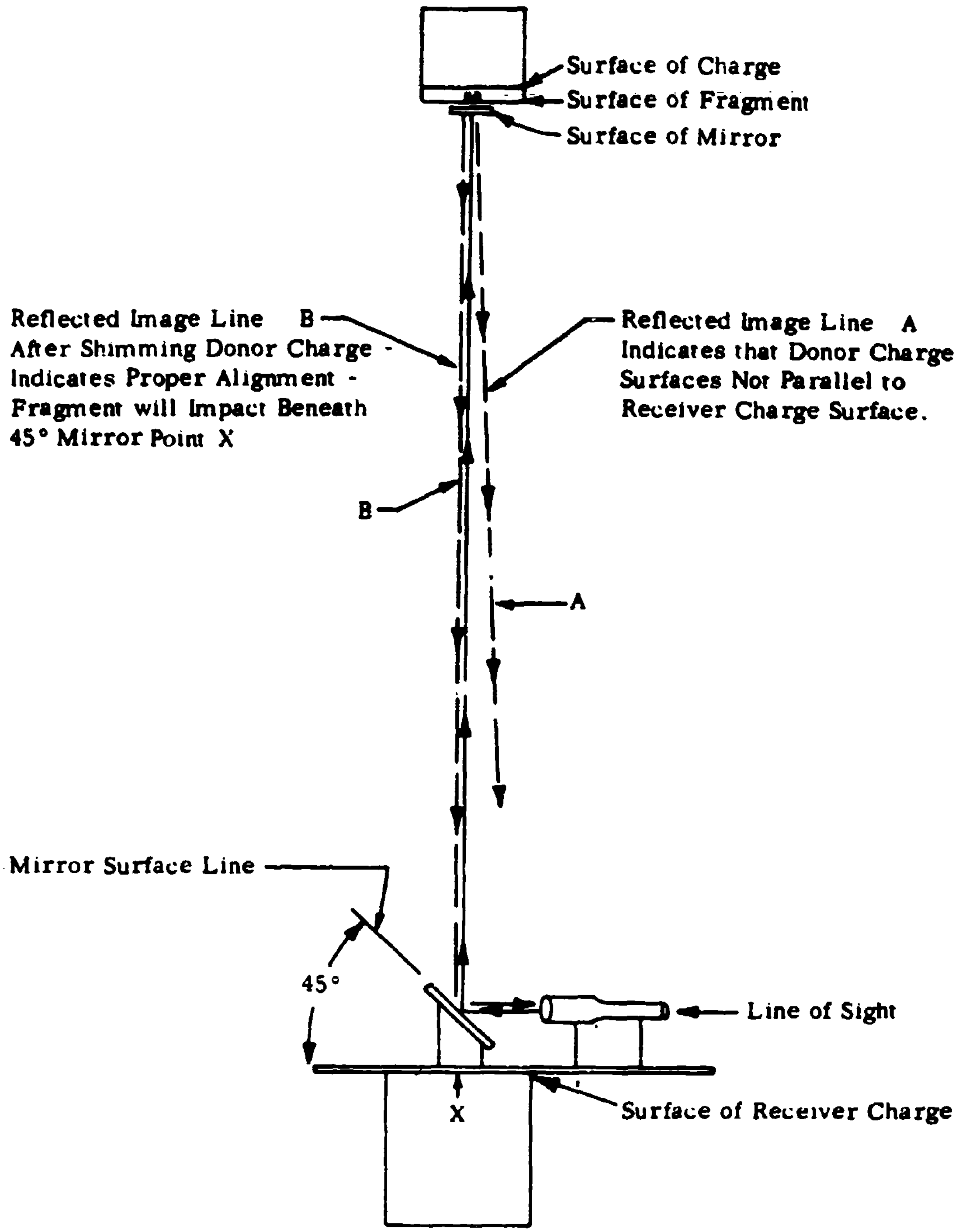


FIGURE 9 SCHEMATIC: FRAGMENT AIMING TECHNIQUE

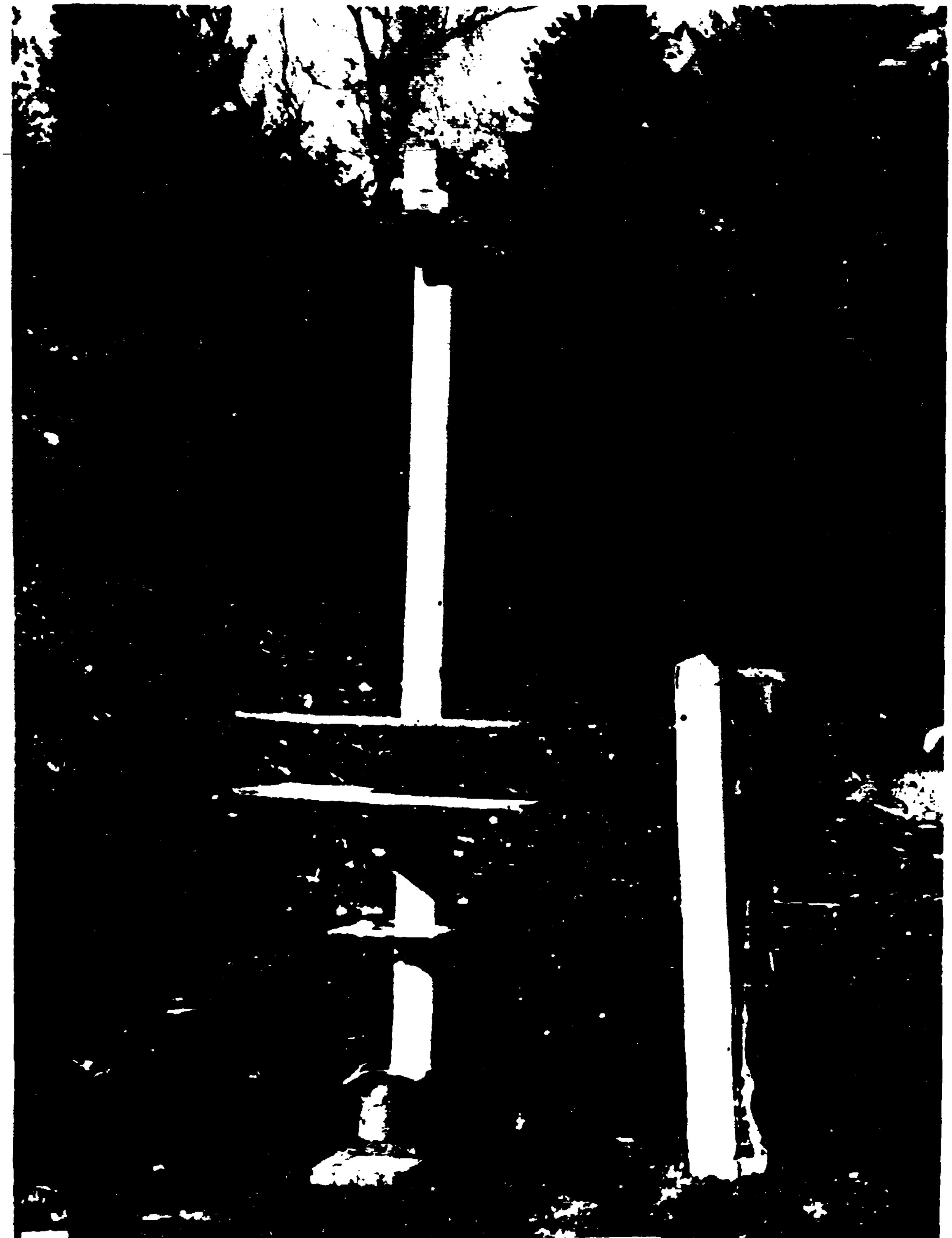


FIGURE 10 - TEST SET-UP

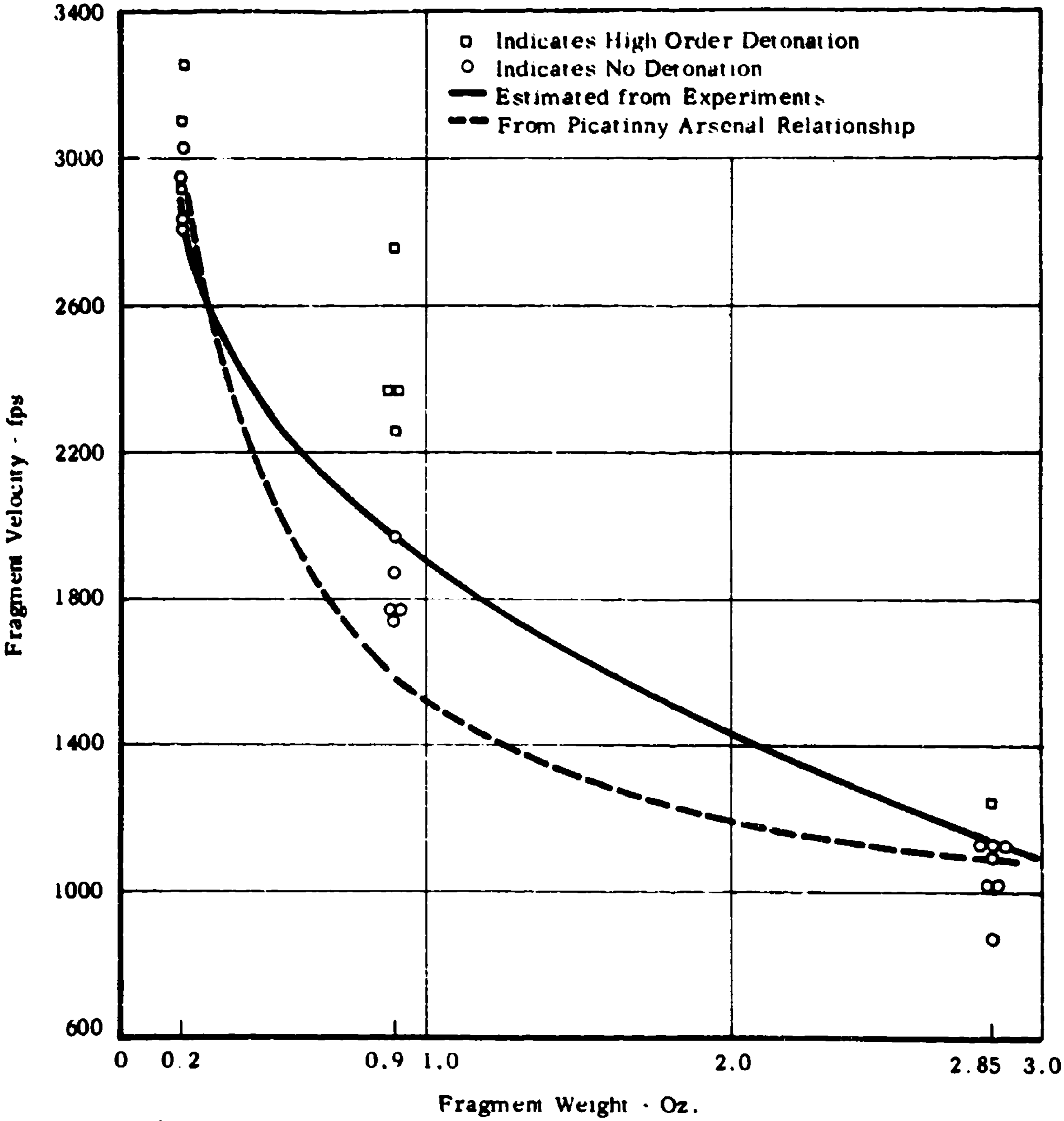


FIGURE 11 BOUNDARY VELOCITY CURVE OF PENTOLITE, SHOWING FRAGMENT IMPACT VELOCITY VERSUS FRAGMENT WEIGHT

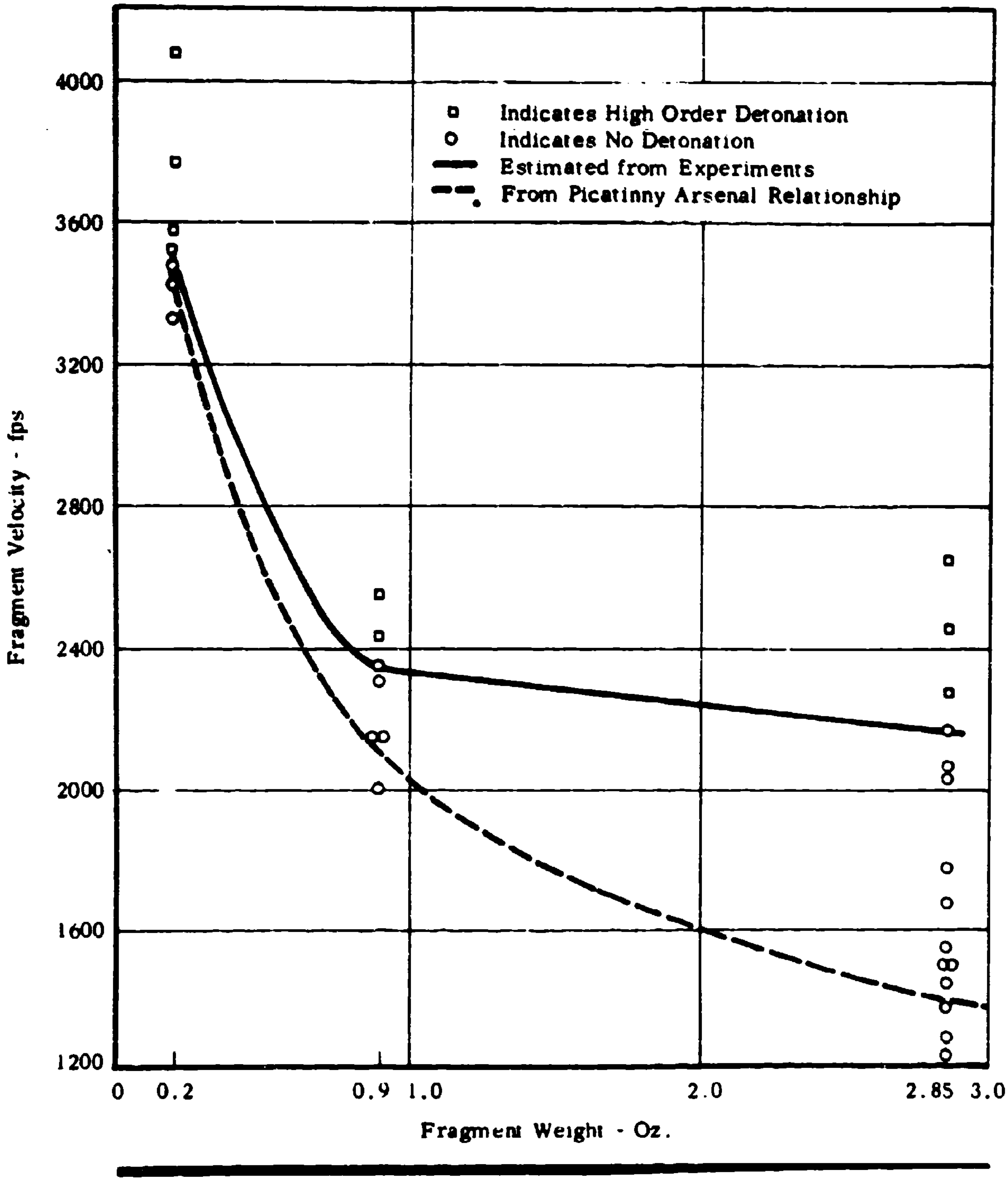


FIGURE 12 - BOUNDARY VELOCITY CURVE OF CYCLOTOL, SHOWING FRAGMENT IMPACT VELOCITY VERSUS FRAGMENT WEIGHT

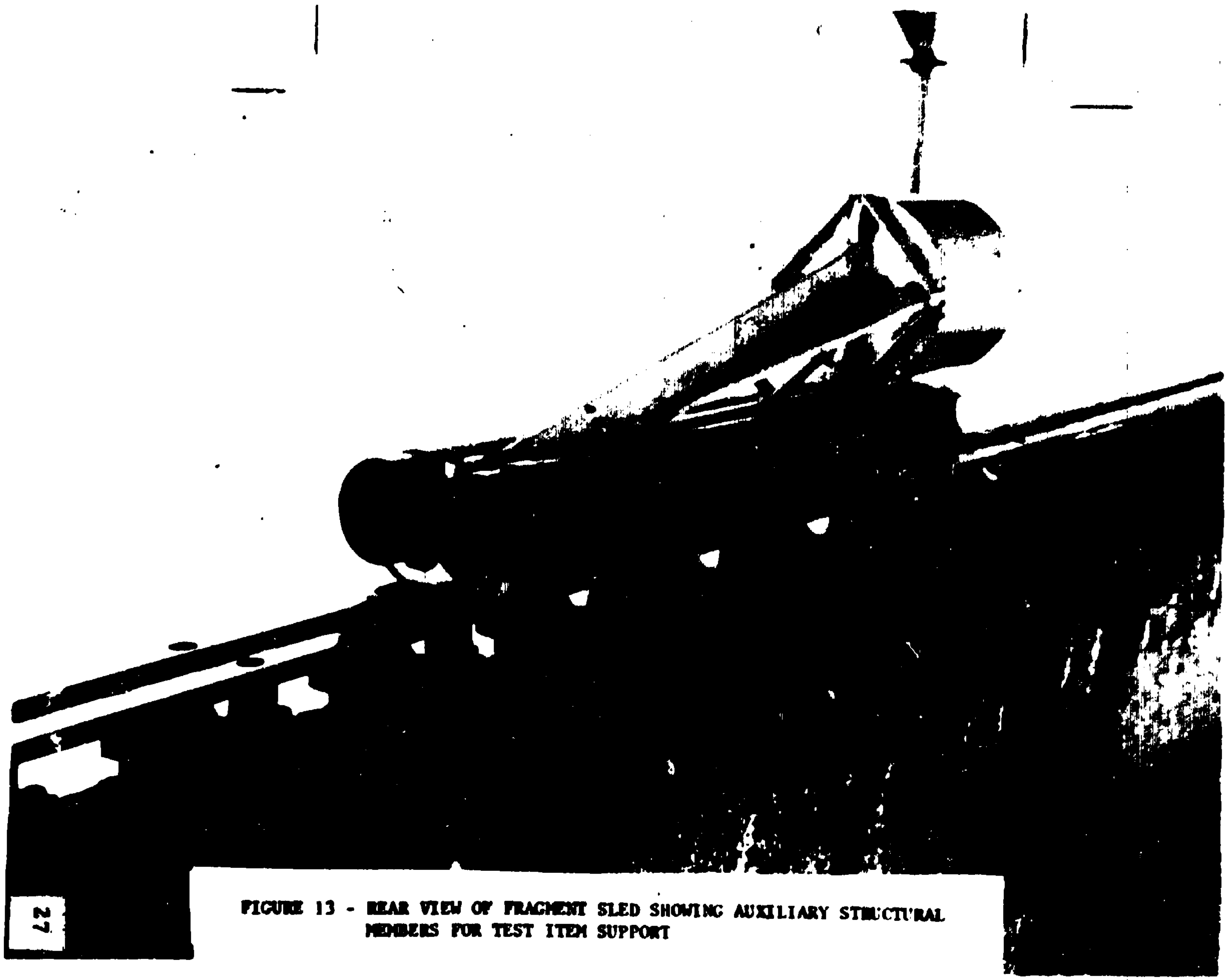


FIGURE 13 - REAR VIEW OF FRAGMENT SLED SHOWING AUXILIARY STRUCTURAL MEMBERS FOR TEST ITEM SUPPORT

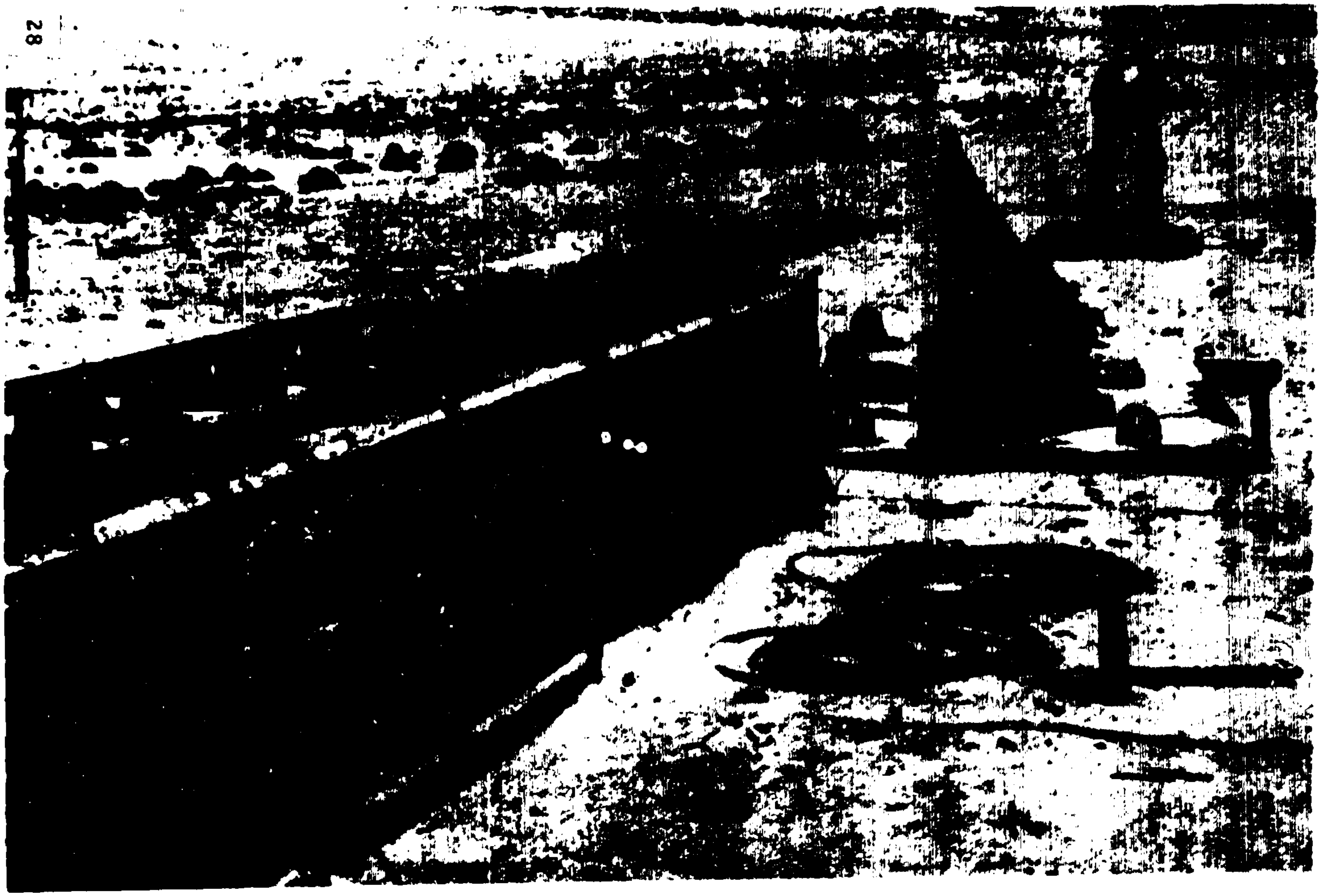


FIGURE 14 - TEST SET UP DETAILS
(WATER BRAKE, DEFLECTOR PLATE, AND ACCEPTOR-CHARGE TARGET)

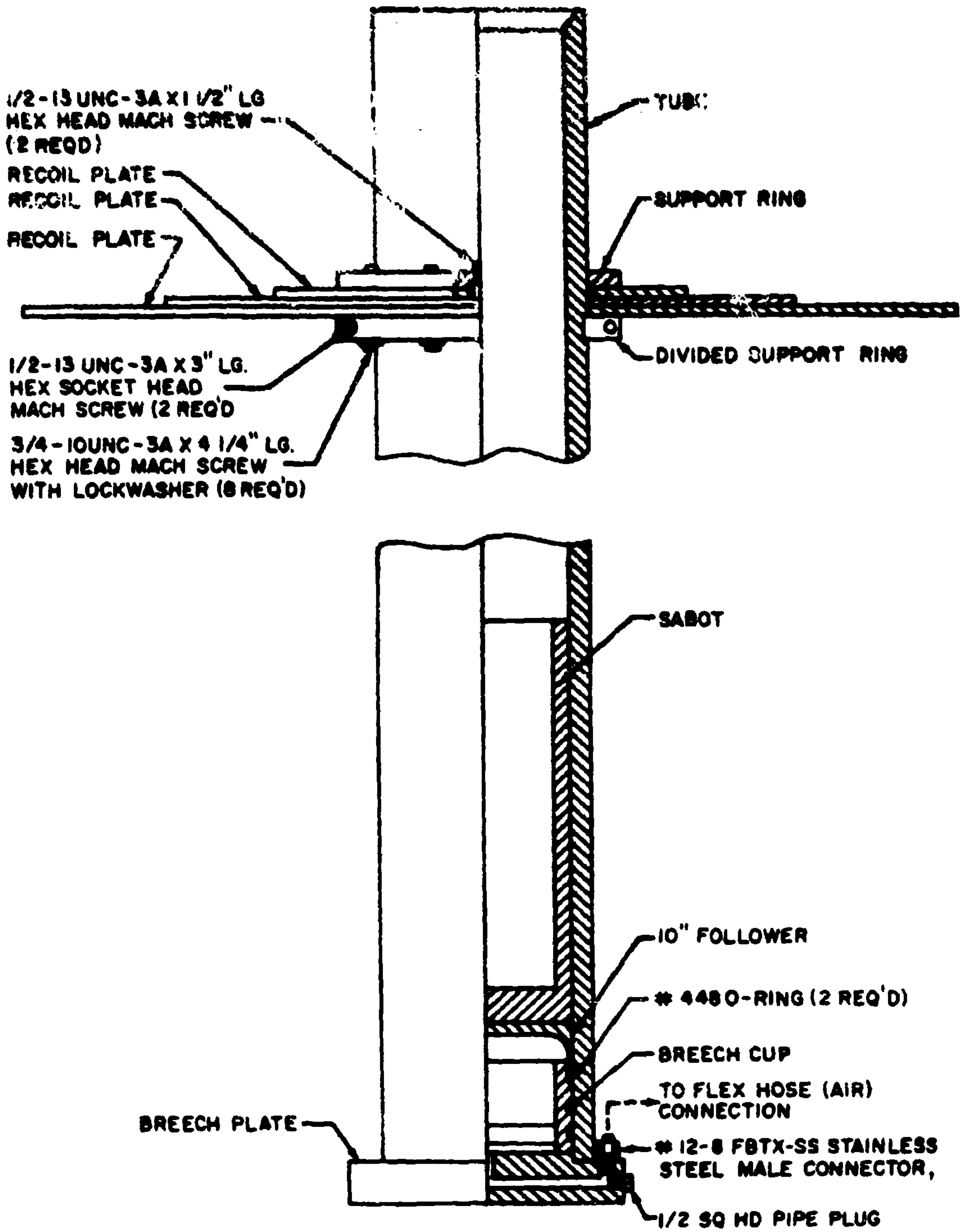


FIGURE 15 - GROUND MORTAR DEVICE ASSEMBLY

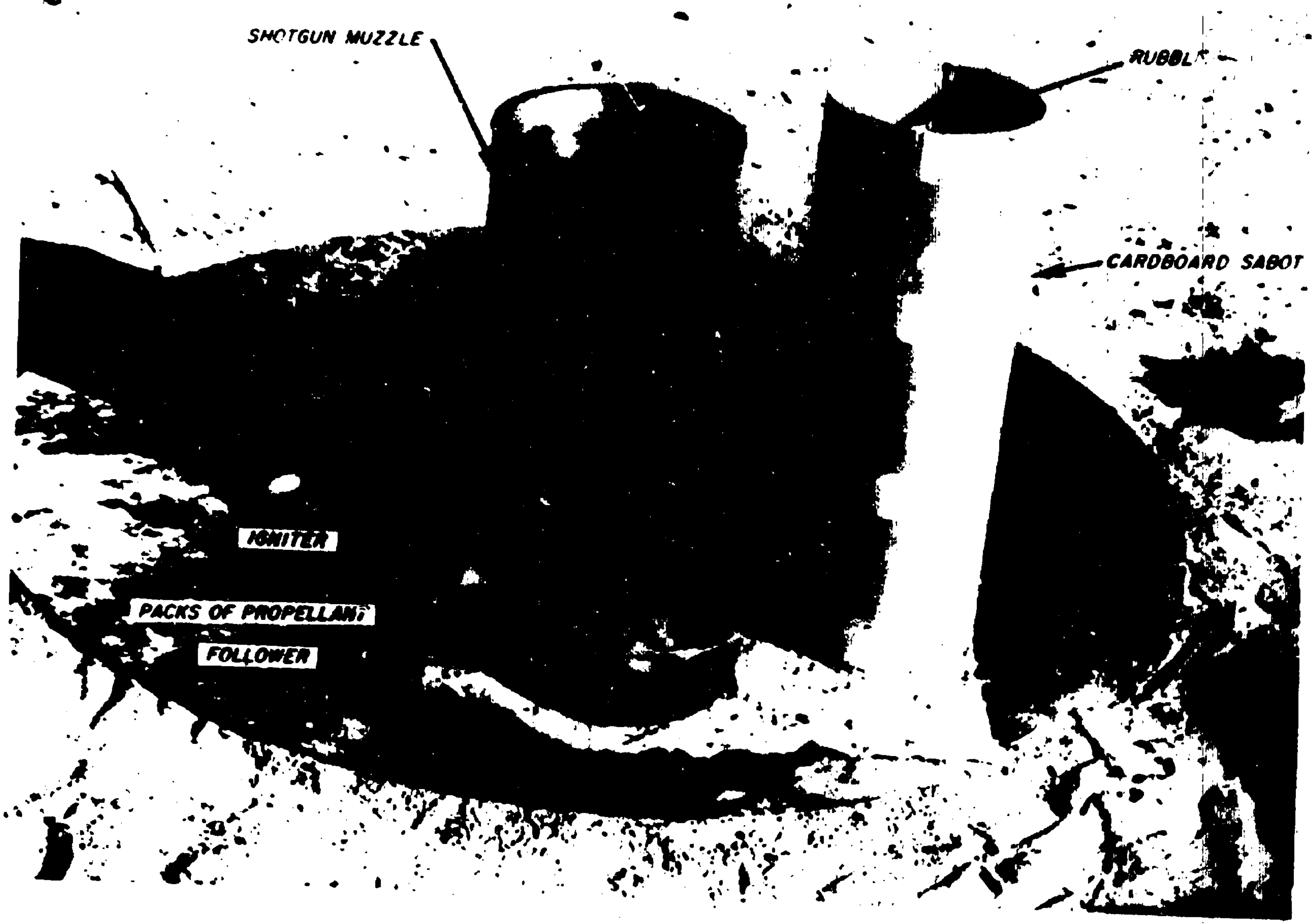


FIGURE 16 - GROUND MORTAR COMPONENTS

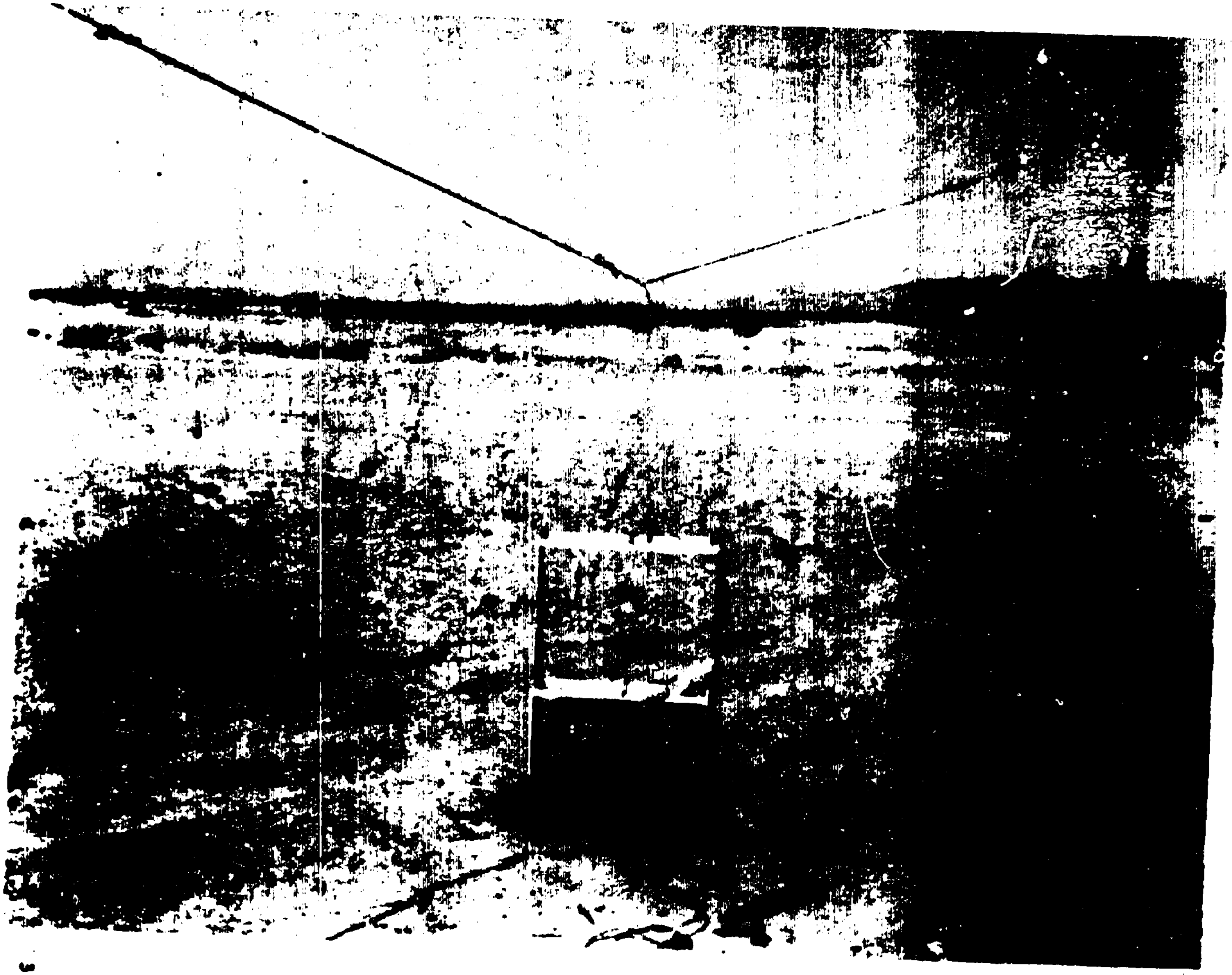


FIGURE 17 - GROUND MORTAR TEST SET UP

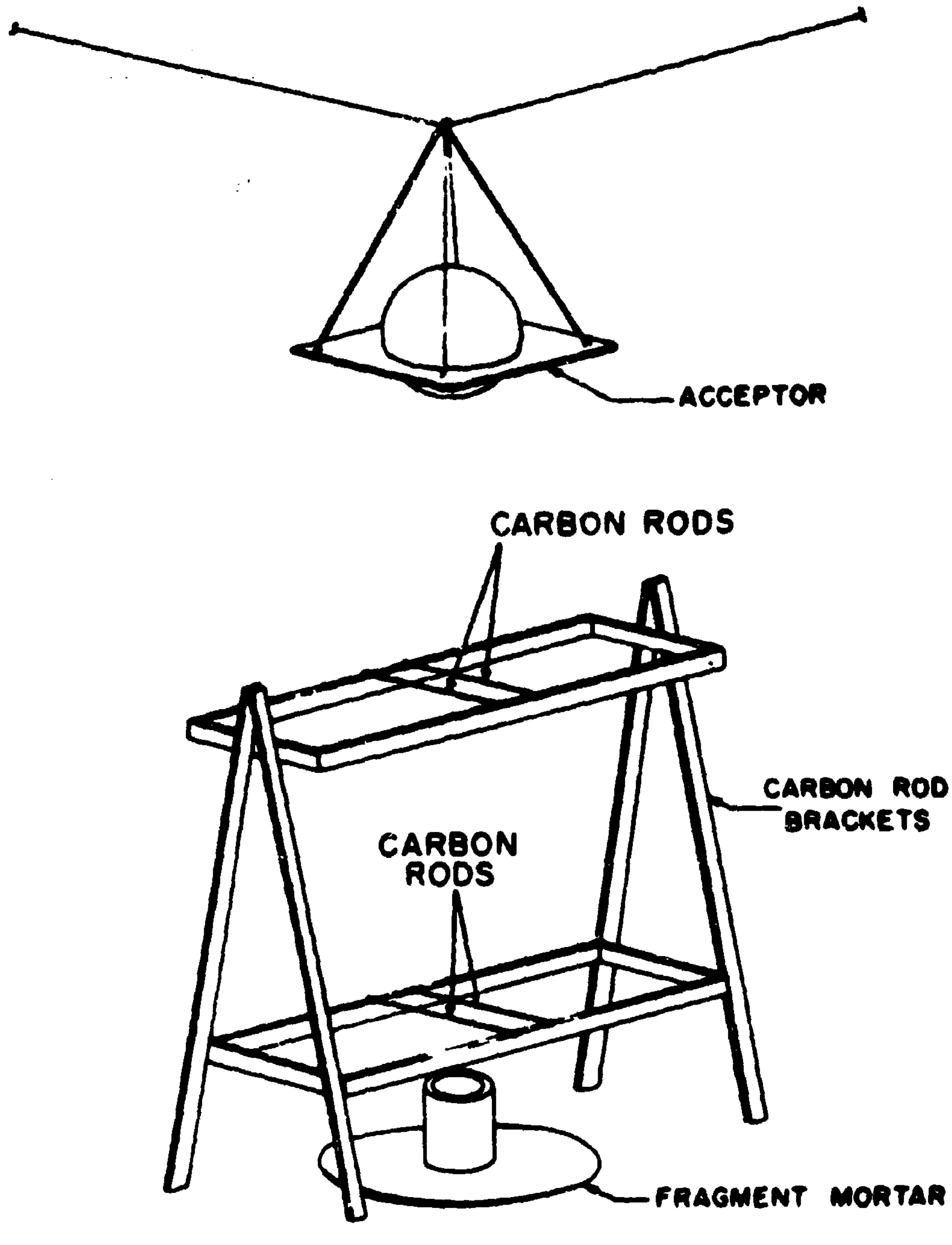


FIGURE 18 - GROUND MORTAR TEST SET UP WITH CARBON RODS IN POSITION

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13. ABSTRACT

This phase of the Safety Design Criteria Program conducted by the Ammunition Engineering Directorate's Process Engineering Laboratory deals with the analytical and experimental determination of the sensitivity of high explosives and high energy propellants to impact by primary and secondary fragments.

This material was the subject of a presentation made at the New York Academy of Sciences' Conference on Prevention of and Protection Against Accidential Explosion of Munitions, Fuels and other Hazardous Mixtures held in New York City 10-13 October 1966.

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Safety Design Criteria Program						
Fragment Impact Study						
Sensitivity of high explosive and high energy propellants						
Primary fragment						
Secondary fragment						
New York Academy of Science						
Explosive Prevention and Protection Seminar						

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