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X-RAY MULTI-FLASH SYSTEM FOR MEASUREMENT OF
PROJECTILE PERFORMANCE AT THE TARGET

by

Chester Grabarek
Louis Herr

September 1966

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SEPTEMBER 1966

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X-RAY MULTI-FLASH SYSTEM FOR MEASUREMENT OF
PROJECTILE PERFORMANCE AT THE TARGET

Chester Grabarek
Louis Herr

Terminal Ballistics Laboratory

RDT&E Project No. 1P014501A33E

ABERDEEN PROVING GROUND, MARYLAND

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CGrabarek/LHerr/cr
Aberdeen Proving Ground, Md.
September 1966

X-RAY MULTI-FLASH SYSTEM FOR MEASUREMENT OF
PROJECTILE PERFORMANCE AT THE TARGET

ABSTRACT

A new technique using a multi-flash x-ray system has been developed to measure projectile striking velocity, angle of yaw at impact, plastic flow properties at the projectile/target interface, penetration time, and the amount and direction of material emerging from the rear surface of the target.

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INTRODUCTION

The terminal ballistic performance of kinetic energy projectiles attacking a target is important to projectile designers and to weapon systems analysts. A knowledge of the behavior of penetration velocities as a function of target material and penetrator material design will permit and assist in the development of new materials for use in kinetic energy projectiles. In order to evaluate the effectiveness of a penetrating projectile, data pertaining to phenomena behind the target are required. The principle contributions to damage behind the target are made by the remaining projectile and fragments from the projectile, and the target following projectile perforation. To evaluate damage behind the target, the dynamics of such fragments in terms of weight, speed, and spatial distribution are needed. A new technique employing a multiple flash x-ray system has been developed and tested which describes projectile approach, penetration, and subsequent emergence and spall characteristics.

MULTI-FLASH X-RAY SYSTEM

The 105-KV x-ray system consists of 12 x-ray tubes arranged as shown in Figure 1. A time delay generator in the system pulses each tube or set of tubes for 0.1 μ sec at preset time intervals ranging from 1 μ sec to 10 m sec. Each tube is contained in a housing 2-1/8 inches in diameter and 12 inches long.

Four tubes arranged in pairs provide simultaneous orthogonal radiographs of the projectile in free flight before target impact. The projectile striking velocity and angle of yaw are measured from these radiographs.

Six tubes mounted in one vertical plane are used to obtain measurements of the projectile deformation at impact and distance-time during penetration.

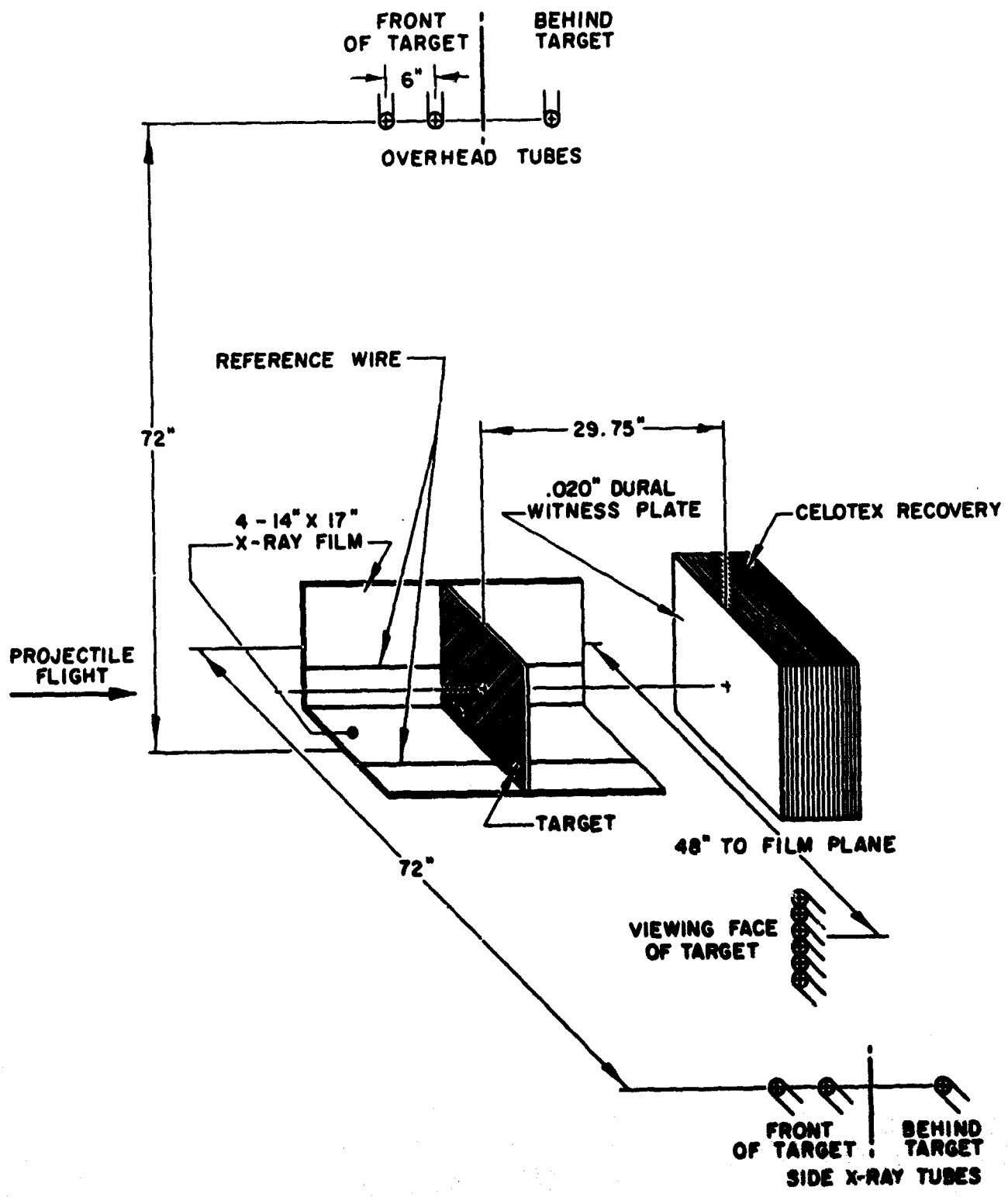


FIGURE 1. - EXPERIMENTAL TEST SET-UP OF X-RAY INSTRUMENTATION FOR OBTAINING PENETRATION DATA FOR PROJECTILES.

Two tubes arranged in an orthogonal plane behind the target are pulsed simultaneously at a preset time to supply the data needed to determine the parameters behind the target.

Celotex sheets located approximately thirty inches behind the target permit the recovery of fragments if desired.

PROJECTILE PERFORMANCE BEFORE AND DURING TARGET IMPACT

The x-rays provide radiographs of the projectile in free flight and at impact, and from these radiographs the striking velocity, yaw and displacement-time are obtained.

Projectile Velocity

The projectile velocity is determined by measurements taken from a sequence of flash radiographs of the projectile in flight. These measurements are corrected by an appropriate magnification factor (K),* to describe the actual projectile path. The system of coordinates used is shown in Figure 2 and the Appendix. The bottom film lies in the X-Z plane and the side film lies in the Y-Z plane. Values of X, Y and Z are obtained directly from the radiographs and K is given by the equation:

$$K = \frac{Y_3 (X_1 - X_4) - Y_1 (X_3 - X_4)}{X_1 Y_3 + (X_3 - X_4) (Y_2 - Y_1)} \quad (1)$$

where X and Y are the horizontal and vertical coordinates respectively. Subscripts denote x-ray tube coordinates and radiographic coordinates of the projectile. The projectile coordinates in space* are:

$$x = X_1 (1 - K) \quad (2)$$

$$y = Y_1 + K (Y_2 - Y_1) \quad (3)$$

$$z = Z_2 K \quad (4)$$

The distance traveled by the projectile between x-ray tube stations is:

$$S = z_2 - z_1 \quad (5)$$

* See Appendix for derivation.

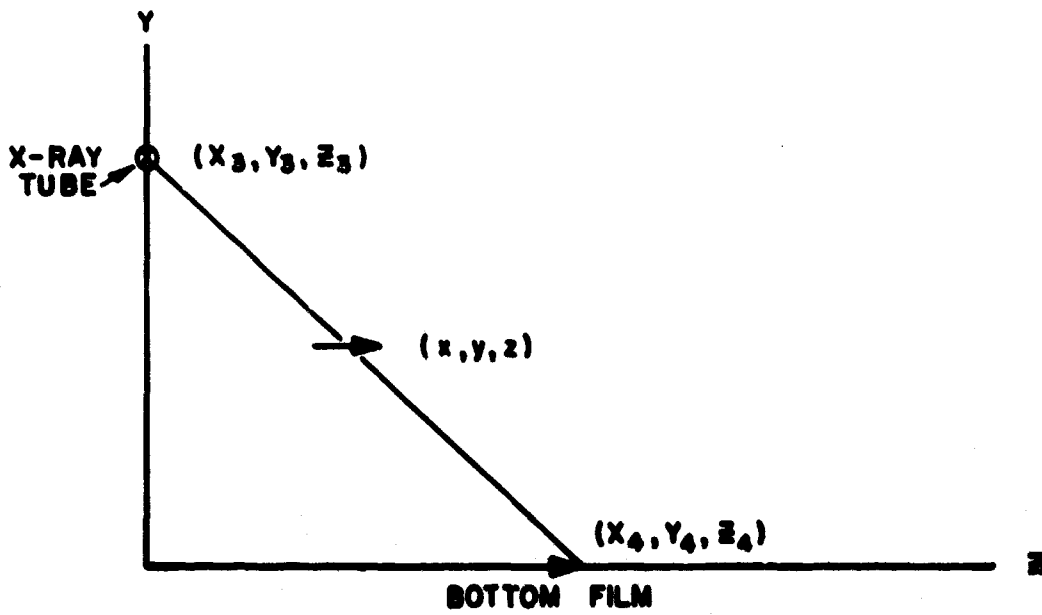
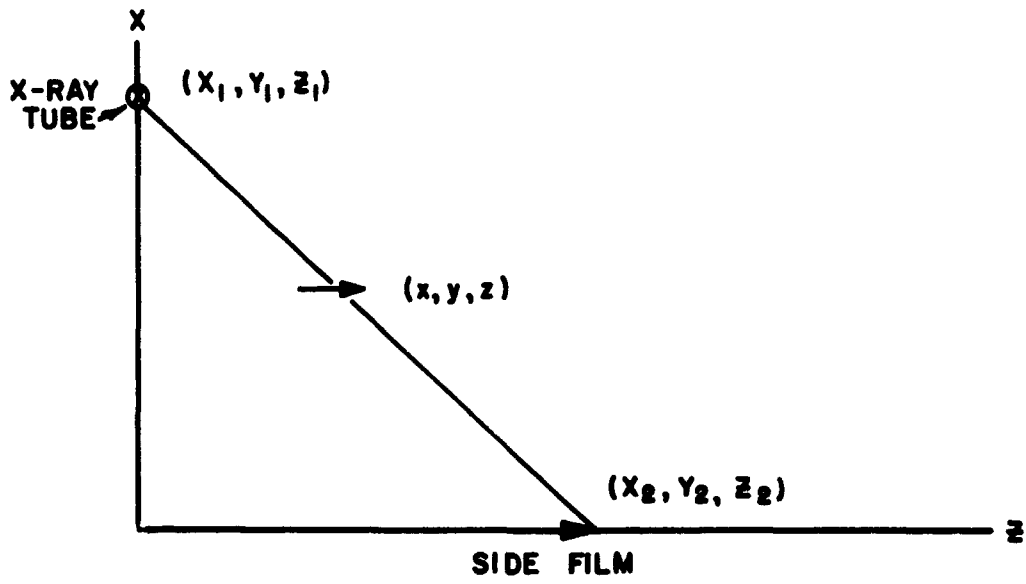


FIGURE 2
COORDINATE SYSTEM

With S and the known time, t, between tube flashes of station 1 and station 2, the average projectile velocity is:

$$v_a = \frac{S}{t} \quad (6)$$

and the projectile striking velocity is:

$$v_s = v_a \exp \left(- K_D \rho \frac{d^2}{M} s \right) \quad (7)$$

where

K_D = drag coefficient

ρ = air density

d = projectile body diameter

M = projectile weight

s = distance of projectile travel to target.

Projectile Yaw

As the projectile moves along its trajectory, its axis of symmetry makes an angle of yaw, δ , with the direction of motion, Figure 3. The angle of yaw is determined by:

$$\tan \delta = \sqrt{\tan^2 \alpha + \tan^2 \beta} \quad , \quad (8)$$

where

α = the angle between the longitudinal axis of the projectile and the line of flight of the projectile measured from the side radiograph.

β = the angle between the longitudinal axis of the projectile and the line of flight of the projectile measured from the bottom radiograph.

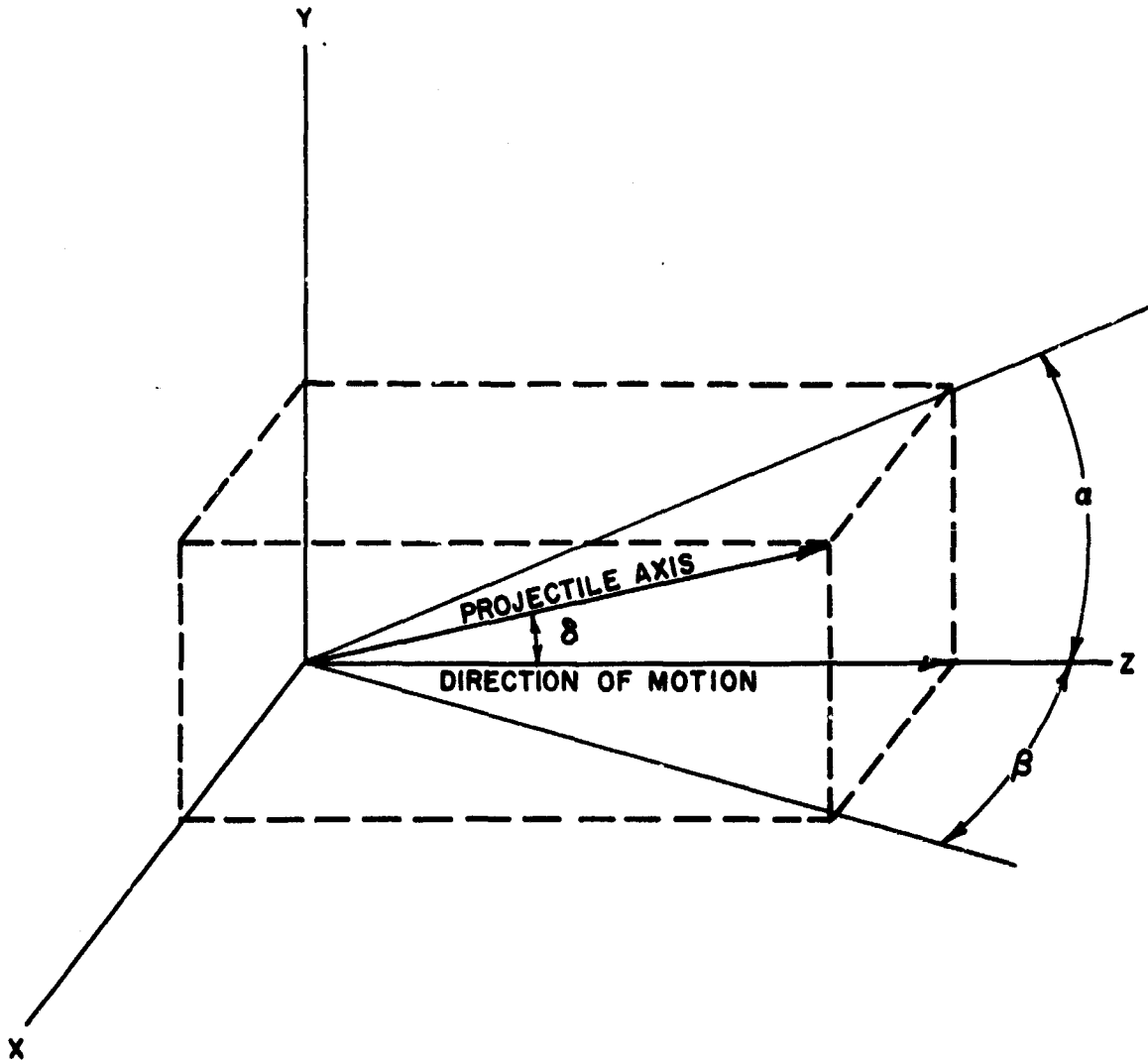


FIGURE 3
PROJECTILE ANGLE OF YAW (δ)

Displacement-Time

Sequential x-ray flashes, superimposed on one x-ray film by six or more tubes mounted vertically in one plane, are used to obtain measurements of displacement-time at the free end of the projectile during penetration. This sequence of radiographs also provides a measure of the plastic deformation of the projectile at the projectile-target interface as a function of time (Figure 4).

The free-end projectile displacement measurement is made from the radiograph by measuring the Z component of projectile length at the different times after the initial impact. The projectile length measurement, L, obtained from the radiograph is corrected to the actual projectile length by:

$$l = L \left(\frac{X_1 - X_m}{X_1} \right), \quad (9)$$

where X_m is the distance from film to target impact point. The projectile free-end velocity is given by:

$$v = \frac{l_1 - l_2}{t_2 - t_1} \quad (10)$$

and the projectile free-end deceleration is given by:

$$-a = \frac{v_2 - v_1}{t_2 - t_1} \quad (11)$$

BEHIND THE TARGET PROJECTILE PERFORMANCE

To characterize the phenomena taking place behind the impacted target, it is necessary to find the weight and spacial distribution, and residual velocity of projectile and spall fragments.

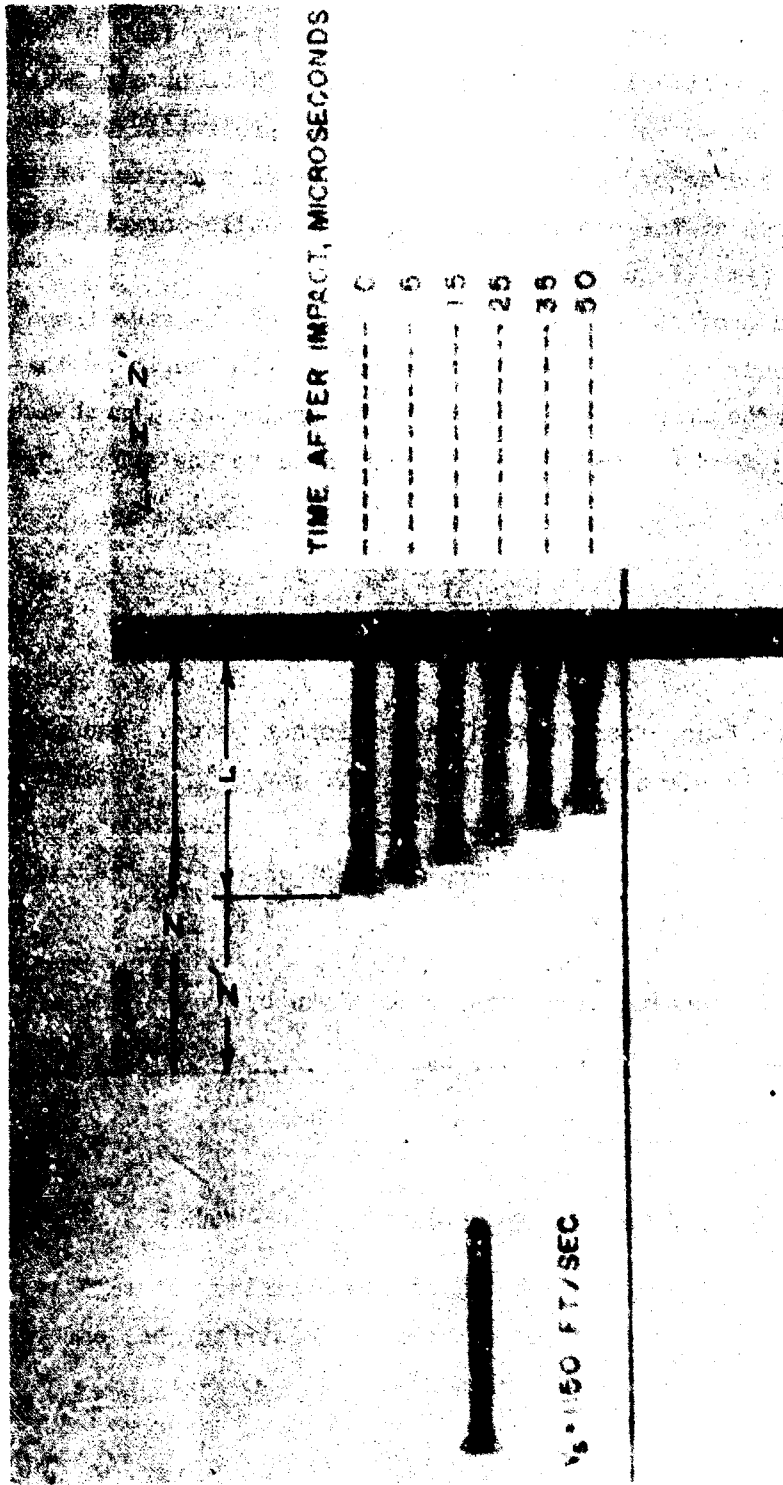


FIGURE 4 FLASH RADIOGRAPH OF A ROD IMPACTING A STEEL TARGET

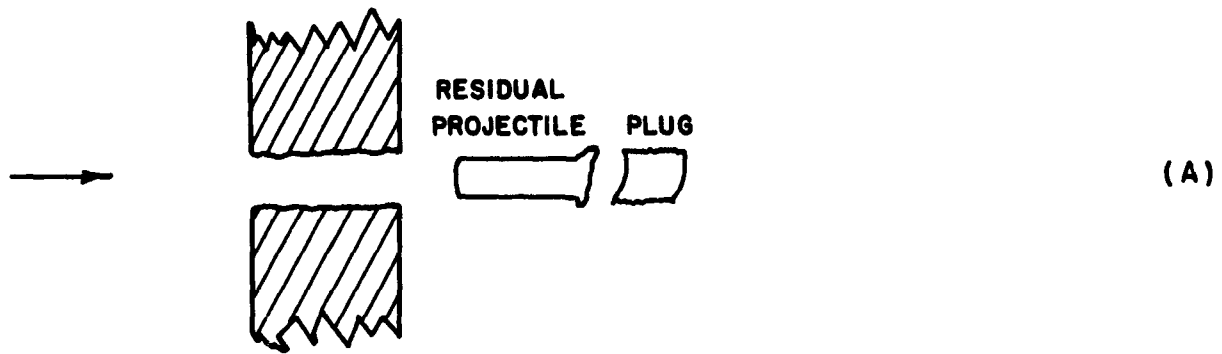
Estimating Fragment Weight

The weights of the target fragments projected from the rear surface of the target can be estimated from the radiographs. These estimates must be checked by measuring the thicknesses in a recovered sample of fragments from a few rounds for the particular projectile-target combination under study. The measured fragment thicknesses are averaged, and this average is used for subsequent rounds of the same projectile-target combination.

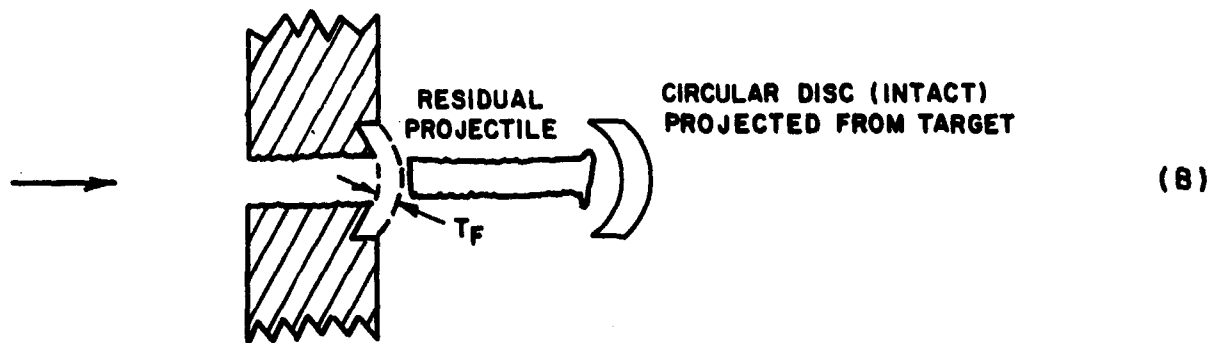
During the projectile penetration around the area of contact, in the case of rolled homogeneous steel armor, a bulge starts to form at the rear surface. Failure of the plate occurs when the bulged portion is sheared from the plate. At striking velocities near the ballistic-limit velocity, the sheared out portion is in the form of a plug whose weight is easily determined from the orthogonal radiographs. As the striking velocity is increased, the sheared out portion changes from a plug to a circular disc considerably larger in diameter than the projectile. Further increases in striking velocity cause the disc to break into fragments of different size. The length and width of the fragment is obtained from the orthogonal radiographs by assuming a rectangular shape for the fragment. However, the fragment thickness is difficult to measure to any degree of accuracy because certain positions of the fragment in free flight result in a projected thickness which cannot be corrected accurately from the orthogonal radiographs to the actual fragment thickness. Consequently, the fragment thickness, T_F , measurement is obtained directly from the rear surface of the target as shown in Figure 5. The measured fragment length, L_F , and width, W_F , obtained from the radiographs, are corrected to the actual size by:

$$t_F = K L_F \quad (12)$$

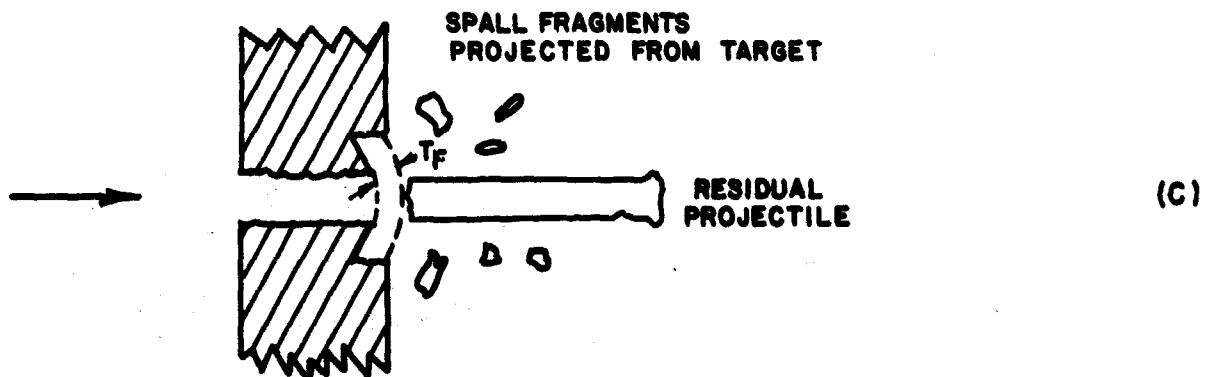
$$w_F = K W_F \quad (13)$$



PROJECTILE STRIKING VELOCITY SLIGHTLY ABOVE THE BALLISTIC LIMIT VELOCITY



PROJECTILE STRIKING VELOCITY INCREASED ABOVE (A)



PROJECTILE STRIKING VELOCITY INCREASED ABOVE (B)

FIGURE 5
PROJECTILE PERFORATING ROLLED HOMOGENOUS ARMOR AT
DIFFERENT STRIKING VELOCITIES

The weight of the fragment is:

$$wt = l_F w_F T_F \rho , \quad (14)$$

where ρ is the fragment material density.

A sample of fragment weights estimated from orthogonal radiographs are compared to actual fragment weights in the following Table. The fragments listed were projected from the rear surface of rolled homogeneous armor.

FRAGMENT WEIGHT, GRAINS

<u>Actual</u>	<u>Estimated</u>
22.6	20.5
18.9	17.4
13.6	14.3
13.4	14.0
12.3	12.3
11.0	10.3
10.0	10.8
8.0	7.1
7.4	8.7
6.5	6.5
6.5	5.7
5.5	5.7
4.0	4.1
3.4	3.8
2.1	2.2
1.9	2.2
1.7	1.5
1.6	1.6
1.1	1.2
.9	.8

The estimated fragment weights, on the average, is within about 8 percent of the actual weight.

For estimating the residual projectile weight, the same procedure is used as that for the fragments, but the estimated weight is, on the average, within about 2 percent of the actual weight.

Space Coordinates

The positions of the residual projectile and spall fragments in space are determined by the measured coordinates of the impact point on the target and the particular projectile and/or fragment space coordinates, Figure 6.

From these quantities the direction angles θ and ϕ are computed. The angle θ is called the departure angle from the line of fire and ϕ the angle of orientation, observed from the origin of the trajectory and measured in a clockwise direction. The angle θ is:

$$\cos^{-1} \theta = \left(\frac{z - z_T}{\sqrt{(x - x_T)^2 + (y - y_T)^2 + (z - z_T)^2}} \right) \quad (15)$$

and ϕ is

$$\cos^{-1} \phi = \left(\frac{y - y_T}{\sqrt{(x - x_T)^2 + (y - y_T)^2}} \right) \quad (16)$$

where the subscript (T) denotes the target impact point coordinates.

Residual Velocity

The residual velocities of the projectile and spall fragments are obtained by the use of two x-ray tubes arranged in an orthogonal view behind the target. The tubes are pulsed simultaneously at a preset time. Figure 7 is a flash radiograph showing the projectile and spall fragments behind the target.

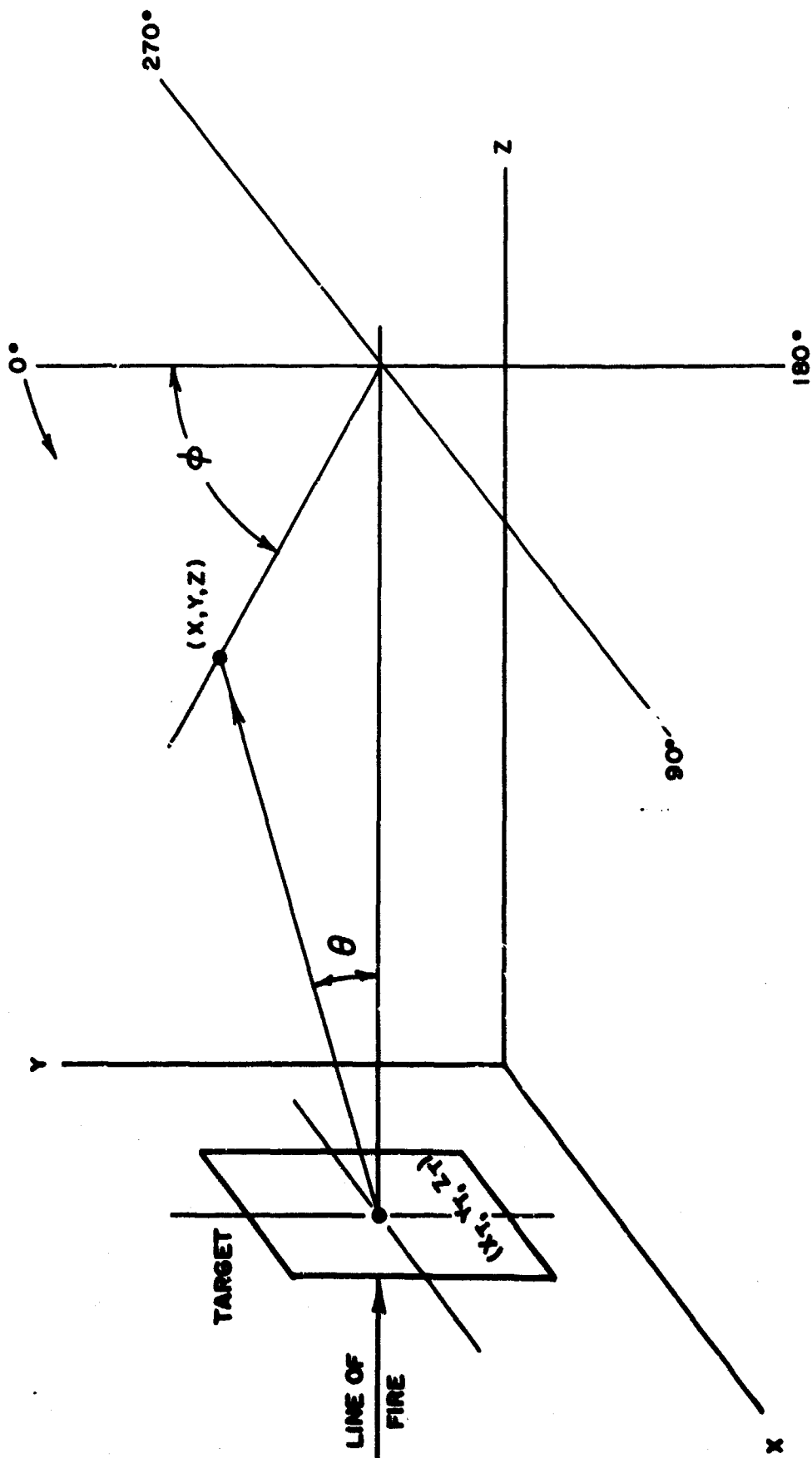


FIGURE 6
 COORDINATE SYSTEM DESCRIBING THE DIRECTION ANGLE θ AND ϕ

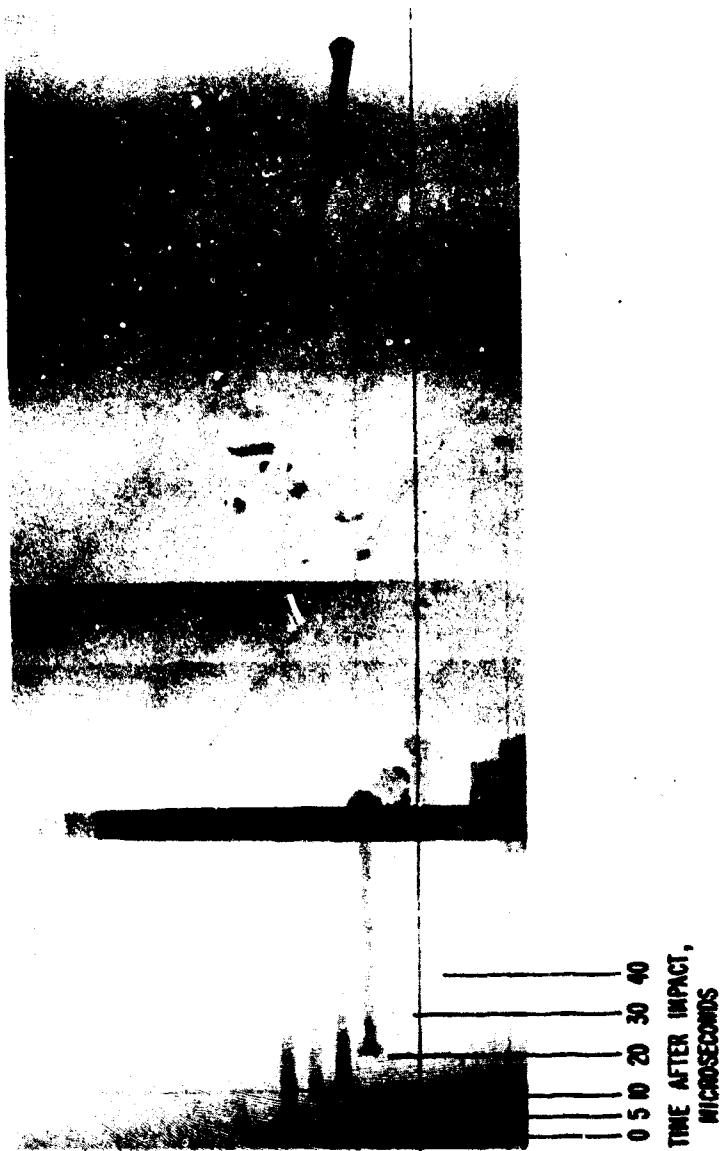
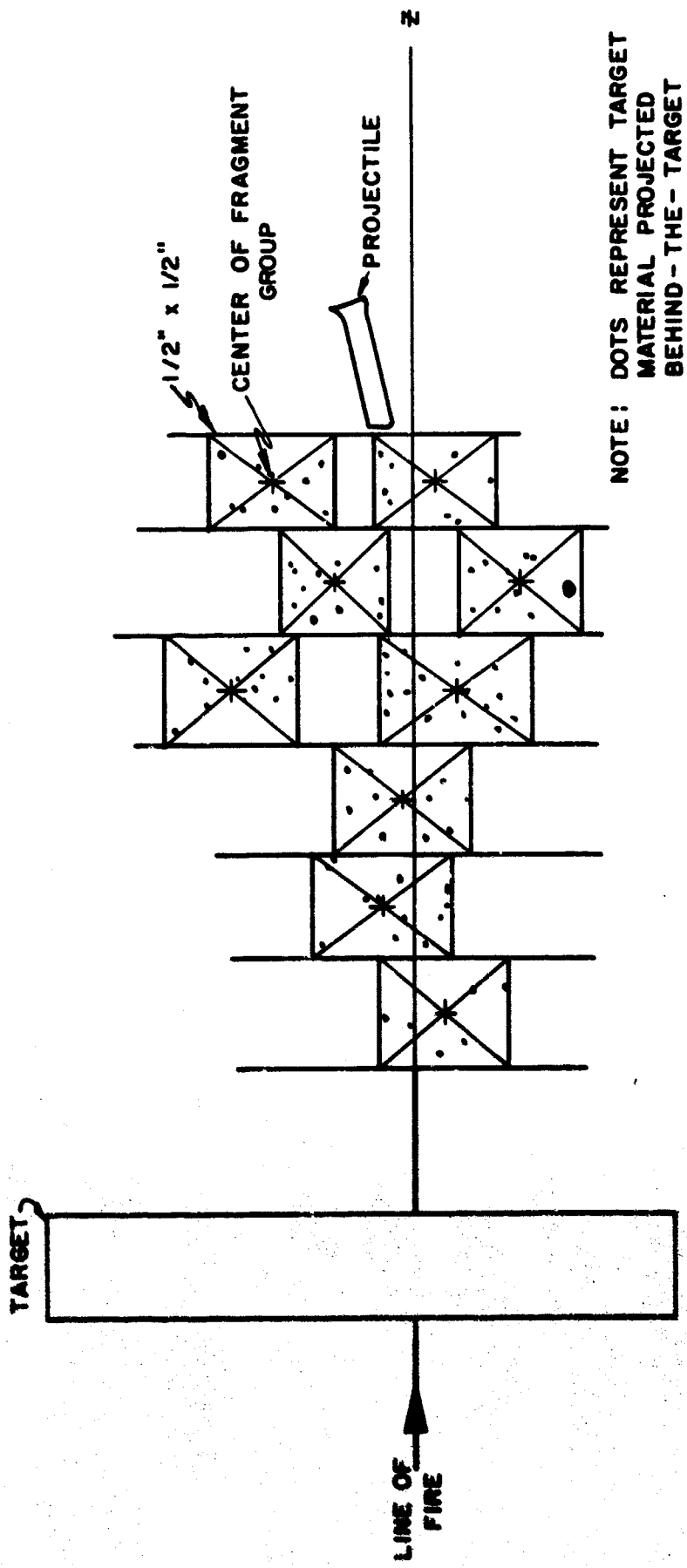


FIGURE 7 - FLASH RADIOGRAPH OF A ROD BEFORE, DURING AND AFTER TARGET IMPACT.

The velocity of each fragment may be accurately calculated from its measured radiograph coordinates. However, for the case where there are many fragments behind the target and a small error in velocity is acceptable, the radiograph reading time is significantly reduced by dividing the area behind the target into zones. The width of the zone determines the accuracy of the fragment velocity measurement. Each zone is bounded by the top and bottom fragment of any consequential size and the center of the zone is marked and read. Figure 8 illustrates a typical zone pattern. The velocity is determined for all fragments contained in any particular zone. For a typical 1/2-inch zone width bounded by a 1/2-inch section, the above procedure gives an average fragment velocity error of approximately three percent.

CHESTER GRABAREK

LOUIS HERR



NOTE: DOTS REPRESENT TARGET MATERIAL PROJECTED BEHIND - THE - TARGET

FIGURE 8
BEHIND THE TARGET FRAGMENT ZONE REFERENCE

APPENDIX

X-RAY SYSTEM PULSE ERROR

The delay time from the initial trigger input to the first tube flash was measured to be 0.4 μ sec, and the time lapse between tube flashes is about 0.1 μ sec. The time lapse between tube flashes is important in time measurements where Δt is required; however, this source of system error is small when projectile and/or fragment velocity measurements are made because of the long delay times (usually greater than 50 μ sec) that are used. The percent time error between tube flashes is

$$E_t = \frac{0.1}{t} \times 100$$

where t is the delay time between tube flashes in μ sec.

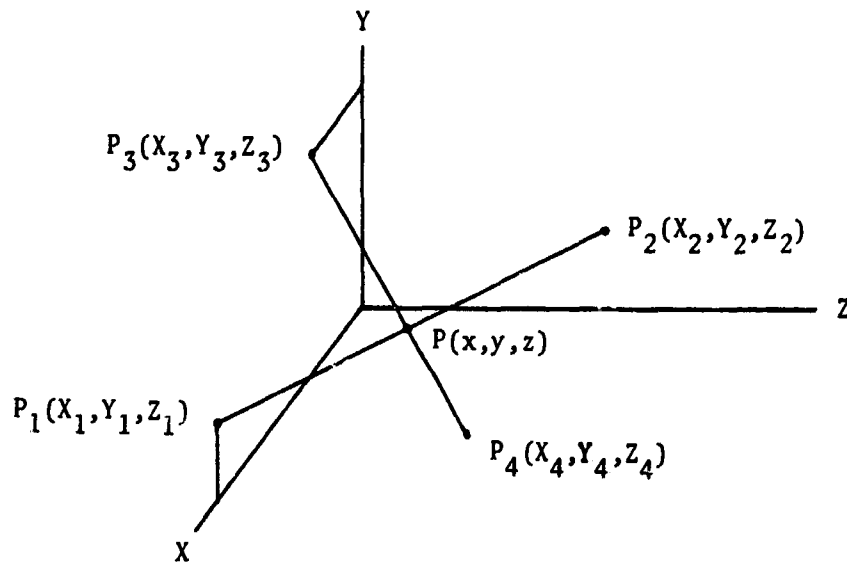
FRAGMENT COORDINATE MEASUREMENTS

The fragment coordinates are measured on a Data Reducer (099). Repeating each measurement several times, the accuracy of the measurement is within ± 0.001 inches. The percent error in the measurement is:

$$E_f = \frac{.001}{S} \times 100$$

where S is the distance traveled by the projectile and/or fragment in inches.

DERIVATION OF PROJECTION FACTOR



For these equations, P_1 and P_3 lie in the $Z = 0$ plane $\left[Z_1 = Z_3 = 0 \right]$.

$$P_1, P, P_2 \text{ collinear, } \frac{x - X_1}{X_1 - X_2} = \frac{y - Y_1}{Y_1 - Y_2} = \frac{z - Z_1}{Z_1 - Z_2} = K \quad (1)$$

$$P_3, P, P_4 \text{ collinear, } \frac{x - X_4}{X_3 - X_4} = \frac{y - Y_4}{Y_3 - Y_4} = \frac{z - Z_4}{Z_3 - Z_4}, Y_4 = 0 \quad (2)$$

$$\text{from (2) } x = X_4 + \frac{y}{Y_3} (X_3 - X_4) \quad (3)$$

$$\text{from (1) } y = Y_1 + \frac{z}{Z_2} (Y_2 - Y_1) \quad (4)$$

$$\text{from (1) } z = Z_2 \left(1 - \frac{x}{X_1}\right), X_2 = 0 \quad (5)$$

Substituting (4) in (3) for y gives:

$$x = X_4 + \frac{(X_3 - X_4)}{Y_3} \left[Y_1 + \frac{z}{Z_2} (Y_2 - Y_1) \right] \quad (6)$$

Substitute (6) in (5) for x and solve for z

$$z = z_2 - \frac{z_2}{x_1} \left[x_4 + \frac{(x_3 - x_4)}{y_3} (y_1 + \frac{z}{z_2} (y_2 - y_1)) \right] \quad (7)$$

$$z = z_2 - \frac{z_2}{x_1} \left[x_4 + \frac{y_1(x_3 - x_4)}{y_3} + \frac{z}{z_2 y_3} (x_3 - x_4) (y_2 - y_1) \right] \quad (8)$$

$$z = \left[z_2 - \frac{z_2 x_4}{x_1} - \frac{z_2 y_1}{z_1 y_3} (x_3 - x_4) - \frac{z}{x_1 y_3} (x_3 - x_4) (y_2 - y_1) \right] \quad (9)$$

$$z + \frac{z}{x_1 y_3} (x_3 - x_4) (y_2 - y_1) = z_2 - \frac{z_2 x_4}{x_1} - \frac{z_2 y_1}{x_1 y_3} (x_3 - x_4) \quad (10)$$

$$\frac{z}{x_1 y_3} \left[x_1 y_3 + (x_3 - x_4) (y_2 - y_1) \right] = \frac{z_2}{x_1 y_3} \left[x_1 y_3 - x_4 y_3 - y_1 (x_3 - x_4) \right] \quad (11)$$

$$z = z_2 \left[\frac{x_1 y_3 - x_4 y_3 - y_1 (x_3 - x_4)}{x_1 y_3 + (x_3 - x_4) (y_2 - y_1)} \right] \quad (12)$$

$$z = z_2 \left[\frac{y_3 (x_1 - x_4) - y_1 (x_3 - x_4)}{x_1 y_3 + (x_3 - x_4) (y_2 - y_1)} \right] \quad (13)$$

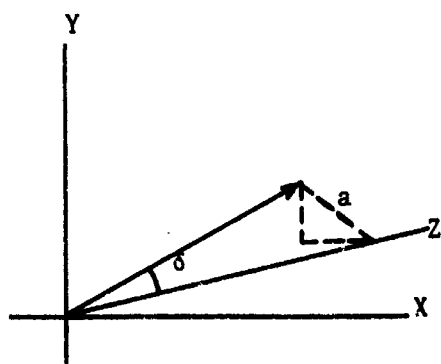
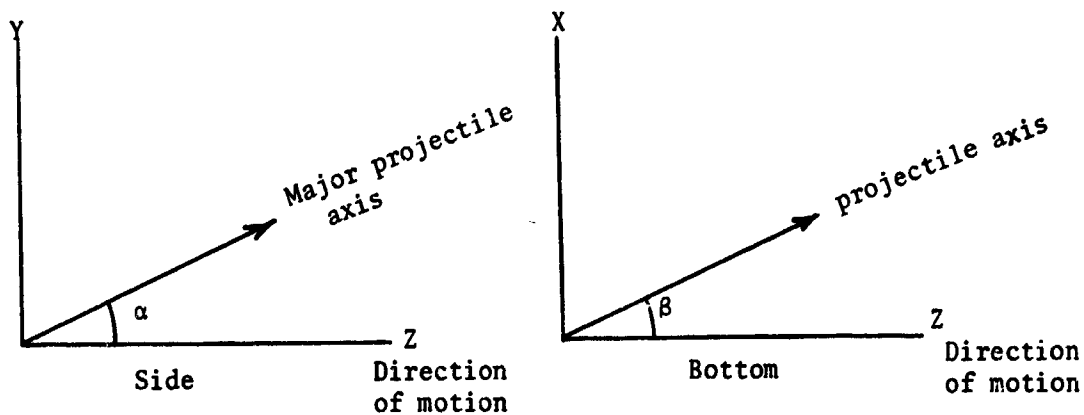
Setting quantity in brackets of (13) equal to K and from (4), (3) and (13), we obtain the space coordinates

$$x = X_1 (1 - K) \quad (14)$$

$$y = Y_1 + K (Y_2 - Y_1) \quad (15)$$

$$z = Z_2 K \quad (16)$$

DETERMINATION OF ANGLE OF YAW



$$\alpha = \tan^{-1} \frac{y}{z} ; \quad \beta = \tan^{-1} \frac{x}{z}$$

$$\delta = \tan^{-1} \frac{a}{z}$$

$$a^2 = x^2 + y^2 = z^2 \tan^2 \delta$$

$$x = z \tan \beta ; \quad y = z \tan \alpha$$

$$z^2 \tan^2 \delta = z^2 \tan^2 \beta + z^2 \tan^2 \alpha$$

$$\therefore \tan \delta = (\tan^2 \beta + \tan^2 \alpha)^{\frac{1}{2}}$$

where:

δ = angle of yaw.

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3. REPORT TITLE X-RAY MULTI-FLASH SYSTEM FOR MEASUREMENT OF PROJECTILE PERFORMANCE AT THE TARGET		
4. DESCRIPTIVE NOTES (Type of report and inclusive dates)		
5. AUTHOR(S) (Last name, first name, initial) Grabarek, Chester L. and Herr, Louis		
6. REPORT DATE September 1966	7a. TOTAL NO. OF PAGES 31	7b. NO. OF REFS
8a. CONTRACT OR GRANT NO. b. PROJECT NO: 1P014501A33E c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Note No. 1634	
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13. ABSTRACT A new technique using a multi-flash x-ray system has been developed to measure projectile striking velocity, angle of yaw at impact, plastic flow properties at the projectile/target interface, penetration time, and the amount and direction of material emerging from the rear surface of the target.		

DD FORM 1473
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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
New Technique Multiple-Flash X-ray Behind-the-Target Damage Displacement-Time Fragment Velocity Fragment Weight Space Coordinates Spall Terminal Ballistics						

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