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Watertown Arsenal Laboratory
Report Number WAL 710/607-2
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21 June 1944

PRINCIPLES OF ARMOR PROTECTION

Third Partial Report

OBJECT

To determine the relative resistance to penetration, with respect to artillery type projectiles, of rolled homogeneous armor and of Dural armor (24 ST).

SUMMARY

In order to facilitate the comparison of different types of armor, a review is given of formulae for ballistic limits, and of the methods for determining the appropriate constants.

Data are presented for the resistance to penetration of Dural (24 ST), taken from a 3/4" plate, by artillery type projectiles. Comparison of these data is made with those previously obtained for the resistance to penetration of 321 BHN steel armor by the same type of projectiles. It is found that the steel armor of 321 BHN must have a 28% greater weight than Dural armor in order to give the same protection under the usual conditions of combat. These conditions are: (1) an obliquity of attack not less than 30°, (2) a striking velocity not greater than 2700 f/s. At striking velocities above this range, steel has the advantage over Dural in that it may shatter the projectiles, while Dural cannot.

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Since previous results indicate that, for obliquities of attack over 30° , 321 BHN lies in the optimum hardness range for homogeneous armor, it is concluded that Dural plate will give more protection than homogeneous steel armor per unit weight of plate, with respect to artillery type projectiles under the usual combat conditions, providing the Dural maintains the same quality as manifested in the $3/4$ " plate. Since face hardened armor over 3" with suitable shock resistance is inferior in penetration resistance to homogeneous armor, it is further concluded that all steel armor over 3" is inferior in resistance to penetration, under the usual combat conditions, to Dural armor of the same weight, again providing the Dural could be made in the heavier gages with the same quality now obtainable in $3/4$ " gage.

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INTRODUCTION

Dural (24 ST) has been found,¹ over wide conditions of attack, to afford better resistance to penetration by cal. .30 and cal. .50 projectiles than rolled homogeneous armor of the same weight per unit area. It is to be expected that the Dural will offer a still greater superiority over homogeneous steel armor with respect to artillery type projectiles of 57 mm. and over, for such projectiles are not fractured, as are the cal. .30 and cal. .50 projectiles, by the homogeneous steel armor under the usual conditions of attack.

The technique of producing Dural plates of such thickness as would give protection against artillery type projectiles of 57 mm. and larger has not yet been developed, and so a direct comparison of Dural and steel plates for resistance to penetration by such projectiles cannot be made at present. It is therefore urgent that such information be obtained by some indirect method in order to determine whether the process of producing thick Dural plate should be developed. An indirect method has been adopted in the present report by using cal. .30 model artillery type projectiles, described in a current report.²

1. J. Sullivan: "Aircraft Armor - An Empirical Approach to the Efficient Design of Armor for Aircraft", Report No. WAL 710/506.
2. D. Van Winkle: "Principles of Projectile Design, Third Partial Report", Report No. WAL 762/231-3.

RESULTS AND DISCUSSION

I Ballistic Formulae for Homogeneous Steel Armor.

In comparing the resistance to penetration of various types of armor, the usual procedure is first to fit the experimental data of each type of plate with a formula relating the ballistic limit to plate thickness and obliquity of attack. These formulae, known as ballistic formulae, are then used to construct tables or curves in which the performances of the various types of plate are compared. These formulae are therefore used primarily for interpolation purposes.

If a formula is used only as a means for interpolation, it is immaterial what form it assumes. Many different types of functions may in fact represent data over a limited range equally well. It is often desirable, however, so to choose the type of formula that the various constants have a physical interpretation. Such formulae have two advantages. (1) They give an insight into the mechanics of the penetration. (2) They may be extrapolated with more confidence than formulae with no physical interpretation.

A successful interpolation formula which gives the dependence of the ballistic limit V upon plate thickness e is of the form,

$$V \sim (e/d)^\alpha ; \theta = \text{constant.} \quad (1)$$

where d is the plate thickness. The quantity α , which will be called the "e/d exponent", is apparently very nearly

independent of the obliquity angle θ . It may however depend upon the shape of the projectile's ogive. The value of the e/d exponent found by the British to represent best their data¹ on the 2 pr. A.P. projectile is 0.715. The value 0.63 best represents the ballistic performance of homogeneous plates with respect to projectiles similar to the German 75 mm. A.P.C. projectile (one caliber radius of curvature at ogive).²

A formula of the type (1) has the great advantage that the parameter α can be simply obtained through a plot of the data on logarithmic paper. It has the disadvantage that a value of α other than $1/2$ has been given no simple interpretation, and therefore it cannot be expected to remain valid except over a limited range of the ratio e/d . A formula of the type

$$V \sim (e/d)^{1/2}, \quad \theta = \text{constant} \quad (2)$$

has been commonly used in this country. It has the advantage that it may be readily interpreted, namely it gives the kinetic energy as proportional to the plate thickness. It has however the disadvantage that its so-called constant of proportionality, the "F" coefficient, is not a constant, but increases to an asymptotic value as e/d

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1. Proceedings of Ordnance Board, No. 24,009.
 2. B. C. Ward: "Principles of Armor Protection, Second Partial Report", Report No. WAL 710/607-1.

increases. Such a formula cannot therefore perform the primary function for which a ballistic formula is designed.

A slight modification of Equation (2) has however been found to represent the ballistic data exceedingly well.¹ This modification is

$$V \sim (e/d - \Delta)^{1/2}, \quad \theta = \text{constant} \quad (3)$$

where Δ is a small numerical constant. The constant of proportionality has been found to be truly constant, within experimental error, over the entire range investigated. This equation has a physical interpretation which is equally as simple as is that of Equation (2). Upon squaring both sides one sees that V^2 , and therefore the kinetic energy required for complete penetration, is proportional to $e - \Delta d$. It is well recognized that the plate material near both sides of the plate is easier to push aside than the plate material in the interior. The quantity Δ , which will be called the e/d defect, is one way of taking account of this boundary effect. According to Equation (3), the energy necessary for complete perforation is proportional to the width of the interior of the plate after removal of a layer of width Δd , distributed between the face and the back of the plate.

1. "Penetration Mechanisms I. The Penetration of Homogeneous Armor by Uncapped Projectiles at 0° Obliquity", U. S. Naval Proving Ground Report No. 1-43.

Over a limited range of e/d , Equations (1) and (3) might both reproduce the ballistic data equally well. This equivalence is illustrated in Figure 1 where the e/d exponent α has been so chosen that Equations (1) and (3) are tangent at $e/d = 1$. The precise relation between the e/d exponent and the e/d defect such that Equations (1) and (3) are tangent at a particular e/d may readily be seen to be given by the following relation:

$$1 - \Delta(d/e) = 1/(2\alpha) \quad (4)$$

This relationship is plotted in Figure 2. Equations (1) and (3) each have certain advantages. The first equation is the most convenient to use, it is a straight line on logarithmic paper. On the other hand, the second equation, which has greater physical content, may be expected to be valid over a wider range of e/d .

No simple formula represents accurately the variation of the ballistic limit with obliquity angle θ over the entire obliquity range. The formula

$$V \propto 1/\cos \theta, \quad e/d = \text{constant} \quad (5)$$

is widely used both in England (Milne Formula) and in this country (Thompson Formula). It reproduces, within experimental error,¹ the observations on the ballistic limits of

1. B. C. Ward: loc. cit.

homogeneous armor with respect to artillery type projectiles for obliquity angles over 30° , providing e/d is in the neighborhood of unity. On the other hand, in the range $0^\circ - 30^\circ$, the formula

$$V \sim 1/\cos^{1/2} \theta, \quad e/d = \text{constant} \quad (6)$$

appears to be the more appropriate¹ for certain projectiles.

Equation (5) may be interpreted by the statement that the success of the projectile in penetrating the plate depends only upon the component of its velocity normal to the plate, $V \cos \theta$, and is independent of the component of its velocity parallel to the plate, namely, $V \sin \theta$. Why this should be so is not entirely clear. A very rough interpretation may be given as follows. At angles over 30° , where Equation (5) is valid, the projectile effectively flattens against the face of the plate, as is illustrated in Figure 3. The projectile then either pushes out a punch, and passes through the hole thereby made, or scoops off the face of the plate. The deciding factor as to which event occurs is the distance the projectile has been pushed sidewise into the plate, which in turn depends solely upon the initial kinetic energy of the projectile associated with the normal component of velocity.

Equation (6) may be roughly interpreted as follows.

1. For references, see C. Zener and R. E. Peterson: "Principles of Projectile Design for Penetration, First Partial Report", Report Number WAL 762/231, pp. 18-19.

The energy required for penetration depends primarily upon the length of the projectile's path through the plate. As the projectile enters a plate its obliquity is at first increased by the transverse forces acting upon its ogive. As the ogive approaches the back of the plate, the transverse force acting upon the ogive is in the reverse direction, and therefore tends to decrease the obliquity. Where e/d is less than, or in the neighborhood of, unity, and when the initial obliquity is less than 30° , the two effects at the face and at the back of the plate tend to cancel. The path of the projectile through the plate is therefore essentially rectilinear, and therefore the length of this path, and hence also V^2 , is proportional to $1/\cos\theta$. Only when the obliquity is over 30° does the initial torque gain complete control, effectively flattening the projectile against the face of the plate.

Upon combining Equation (1) with Equation (5) one obtains

$$V = V_\alpha (e/d)^\alpha / \cos \theta, \quad \theta > 30^\circ \quad (7)$$

and upon combining Equation (3) with Equation (5) one obtains

$$V = V_\Delta (e/d - \Delta)^{1/2} / \cos \theta, \quad \theta > 30^\circ \quad (8)$$

From the above discussion of the physical interpretation of Equation (3), it would seem that the parameters α and Δ would be independent of the obliquity angle θ . This

independence has been observed.¹ The constant V_{α} may be interpreted as the ballistic limit matching plate would have at zero obliquity if Equation (7) continued to be valid below 30° obliquity. It is obtained by plotting V vs. $\cos \theta$ on logarithmic paper, and extrapolating the straight line portion to $\cos \theta = 1$, as is illustrated in Figure 4. In the case illustrated, V_{α} is 1760 f/s, while the ballistic limit for matching plate at zero obliquity is 1975. Similarly, the quantity V_{Δ} may be interpreted as the ballistic limit a plate of thickness $d + \Delta \cdot d$ would have at zero obliquity if Equation (8) were valid at this obliquity. Upon comparing Equations (7) and (8), one sees that V_{Δ} may be obtained from V_{α} by the relation

$$V_{\Delta} = V_{\alpha} / (1 - \Delta)^{1/2} . \quad (9)$$

Thus in the case illustrated in Figure 4, the e/d exponent is 0.63 taken from data in the neighborhood of $e/d \approx 1$ and therefore, from Figure 2, $\Delta = 0.20$, and thus from Equation 9, $V_{\Delta} = 1970$.

The values given above for V_{α} and for V_{Δ} refer only to homogeneous plate of 321 BHN, and strictly only with respect to the cal. .30 model artillery type projectiles. From previous studies² with these projectiles, an estimate

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1. B. C. Ward: loc. cit. (Figure 2).
 2. C. Zener: "Principles of Armor Protection, First Partial Report", Report Number WAL 710/657.

may be made as to the manner in which V_a varies with plate hardness. This estimate is given in Figure 5. It is to be observed that this estimate has a plateau which contains the hardness level 321 BHN.

Most ballistic formulae used in the past have attempted to take partial account of the type of projectile in some manner. The energy of the projectile, $(1/2)M v^2$, is equated to some function of e , θ and d . The physical reasoning back of this procedure is that a certain amount of energy is needed for the formation of a hole of given caliber in a plate, and that it is immaterial whether this energy is concentrated in a long or in a short projectile. This reasoning has been carefully vindicated by the British¹ in firings in the range $0^\circ - 30^\circ$, but is not applicable to the high obliquity impacts illustrated in Figure 3. The longer the projectile the greater is the distortion which the plate must undergo before the projectile penetrates. This increase in energy of distortion tends to weaken the variation of the ballistic limit, at high obliquity, with the projectile length, and hence with projectile mass. No attempt will therefore be made to generalize the formulae of Equations (7) and (8) by inclusion of the projectile mass.

The above mentioned relative independence of ballistic

1. Proceedings of the British Ordnance Board, No. 24,009.

limit at high obliquities upon projectile length/caliber ratio suggests that the ballistic limits of plates at high obliquities should be nearly the same for all types of non-deforming non-fracturing projectiles. Figure 6 is presented in support of this viewpoint.

II Ballistic Formulae for Dural (24 ST).

No information is in the literature as to the resistance to penetration of Dural with respect to artillery type projectiles. A study has therefore been made with cal. .30 model artillery type projectiles. Two plate thicknesses were used, 0.75" and 0.56". The latter plates were ground down from 0.75" plates. The results are presented in Table I and are plotted vs. $\cos \theta$ upon logarithmic paper, in Figure 7.

Since the observed ballistic limits for each plate thickness lie upon a straight line of slope -1, the ballistic limits obey the relation

$$V \sim 1/\cos \theta \quad (10)$$

from zero obliquity to the highest obliquity used, 55° . This equation is identical with Equation (5) which is obeyed by steel armor for obliquities over 30° . The author is not aware of any satisfactory physical interpretation why the ballistic limit for Dural should follow Equation (10). The arguments advanced in the case of steel armor are not here applicable, since the projectiles do not

flatten against Dural plates as is depicted in Figure 3 for the case of steel armor.

The analysis of the straight lines of Figure 7 is given in Figure 8. It is seen that these lines, and therefore the ballistic data, are given by the formula

$$V = 2060 (e'/d)^{0.63} / \cos \theta . \quad (11)$$

The ballistic data may also be represented by a formula of the type of Equation (8). The two ballistic formulae are made tangent in the middle of the e'/d range, namely at 0.78, by taking the e'/d defect as 0.17, as may be seen from Figure 2. The constant V_{Δ} is then found from Equation (9) to be 2260. Therefore

$$V = 2260 (e'/d - 0.17)^{1/2} . \quad (12)$$

The e'/d defect, in contrast to the e'/d defect, is equal to $2.8 \times 0.17 = 0.48$. This is 2.4 times as large as for the steel armor previously investigated with the same projectiles. The interpretation of this relatively large value of Δ may be in the bad spalling character of the Dural plate, in contrast to the non-spalling character of the steel armor used. Such spalling would necessarily increase the thickness of the back layer which effectively contributes nothing towards resistance to penetration.

III Comparison of Steel and of Dural.

The ballistic performance of steel and of Dural may

TABLE I

NAVY BALLISTIC LIMITS FOR DURAL (24 ST) PLATE WITH RESPECT TO CAL. .30 MODEL ARTILLERY TYPE PROJECTILES.

OBLIQUITY	Actual plate thickness	
	0.56"	.75"
	Equivalent plate thickness*	
	0.20	.27"
0°	1590 f/s	1877 f/s
30°	1860	2257
40°	2050	2525
45°	----	2750
50°	2585	3150
55°	2840	----

* Thickness of steel plate of same weight per unit area.

best be compared through their respective ballistic formulae of the type in Equation (7). These are

$$\left. \begin{array}{l} V = 1760 (e/d)^{0.63} / \cos \theta , \\ \text{Steel (321 BHN), } \theta > 30^\circ \end{array} \right\} \quad (13)$$

and

$$\left\{ \begin{array}{l} V = 2060 (e'd)^{0.63} / \cos \theta \\ \text{Dural (24 ST), all obliquities} \end{array} \right. \quad (14)$$

These equations are identical, save for the numerical multiplicative constants. The ratio e/e' of the thickness of steel armor to thickness of Dural armor which will have the same ballistic limit at the same obliquity ($\theta > 30$) is the same for all ballistic limits. It is given by

$$(e/e')^{0.63} = \frac{2060}{1760} ,$$

the solution of which is

$$e/e' = 1.28, \quad (\theta > 30^\circ) . \quad (13)$$

Therefore steel armor of 321 BHN must have a 28% greater weight than Dural armor to give the same ballistic limit ($\theta > 30$).

The precise values of the constants in the ballistic formulae for steel (321 BHN) and for Dural (24 ST) will depend somewhat upon the particular type of projectile. It is to be expected that the ratio of Equation (13) will however be relatively independent of projectile type.

The ratio 1.28 of Equation (13) refers specifically only to steel of 321 BHN. As has already been pointed out,¹ homogeneous steel armor of no other hardness offers a higher resistance to penetration, with respect to artillery type projectiles, for $\theta > 30$. Further, face hardened armor with thicknesses of 3" and over offers less resistance to penetration than homogeneous steel armor.² Therefore Equation (13), compares the best obtainable steel armor, of 3" and over, with Dural of the quality now obtainable in 3/4" thickness.

The comparison of Equation (13) refers specifically only to obliquities of 30° and over. At lower obliquities Dural armor will not have as much superiority over steel as given by this equation. In most cases, however, armor is so disposed that impacts at obliquities under 30° are very rare.

Dural has an advantage over steel quite apart from that given by a comparison of their respective ballistic formulae. From these formulae it is evident the larger the obliquity, the smaller is the weight of plate needed to give the same protection to a given area. In other words, to obtain the maximum protection by a given weight of armor, a very large obliquity angle must be used. However, when this angle is made sufficiently large the corresponding

1. C. Zener: Loc. cit.

2. Aberdeen Proving Ground Armor Test Report AD-652.

plate thickness is so small that non-penetrating impacts permanently injure the plate by indentation. The greater rigidity of Dural for a given weight per unit area, which increased rigidity is associated with its smaller density, will allow Dural to be used at larger obliquity angles without indentation than is possible in the case of steel.

FIGURE 1

COMPARISON OF THE TWO BALLISTIC FORMULAE

$$V \sim (e/d)^{\alpha} \quad (1)$$

$$V \sim (e/d - \Delta)^{1/2} \quad (2)$$

— EQ. (1) WITH $\alpha = 0.625$

○ EQ. (2) WITH $\Delta = 0.2$

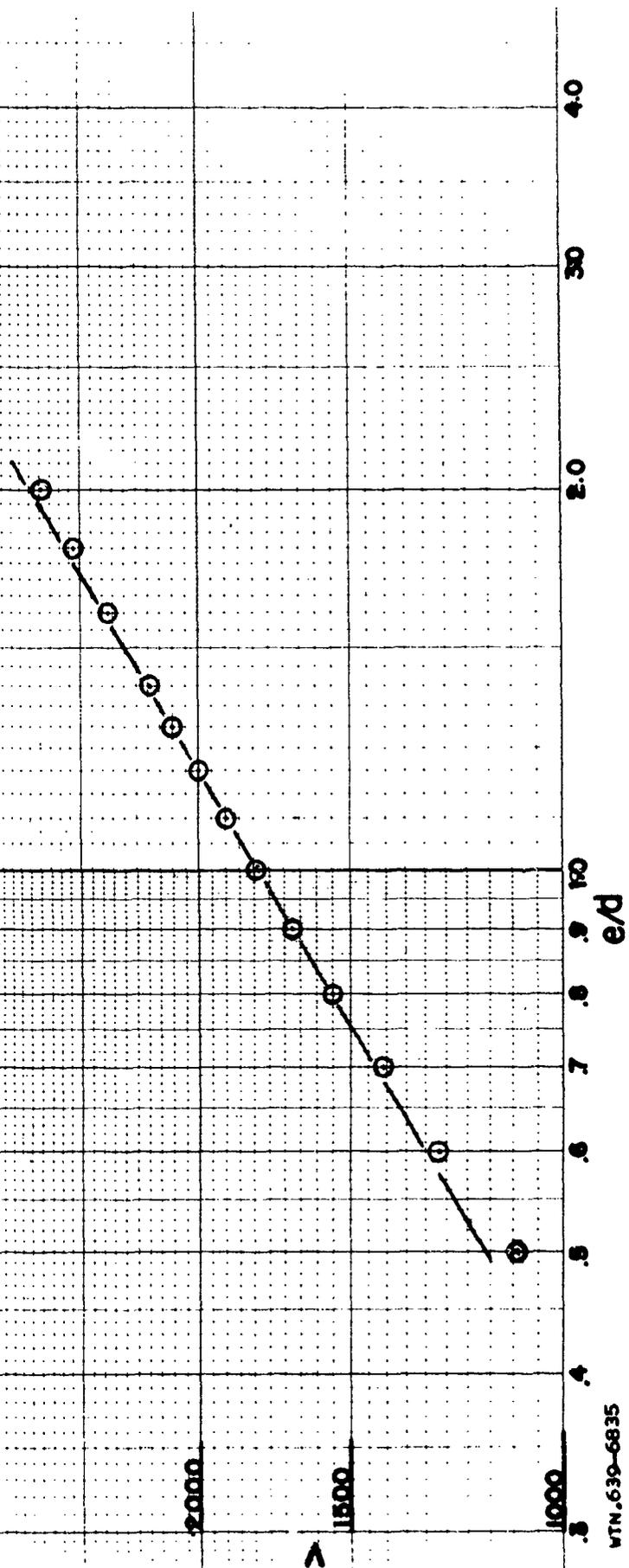


FIGURE 2
RELATION BETWEEN α Δ AND e/d

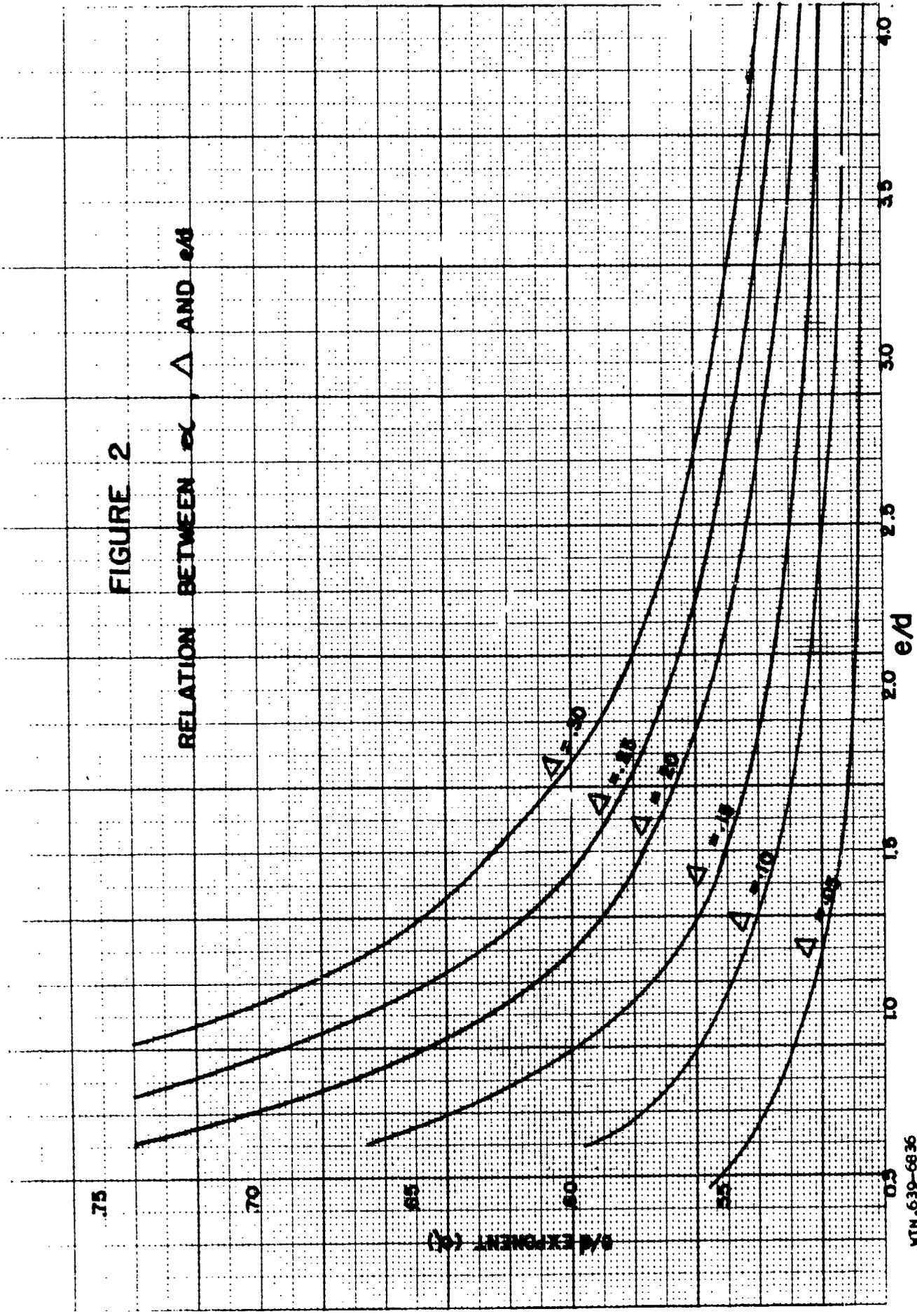
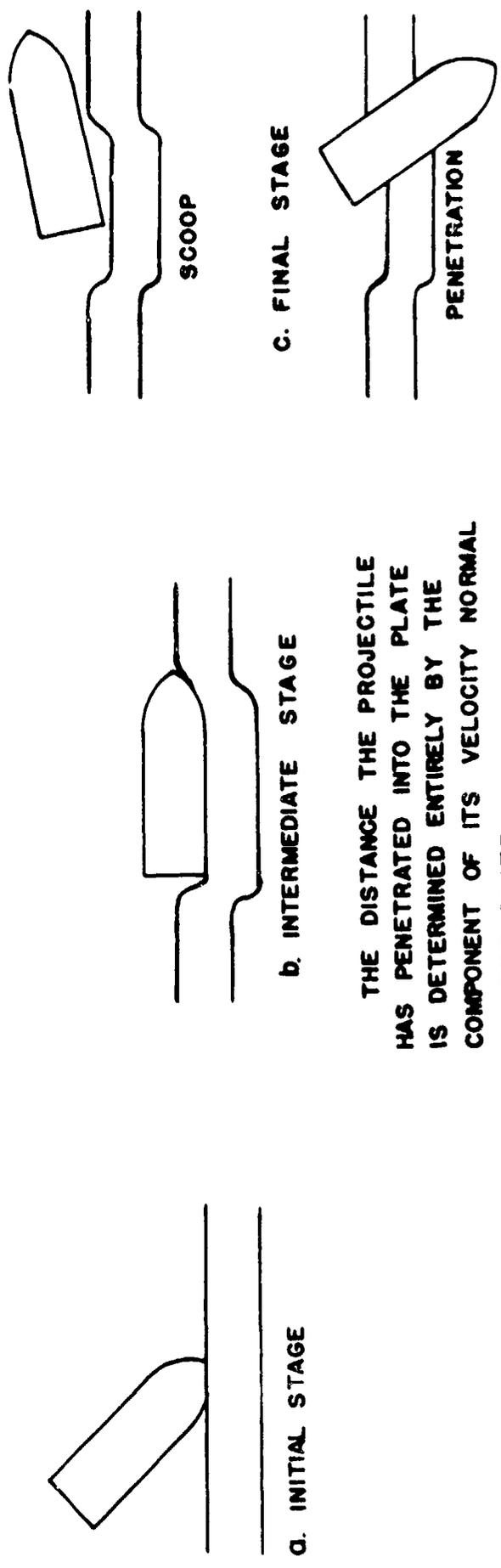


FIGURE 3

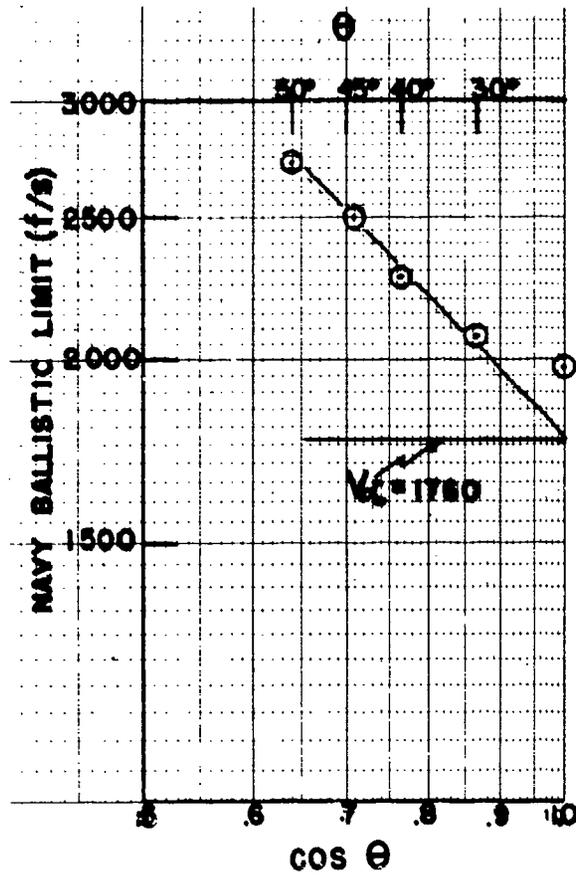
ILLUSTRATION OF INTERPRETATION OF FORMULA $V \sim 1/\cos \theta$
FOR CASE OF MATCHING AND UNDERMATCHING PLATE



THE DISTANCE THE PROJECTILE
HAS PENETRATED INTO THE PLATE
IS DETERMINED ENTIRELY BY THE
COMPONENT OF ITS VELOCITY NORMAL
TO THE PLATE.

FIGURE 4

EXAMPLE OF METHOD
FOR
DETERMINING V_d

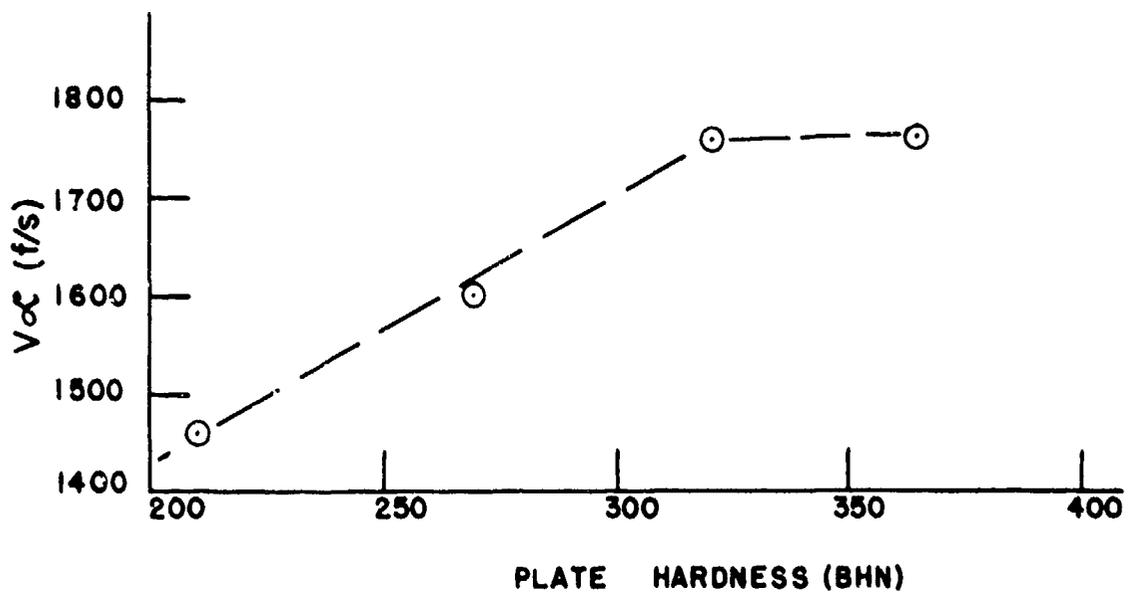


(BALLISTIC DATA FOR 321BHN PLATE,
 $\sigma/d = 1$, TAKEN FROM WAL 710/807-1)

FIGURE 5

INFLUENCE OF PLATE HARDNESS
UPON BALLISTIC FORMULA

(DATA OBTAINED FROM CAL. 30
MODEL ARTILLERY TYPE PROJECTILE)

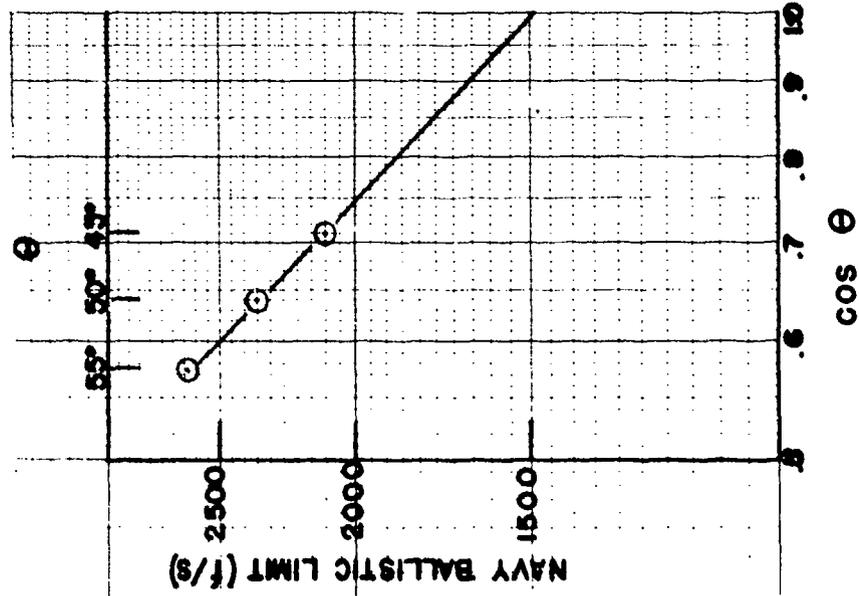


WTN.639-6839

FIGURE 6

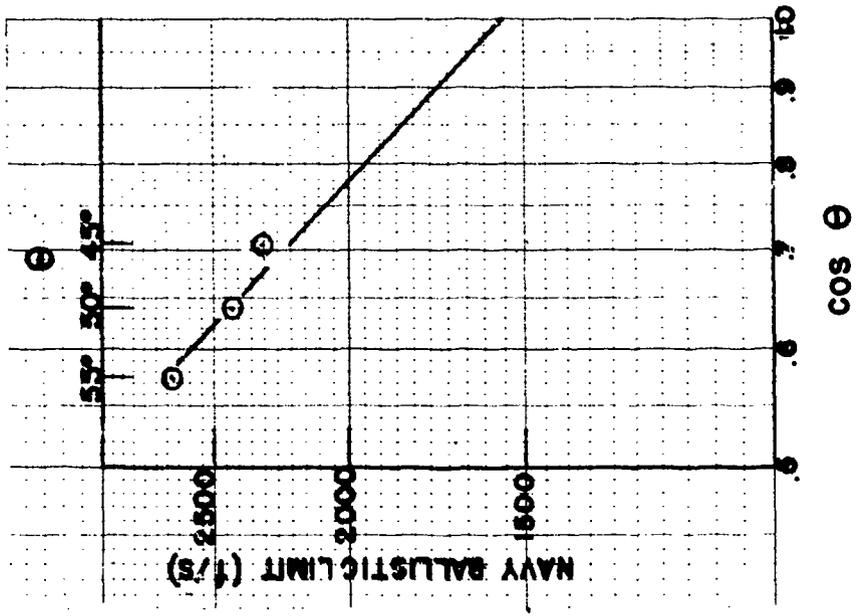
EXAMPLES OF BALLISTIC LIMITS AT HIGH OBLIQUITIES

LINES ARE DRAWN WITH SLOPE OF 45°.
 (DATA FROM ABERDEEN PROVING GROUND REPORT, NO. AD-542)



90 MM A.P.C. PROJECTILE, VS 2 1/2" 269
 BHN PLATE. $\phi A = 0.71$; $V_{\alpha} = 1860$

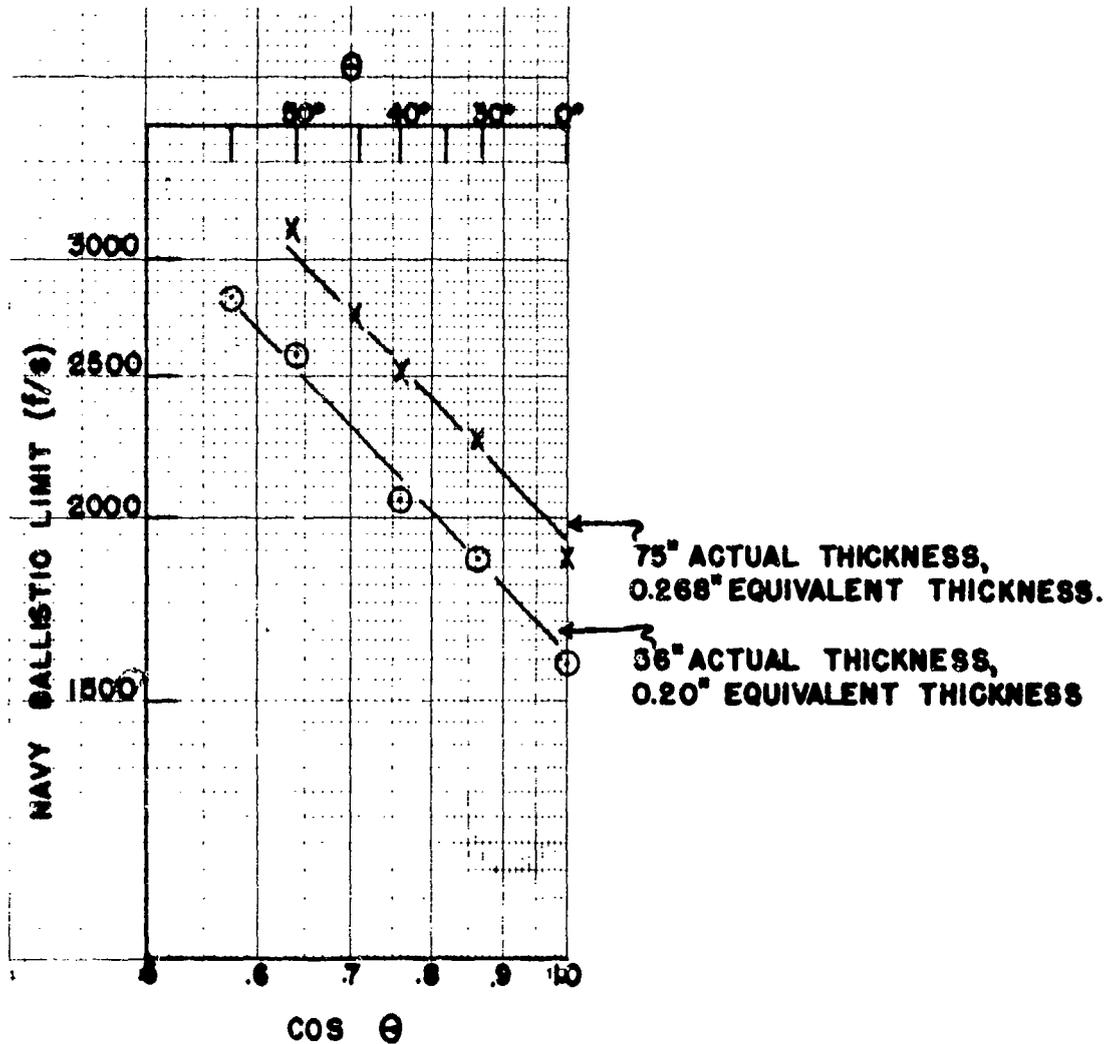
WTN-630-6840



3" A.P.C. M62 PROJECTILE, VS 2 1/2" 269
 BHN PLATE. $\phi A = 0.84$; $V_{\alpha} = 1740$

FIGURE 7

BALLISTIC DATA FOR DURAL WITH
RESPECT TO CAL. .30 MODEL
ARTILLERY TYPE PROJECTILES.



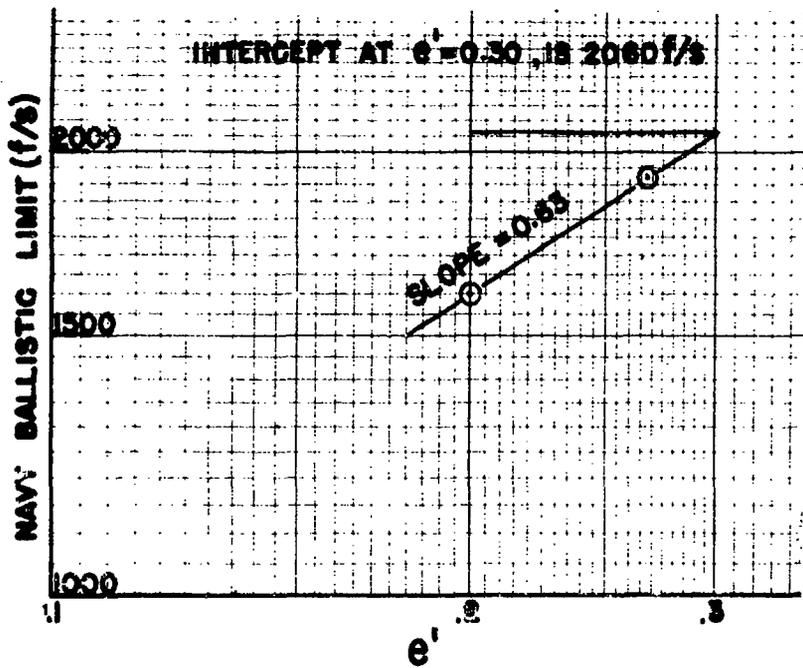
LINES, DRAWN TO HAVE SLOPE OF 45°,
FOLLOW THE FORMULA

$$V = 2050 (\theta'/d) / \cos \theta$$

θ' = EQUIVALENT THICKNESS

FIGURE 8

DETERMINATION OF CONSTANTS IN BALLISTIC EQUATION FOR DURAL



⊙ INTERCEPTS OF LINES IN FIGURE 7 AT 0°

WTN.639-6642