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(6) PRINCIPLES OF ARMOR PROTECTION. (12) 27

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OBJECT

To determine the relative effects upon resistance to penetration by artillery type projectiles of changes in plate hardness, in plate thickness and in obliquity.

SUMMARY

Cal. .30 artillery type projectiles were fired against plates at a variety of hardness levels and thicknesses, and at angles of obliquity up to 55°. Critical angles for penetration were determined rather than critical velocities, the velocities of all projectiles being maintained as closely as possible at 2400 f/s. From these ballistic data the combinations of plate thickness, plate hardness, and obliquity are deduced which offer the same resistance to penetration by nondeforming nonfracturing projectiles with this striking velocity. The influence of the characteristics of the particular test projectiles used was minimized by making the projectiles so well that they remained practically undeformed by impact with the plate.

The greater the obliquity θ the smaller need be the plate thickness e. Up to 35° obliquity the relation between these two quantities for equal resistance to

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penetration is given by UNCLASSIFIED

$$e/\cos\theta = \text{constant}. \quad \theta < 35^\circ .$$

This relation is such that, in its range of validity, the total weight of plate needed to protect a given area is independent of obliquity and depends only on plate quality. As the obliquity increases from 35° to 40° the plate thickness for equal protection decreases considerably faster than would be indicated by this formula, corresponding to a decrease of total plate weight by about 12% for protection of a given area. An increase of obliquity angle beyond 40° introduces only very slight saving in weight.

In the range 210-320 BHN the higher the plate hardness the smaller need be the plate thickness for protection at a given angle. Thus for angles of 40° and over, plates of 210 BHN must have a 30 to 35% greater thickness than plates of 320 BHN for the same protection. The advantage of hard plates will be all the more marked when the attacking projectiles are less perfect than those used for this report, for any deformation of the projectile reduces its ability to penetrate. The same consideration applies to obliquity, for an increase in obliquity per se increases the tendency of the projectile to fracture or to deform. Further, the reduction in thickness allowed by an increase in obliquity

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increases the hardness to which the plate may be heat treated with the avoidance of poor shock properties. This allowable increase in hardness again increases the ability of the plate to fracture or to deform the projectile.

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CONTENTS

INTRODUCTION

The primary purpose of armor is to resist the penetration of projectiles and the fragments thereof. Armor may resist penetration in three distinct ways.

(1) The armor may fracture or deform the projectile. In this case the projectile is not only made to absorb part of its own kinetic energy, but is also so changed by the fracture or the deformation that it is less able to use effectively the kinetic energy which remains. The major variable factor of armor which determines its ability to fracture projectiles is its hardness. The plate thickness and obliquity of attack also affect somewhat the ability of a plate to fracture or to deform a projectile, the thicker the plate, or the greater the angle of obliquity, the lower is the critical plate hardness for fracture or deformation.

(2) The armor may deflect the projectile, thereby avoiding the necessity of absorbing its kinetic energy. The major factor which determines the ability of armor to deflect a projectile is the obliquity of attack. The plate thickness and hardness also affect to some extent the ability of a plate to deflect projectiles, the thicker and harder the plate the lower the critical angle for deflection.

(3) The armor may absorb, through plastic deformation,

the kinetic energy of the projectile. The thicker the plate the greater is the volume of material which a projectile must deform in order completely to perforate the plate, and therefore the greater is the kinetic energy which the plate can absorb. The greater the obliquity, the greater is the length of path through the plate, and therefore the greater is the kinetic energy absorbed. Also, the higher the hardness, the greater is the kinetic energy required to produce in the plate a hole of a given volume.

The problem of armor protection is not merely a question of avoiding penetration. The resistance to penetration by any of the three methods of fracturing or deforming the projectile, of deflecting the projectile, or of absorbing its kinetic energy can be increased by an increase in any one of the three factors - plate hardness, plate thickness, obliquity. Rather the problem of armor protection is concerned primarily with the optimum balance between conflicting factors. Thus in planning the disposition of the armor, a balance must be struck between the ballistic advantages of a large obliquity and the constructional difficulties attendant thereon. Again, in determining the appropriate plate hardness, a balance must be reached between the increased resistance to penetration associated with increasing plate hardness, and the decrease of shock resistance associated therewith. The purpose of the present report is to present ballistic data which may be used in arriving at the optimum compromises.

The ballistic data obtained with any one type of projectile are strictly applicable only to that one particular type. This is especially the case when the projectile deforms appreciably or fractures, for the critical conditions for deformation or for fracture will be quite different for different types of projectiles, or even for the same type of projectiles produced by different manufacturers. In obtaining the data for the present report, the projectiles were heat treated as well as the authors knew how in order to avoid fracture or excessive deformation. Only those conditions of attack were studied in which the projectiles were not appreciably altered by impact with the armor. In this manner the dependence of the ballistic data upon the type of projectile was minimized. This method of approach has precluded a comparison of face hardened with homogeneous plate since the projectiles used deformed when fired against face hardened plate at obliquities. The use of nonfracturing projectiles has also removed any ambiguity which might exist as to the meaning of complete penetration. When the test projectile fractures, uncertainty often exists as to what to call complete penetration. When, as in the present experiments, the projectile remains whole, no doubt ever exists as to whether the projectile has or has not passed through the plate. The type of projectile chosen for testing was modelled after the German 75 mm projectile in order that the results obtained might be directly applied to the design of armor for protection against this projectile.

In obtaining the ballistic data small caliber projectiles, scaled down from large caliber sizes, were fired against correspondingly thin plates. Such small scale experiments have two distinct advantages over the firing of full size projectiles. Firstly, the characteristics of the plate and of the projectiles may be more rigorously controlled. The difficulties which accompany the heat treatment of large masses of steel are such as to render it doubtful if large caliber projectiles have ever been produced of such high quality as the small caliber projectiles used in the experiments described in this report. Secondly, the firing conditions are more controllable. Thus at high angles of attack (45°-60°), a change of only one degree in obliquity may effect the ballistic limit by as much as 100 ft/sec. It is doubtful if in the testing of plates with large caliber projectiles the angle of attack can be controlled so as to lie within a range smaller than several degrees, which corresponds to an effective uncertainty in ballistic limit of several hundred ft/sec. at high obliquities. Again, only several shots of large caliber projectiles may be made upon a single plate, necessitating the use of more than one plate in a set of firing, and therefore the introduction of an uncertainty as to the constancy of the plate characteristics.

It is anticipated that objections to the present program upon scaled down projectiles will be made. Only two objections are justifiable. One is that the metallurgical structures of thick and of thin plates of the same hardness are not necessarily identical. Differences in metallurgical structure have however only slight effect upon the resistance to penetration. The primary effect of such differences is upon the shock properties. The second justifiable objection is that the rate of deformation of the plate material is greater during the impacts of the scaled down projectiles than during the impacts of large caliber projectiles. As is well known, the resistance to deformation of steel increases with rate of strain, and it might therefore be argued that the plate material in the model firings does not react in the same manner as in the firing of major caliber projectiles. However, it has recently[1] been shown that this effect of strain rate is exceedingly small, an increase of strain rate by 1000 %, corresponding to the scaling down from a 3" projectile to a caliber .30 projectile, raises the plastic resistance of the material by less than 1.5 %.

Conventional ballistic data are expressed in terms of critical velocities. These velocities are defined, for a given plate at a specified obliquity, as the mean between the velocities of a partial and a complete penetration. It is customary to adhere to some convention as to the maximum allowable range between the velocities for partial and for complete penetration. In the present work, where only relative effects of various parameters are sought, it is more convenient to fire at a given velocity and to determine a critical obliquity. As in the case of critical velocities, critical angles must be defined as the mean between an obliquity which allows complete penetration and one which allows only partial penetration. In the present report, these two angles are taken 5° apart. In all the firings in the present report the constant velocity was taken as 2400 f/s.

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1. C. Zener and J. H. Hollomon: "Effect of Strain Rate Upon Plastic Flow of Steel", J. Applied Physics 15, 22 (1944).

This is the velocity of the enemy 75 mm. projectile at a battle range of about 900 yards.

RESULTS AND DISCUSSION

I TEST PROJECTILES

The projectiles used in obtaining the ballistic data were models of the German 75 mm. A.P.C. Pak 40, scaled down to cal. .30 size, i.e., scaled down in linear dimensions by a factor of 10. The original and the replica are compared in Figure 1. Although the overall dimensions, as well as those of the cap and of the ogive, were scaled down accurately, no attempt was made to reproduce the details of the base. The changes introduced, however, can have only a very slight effect upon the ballistic performance, since the changes consist primarily of a redistribution of mass. Thus no H.E. cavity was made, but relatively more metal was removed for the rotating band in the case of the small replica. A comparison of the test projectiles with the 3" M62 is given in Table I.

No attempt was made to reproduce the hardness pattern of the original German projectile, except in the case of the cap, which was kept at 42 RC as in the original.[1] Rather the body of the projectile was made

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[1] E. F. Hutchinson: "Metallurgical Examination of a German 75 MM Pak 40 H.E. - A.P.C. and B.C. Projectile Produced in 1942", WAL 762/229.

TABLE I

COMPARISON OF TEST PROJECTILE WITH 3" M62

	Test Projectile	Equivalent 3" Projectile	3" M62
Core	0.0126 lbs.	12.6 lbs.	11.4 lbs.
A.P. Cap	0.0024	2.4	2.06
Band	0.0022	2.2	0.46
Total	0.0172	17.2	13.9 (empty)

as well metallurgically as the authors knew how. The ogive was kept at the as quenched hardness of 62-63 RC, and the base was tempered just enough to prevent fracture of the body at oblique incidences.

The heat treatment, the method of base tempering, banding and capping, as well as a description of the plate holder, is given in a current report.[1]

II RELATION BETWEEN PLATE THICKNESS AND OBLIQUITY

In this section a study is made of the relation between the plate thickness and the obliquity of attack, for a constant plate hardness, which will just give protection against the test projectile at some predetermined velocity. All projectiles were fired at the same velocity, namely 2400 f/s. For each plate two obliquities were found, 5° apart, at the lower of which the projectile passes through the plate, at the higher of which the projectile fails to pass through. The ballistic data are given in Table II, and are plotted in Figure 2.

In this Figure the plate thickness e is plotted on log paper against the cosine of the obliquity angle θ. In this manner of plotting, the effect of a change in obliquity upon necessary plate weight may

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[1] D. Van Winkle: "Principles of Projectile Design For Penetration, Second Partial Report", WAL 762/231-1.

TABLE II

BALLISTIC DATA

ANGLES FOR COMPLETE AND FOR INCOMPLETE PERFORATION

Plate Thickness (in inches)	PLATE HARDNESS				
	210 BHN	269 BHN	320 BHN	364 BHN	420 BHN
.25		50°-55°	45°-50°	45°-50°	40°-45°
.30	50°-55°	45°-50°	35°-40°	35°-40°	30°-35°
.35		35°-40°	30°-35°	25°-30°	*
.40	35°-40°	35°-40°	0°-10°	*	
.45		25°-30°	*		
.50	25°-30°	*			

*Complete penetration not obtained at normal.

be readily seen. Thus the weight of a plate which protects a given area is proportional to $e/\cos\theta$. A constant weight plate therefore implies a direct proportionality between e and $\cos\theta$, and therefore a 45° slope on the log paper. A decrease of weight with obliquity implies a slope greater than 45°. For the hardnesses 269 and 364 BHN an upper limit was determined for the plate thickness at which penetration occurs at zero obliquity. The experimental data are consistent with a 45° slope (dashed lines) from 0° to 35° obliquity. The ballistic data are further consistent with a 45° slope beyond 40° obliquity. The only marked decrease in weight of armor necessary to protect a given area therefore occurs from an increase of obliquity from 35° to 40°.

The ballistic data are replotted in a different manner in Figure 3. An estimate was made from Figure 2 as to the critical plate thickness at zero obliquity which will just give protection. The data in Figure 2 were then replotted with the abscissa as the ratio of the plate thickness to the estimated critical plate thickness at zero obliquity. The data for all hardness levels below 364 BHN are seen to lie within experimental error upon a common curve (curve C, drawn through the 5° critical angle range for 210, 269 and 320 BHN).

This common curve follows the formula

$$e_\theta/e_o = \cos\theta \qquad (1)$$

up to an obliquity of 35°. It then drops slightly below the curve given by this formula. The deviation from the formula of Eq. (1) is less for the 364 BHN plates than for the plates of lower hardness.

III RELATION BETWEEN PLATE THICKNESS AND PLATE HARDNESS

From the data in Figure 2 an estimate may readily be made of the effect of plate hardness upon the plate thickness necessary to give protection at a fixed obliquity. Since the curves in Figure 2 are all parallel in the range 0-35° and also in the range 40-55°, the effect of a change in hardness level may be represented by a single factor for each of the above ranges of angle. In Figure 4 is given the factor by which the plate thickness at 320 BHN must be multiplied to give the thickness at another hardness level for equal protection.

An example will be given of the use of this Figure. Suppose 6" armor cannot be made harder than 210 BHN if poor shock properties are to be avoided. The possibility then arises that it may be possible to obtain the same resistance to penetration in a thinner plate since such plates may be heat treated to a higher hardness level without poor shock resistance. From Figure 4 one may deduce that a 320 BHN plate of thickness 6"/1.33, i.e. 4.5", will have at least as good resistance to penetration as the 6" plate at 210 BHN.

IV CORRELATION WITH DATA IN LITERATURE

It has been reported in the literature[1] that at normal obliquity the critical velocity for complete penetration (Navy B.L.) of artillery type projectiles varies with the plate thickness as

$$V^2 \sim (e/d - \alpha) \text{ , } \theta \text{ constant} \qquad (1)$$

where e is the plate thickness, d is the projectile calibre, and α is a numerical constant with a value of about 0.1. In order to test the validity of this equation for the lower obliquity range (0°-35°), the ballistic limits (for complete perforation) of the projectiles described in Section I were found for a range of plate thicknesses at 25°. The results, given in Table III and in Figure 5, agree, within experimental error, with Eq. (1). This equation may be closely approximated to by the following relation:

$$V \sim e^{1/2} \text{ , } \theta \text{ constant.} \qquad (2)$$

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

It has also previously been mentioned in the literature[1] that, in the range 0°-30°, the critical velocity for complete penetration (Navy B.L.) of artillery type projectiles varies with obliquity as

$$V \sim 1/\cos^{1/2}\theta, \quad e \text{ constant} . \qquad (3)$$

Upon combining Eqs. (2) and (3) one obtains

$$V \sim (e/\cos\theta)^{1/2} . \qquad (4)$$

Therefore in the obliquity range 0°-30° the relation between e and θ at constant V, that is, at constant resistance to penetration, is given by

$$e \sim \cos\theta . \qquad (5)$$

The relation is in agreement with the slope of unity for the 0°-35° range in the diagrams of Figure 2.

The authors are aware of only one source of data[2] for artillery type projectiles with which the approximate linearity between e and cos θ, with constant V, may be checked for the high obliquity range. In this obliquity range the ratio of the Navy ballistic limits of a 260 BHN plate of 2.5" and 2.25" thickness is 1.07.

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

[2] Aberdeen Report AD-542.

TABLE III

BALLISTIC LIMITS (NAVY) OF 269 BHN PLATE AT 25° WITH RESPECT TO MODEL ARTILLERY TYPE PROJECTILES

Thickness (inches)	B.L. (ft/sec)	(B.L.)^2 x10^{-6} (ft/sec)^2
.25	1720	2.95
.30	1885	3.55
.35	2095	4.38
.40	2270, 2230	5.15, 4.95
.45	2405, 2350	5.78, 5.50
.50	2660*	7.08

*Bourrelet suffers slight plastic deformation.

Further, from the plot of the data for the 2.5" plate one deduces that

$$V \sim 1/\cos^{0.67}\theta, \quad e \text{ constant.} \qquad (3')$$

Upon combining Eqs. (2') and (3') one deduces, within the error of the firing data

$$V \sim (e/\cos\theta)^{0.67} . \qquad (4')$$

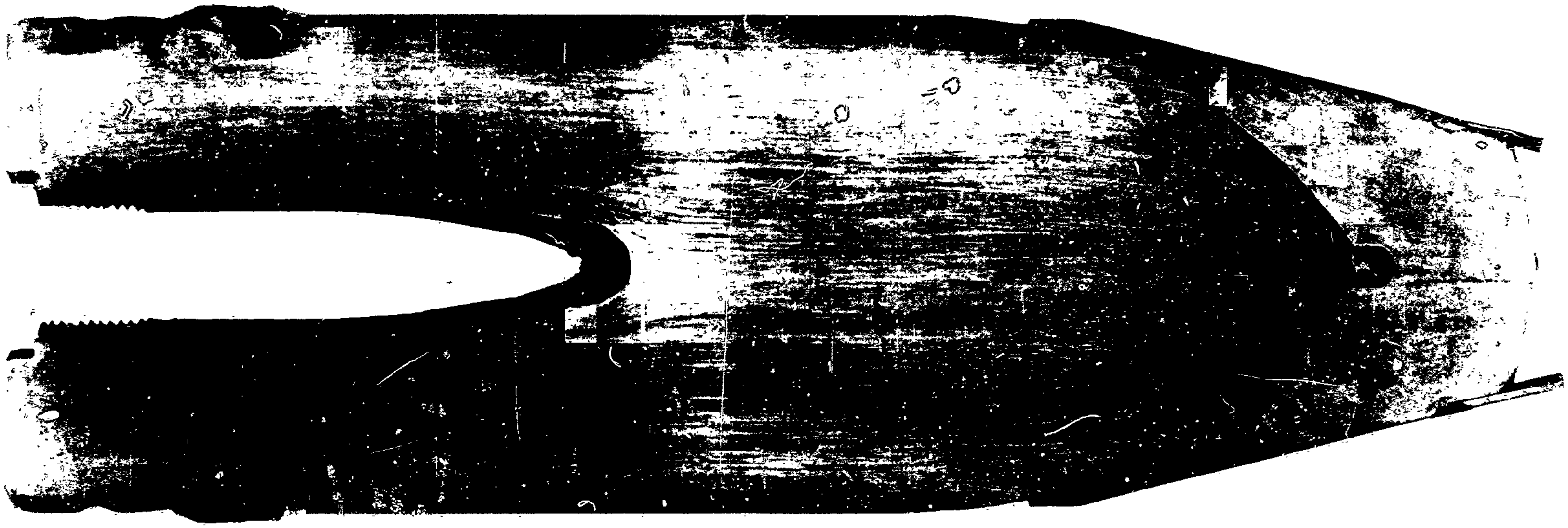
One therefore infers that also in the high obliquity range the relation

$$e \sim \cos\theta, \text{ constant } V$$

is valid. The constant of proportionality is of course slightly different in the high and in the low obliquity ranges.

ACKNOWLEDGMENT

All the firings in this report were conducted by Mr. Bruce Ward. The author wishes to express his gratitude for the competency with which these were carried out.



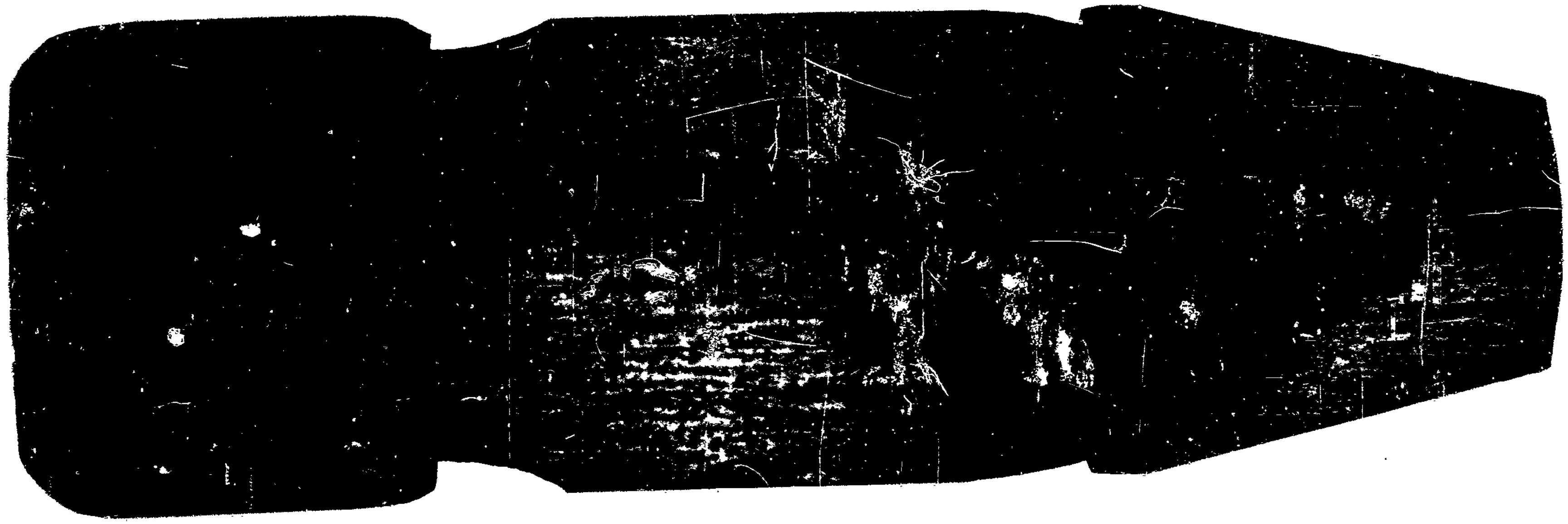
GERMAN 75mm Pak 40
X1

21 SEPTEMBER 1943

WTN.751-1269

GERMAN 75mm Pak 40
X1

21 SEPTEMBER 1943 WTN.751-1269



CAL. .30 MODEL
X 10

FIGURE 1

COMPARISON OF MODEL ARTILLERY TYPE PROJECTILE WITH GERMAN 75MM

WTN.639-6500

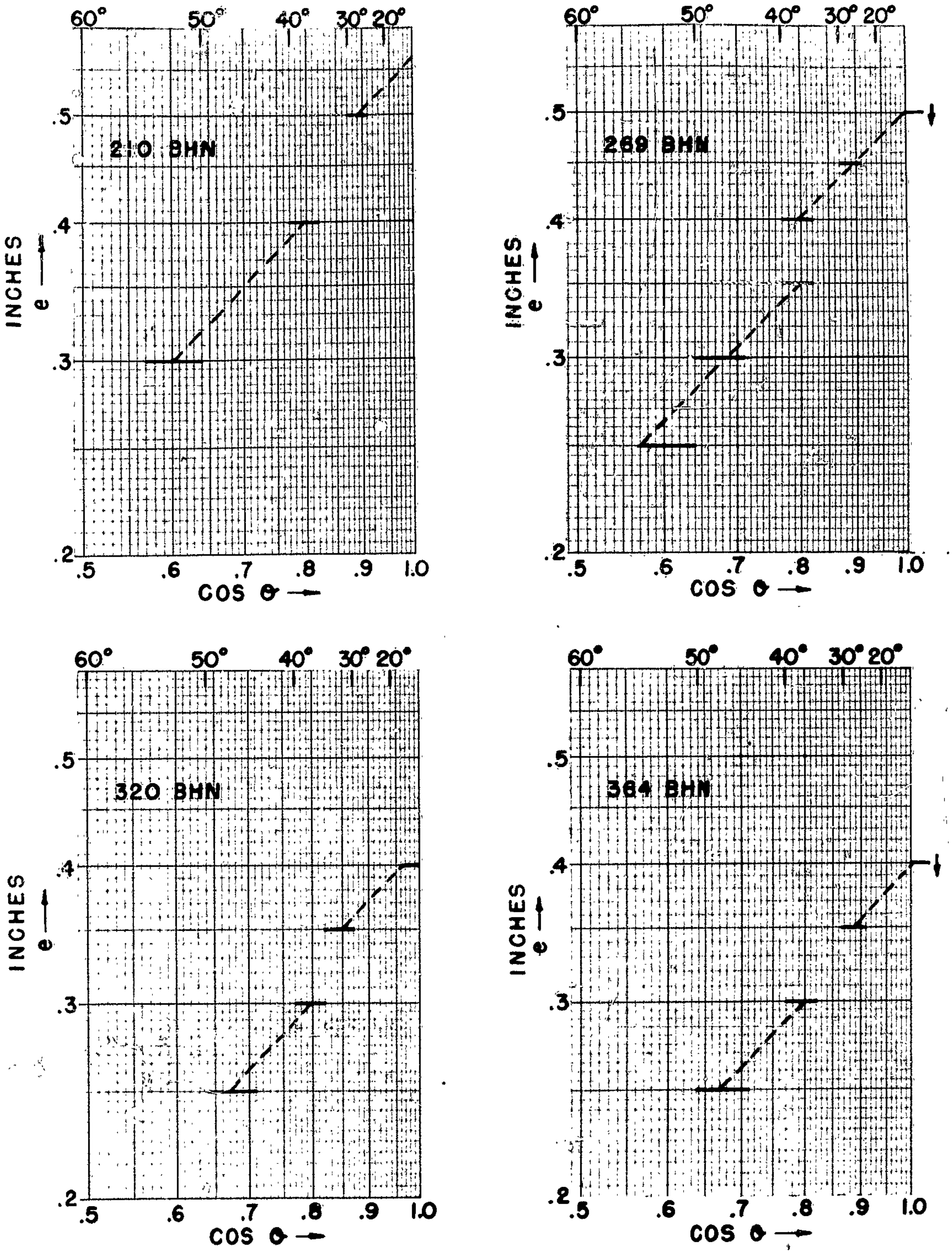


FIGURE 2

PLOT OF BALLISTIC DATA
FROM TABLE I
(HORIZONTAL LINES REPRESENT 5° RANGE)
(DASHED LINES ARE AT 45°)

WTN.639-6458

CURVE A —
THEORETICAL FOR
PROTECTION PER UNIT
WEIGHT BEING INDEPENDENT OF ANGLE

CURVE B —
THEORETICAL THOMPSON FORMULA

CURVE C —
OBSERVATIONS FOR
210 AND 269 BHN
PLATES

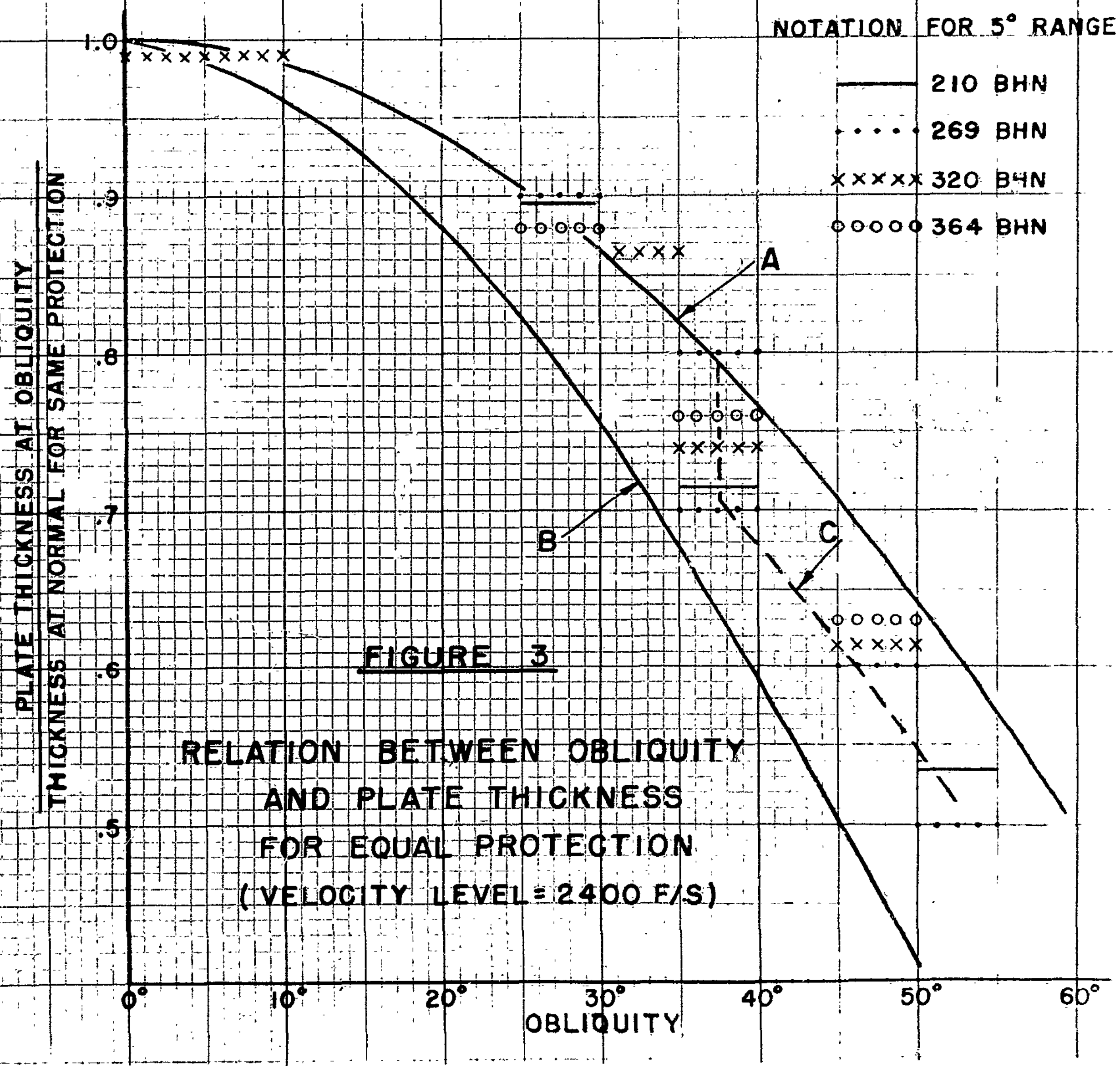


FIGURE 3

RELATION BETWEEN OBLIQUITY
AND PLATE THICKNESS
FOR EQUAL PROTECTION
(VELOCITY LEVEL = 2400 F/S)

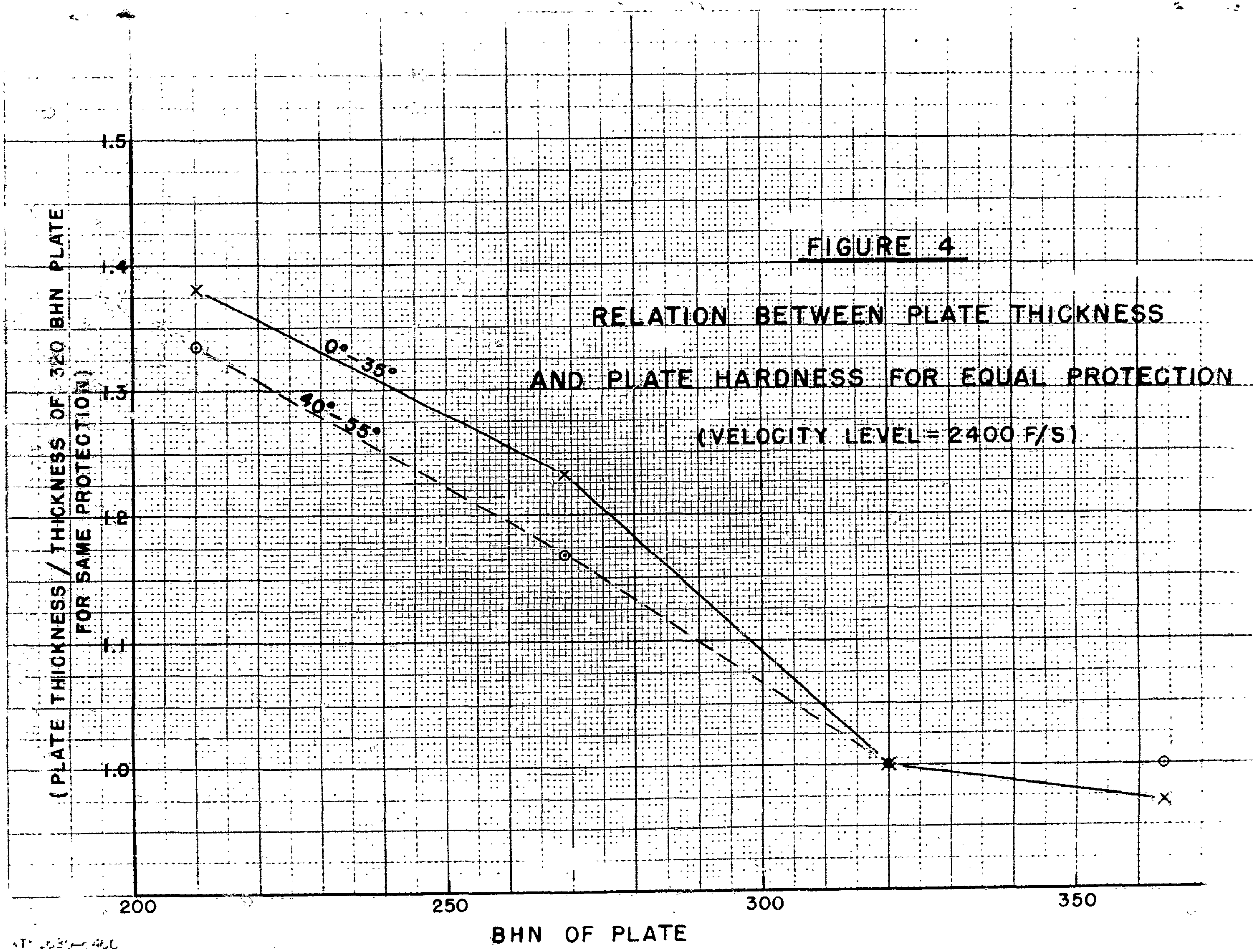


FIGURE 4

RELATION BETWEEN PLATE THICKNESS AND PLATE HARDNESS FOR EQUAL PROTECTION

(VELOCITY LEVEL = 2400 F/S)

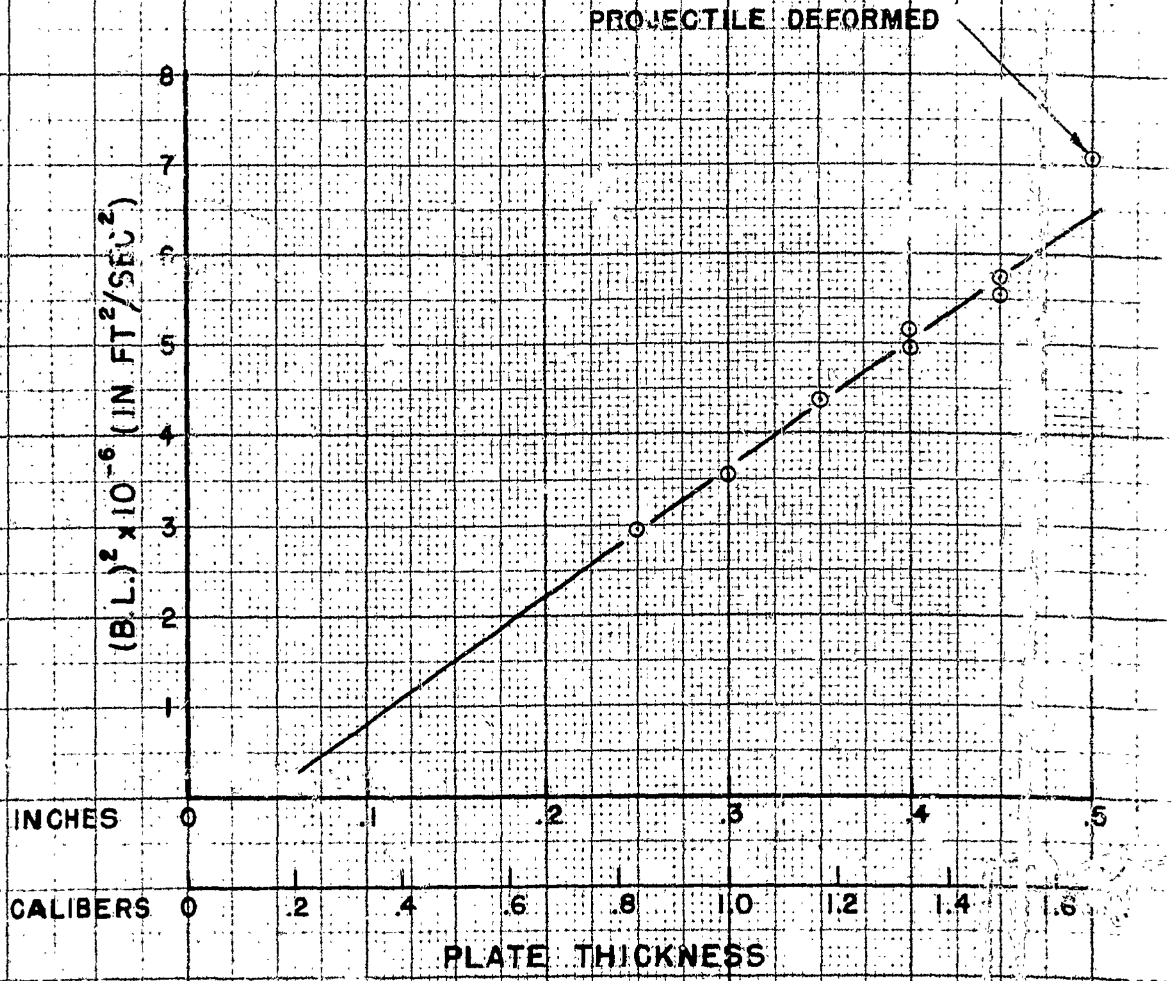


FIGURE 5

BALLISTIC LIMITS (NAVY) OF 269 BHN PLATE AT 25° WITH RESPECT TO MODEL ARTILLERY TYPE PROJECTILES