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NAVAL PROVING GROUND

DAHLGREN, VIRGINIA

PENETRATION MECHANISM

REPORT No. 4-44

III The Penetration of Homogeneous Plate at Various Obliquities

4 April 1944

CONFIDENTIAL

NAVAL PROVING GROUND

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APPROVED for Public Release; Distribution Unlimited.

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CAPTAIN, USN,
COMMANDING OFFICER.

P R E F A C E

AUTHORIZATION

This report is based upon part of the project authorized in Bureau of Ordnance letter NP9/A9 of 9 January, 1943 as Naval Proving Ground Research Project APL-2.

OBJECT

To present a preliminary discussion of the penetration mechanisms involved in oblique impact, with reference to the various factors involved.

SUMMARY

The problem of oblique impact penetration of armor is analyzed in the following way, based on extensive examination of impacts: A distinction is first made between low obliquity and high obliquity impacts. A low obliquity impact is characterized by the rejection of the projectile in incomplete penetrations in a direction approximately reversed to the incident trajectory. In high obliquity impacts, a rejected projectile ricochets in a considerably different direction. The distinction has practical importance in naval practice, corresponding effectively to the cases of side armor penetration and deck armor penetration by projectiles respectively.

The mechanism of low obliquity impacts is shown experimentally to be more complicated than normal obliquity in that the mere application of a factory sec θ is inadequate to extend the normal results to the new obliquity. A detailed examination is made of the forces on the nose of the impinging projectile and the resulting yawing motion during the penetration.

For high obliquity penetrations, a discussion of the steps in the cycle is given and qualitative criteria for penetration are suggested.

CONTENTS

LIST OF FIGURES

I. INTRODUCTION:

In a previous report (reference (1)) a theory was presented covering the penetration of homogeneous plate by uncapped projectiles at 0° obliquity. Additional experimental data and a discussion of the importance of friction as a factor in penetration resistance are given in reference (2). Summaries of references (1) and (2) are given in Appendix A. While a considerable advance in our understanding of normal impact has been made in these reports and in reports originating elsewhere (see bibliographies of references (1) and (2)), they do not deal with the case of primary practical interest, namely, oblique impact. This report is a preliminary discussion of the subject, describing the phenomena observed and discussing the mechanics of oblique penetration. A complete empirical study of oblique penetration by uncapped solid shot will be presented in a subsequent report, and will be followed by a similar study for capped projectiles.

When the obliquity is 0° the mechanics of penetration takes its simplest form because of the symmetry of the stresses acting within the armor plate and upon the projectile. In oblique impact the situation is complicated by the existence of unbalanced lateral stresses which produce a complicated yawing motion of the projectile as it passes through a plate, so that in general it emerges from the back of the plate with a different direction of motion and different orientation than immediately before the impact.

Two cases may be distinguished, which will be denoted as low obliquity and high obliquity impact. The distinguished feature of these two types of impact is that in the so-called low-obliquity impact, a projectile fired at a velocity insufficient to penetrate the plate will be rejected more or less in the reverse direction to the direction of attack, while in the high-obliquity case a projectile fired at a velocity insufficient to penetrate the plate will ricochet, in a direction given roughly by the optical law of reflection-i.e., the angle of reflection equals the angle of incidence. The experienced ballistician will at once recognize that the obliquity at which the transition between the two mechanisms of below-limit behavior occurs will vary with plate thickness, projectile shape, and projectile quality. The relation between plate hardness and projectile hardness will be important, as is shown in very striking fashion in reference (3), Figure 9. This figure illustrates an experiment in which a series of projectiles of hardnesses ranging

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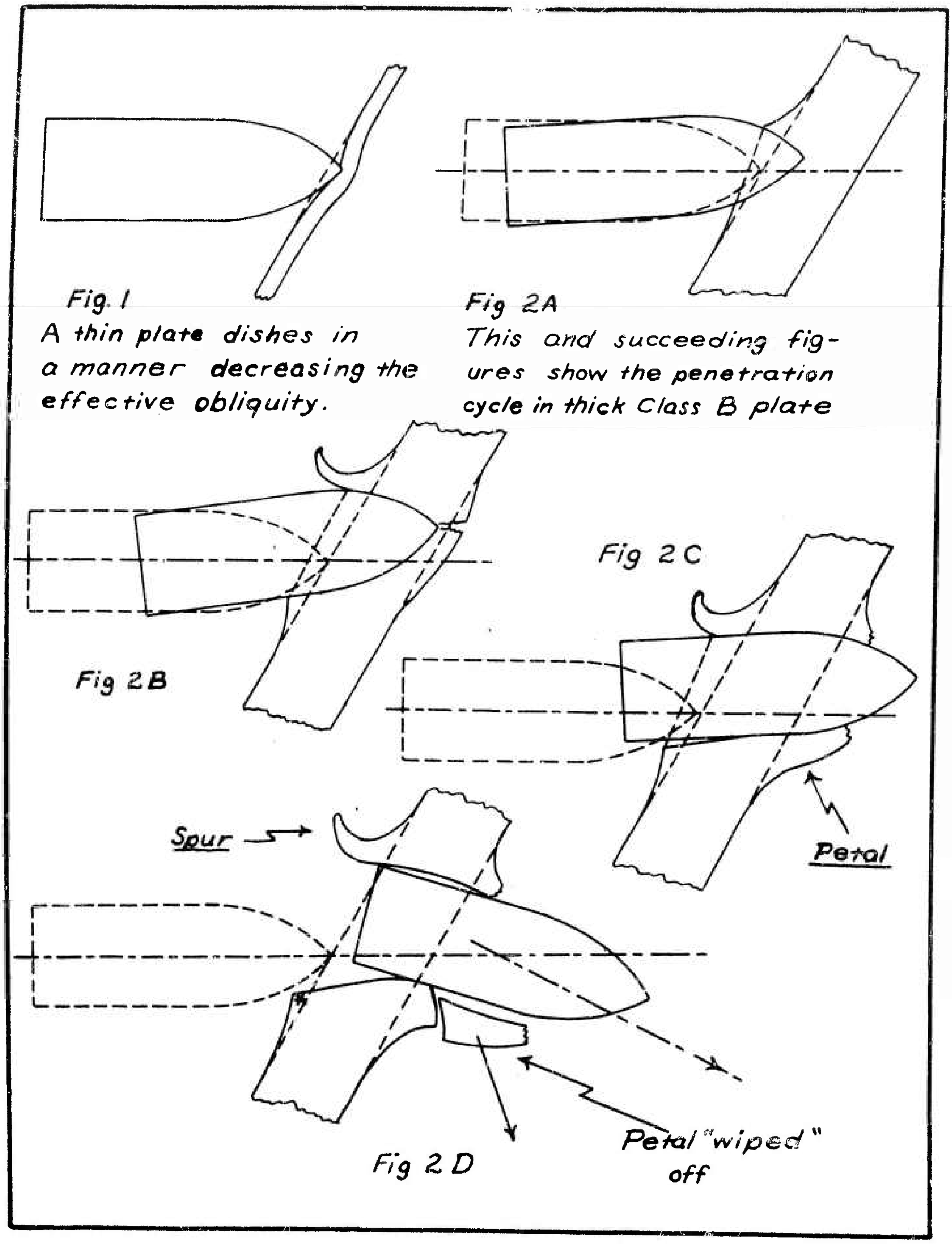


Fig. 1 A thin plate dishes in a manner decreasing the effective obliquity.

Fig 2A This and succeeding figures show the penetration cycle in thick Class B plate from R_c 45 to R_c65 were fired at fixed striking velocities and obliquities at a very thick plate of BHN 155. The harder projectiles passed through the plate; those of intermediate hardness were stopped inside the plate, but still headed through it, while the softer projectiles ricocheted after penetrating into the plate to various depths. The ricochet was evidently due to deformation of the projectile nose, which produced the same effect on the projectile as an increase in obliquity.

Plate thickness will also be an important determining factor in differentiating ricochet from rebound. If the plate dishes ahead of the projectile the effect will be to decrease the effective obliquity and inhibit ricochet. (See Fig.1). As thin plates dish more on impact than do thick plates, it is to be expected that ricochet will set in at lower obliquities for thick plates than for thin ones.

Because of the number of variables that affect the onset of ricochet, it is not practicable to give any general rule determining the critical obliquity as a function of, say, e/d. However, service conditions delimit two general types of impact condition; vertical armor on ships approximates caliber thickness, and cannot be penetrated at the actual velocities occurring at battle ranges at obliquities over 30°, while deck and other horizontal armor presents e/d values from around 0.25 to 0.35, with significant obliquities ranging from about 40° upwards for attack by gunfire, and from 15° downwards for attack by AP bombs. It follows that low obliquity attack will be of interest over the entire range of e/d, and is not likely to approach the critical obliquity, while high obliquity firing will be of interest primarily at values of e/d of 0.35 or less and at obliquities definitely in the ricochet range. The division between low and high obliquity impact in this report conforms to the general conditions outlined above.

II LOW OBLIQUITY

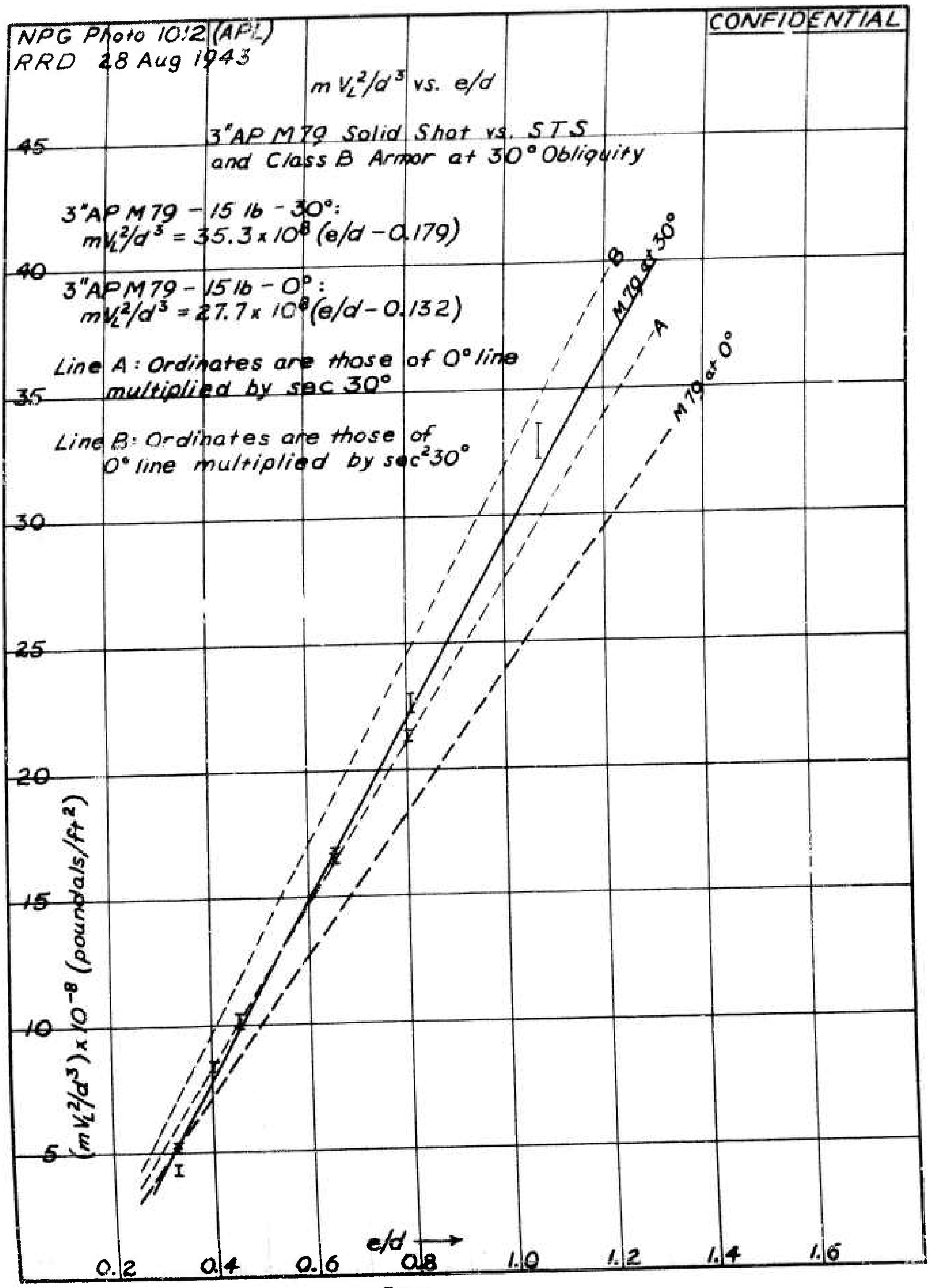
1. The Observational Data

Inspection of many impacts, both complete and incomplete penetrations, and of the projectiles making the impacts, shows that when a projectile which is not too blunt strikes a homogeneous plate at a low obliquity, a fairly definite sequence of operations occurs. This is best illustrated by Figure 2, which shows the penetration cycle at a striking velocity just sufficient for complete penetration. For reference, the initial position of the projectile, at the instant of contact with the plate, is shown by the dotted outline in each diagram of Figure 2. It is to be noted that the trajectory of the center of gravity, as well as the path of the point, of the projectile is initially upward, the general tendency being for the projectile to travel parallel to its axis, as the position of the axis changes under the action of the torques set up by the unsymmetrical pressures on the projectile. The general upward motion of the projectile is shown by the failure of the body or base of the projectile to completely obliterate the mark originally made by the nose of the projectile at point (*) in Figure 2D, the mark being recognized by its small radius of curvature; elementary mechanical condiderations confirm this result.

As the projectile-nose approaches the back of the plate (Figure 2 B&C) the static term in the pressure on the upper part of the nose will be the full yield stress of the plate, while on the lower part of the nose, confronted only by a bending petal, the pressure will be less. This unbalanced pressure will tend to force the nose of the projectile down (towards the normal to the plate), and the projectile emerges from the back of the plate at a considerably lower obliquity than the obliquity of impact. As the projectile turns toward the normal, the body and base must enlarge the hole in the plate in order to make the turn, and a severe strain on the base occurs which may result in the tearing off of the base. This does not seem to involve any considerable amount of friction, as studies like those of reference (2) show that friction is very small in oblique impacts as well as in normal impacts.

As the striking velocity is increased to successive values above the limit velocity, the yawing motion of the projectile in its passage through the plate is decreased in amplitude, and the trajectory is less refracted in passage through the plate, so that at a very high striking velocity the projectile emerges from the back of the plate in almost its original direction, and with very little yaw.

When plate thickness and obliquity provide a severe test of the projectile, failure to penetrate may be accompanied by projectile breakage. This may be overcome by a moderate increase in velocity, when the projectile penetrates intact, except possibly for base damage.



NPG Photo 1012 (APL)
RRD 28 Aug 1943
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m V_L^2/d^3 vs. e/d
3"AP M79 Solid Shot vs. STS
and Class B Armor at 30° Obliquity
3"AP M79 - 15 lb - 30°:
mV_L^2/d^3 = 35.3 x 10^8 (e/d - 0.179)
3"AP M79 - 15 lb - 0°:
mV_L^2/d^3 = 27.7 x 10^8 (e/d - 0.132)
Line A: Ordinates are those of 0° line multiplied by sec 30°
Line B: Ordinates are those of 0° line multiplied by sec²30°
B
M79 at 30°
A
M79 at 0°
(mV_L^2/d^3) x 10^-8 (poundals/ft^2)
e/d
45
40
35
30
25
20
15
10
5
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6

Fig. 4.

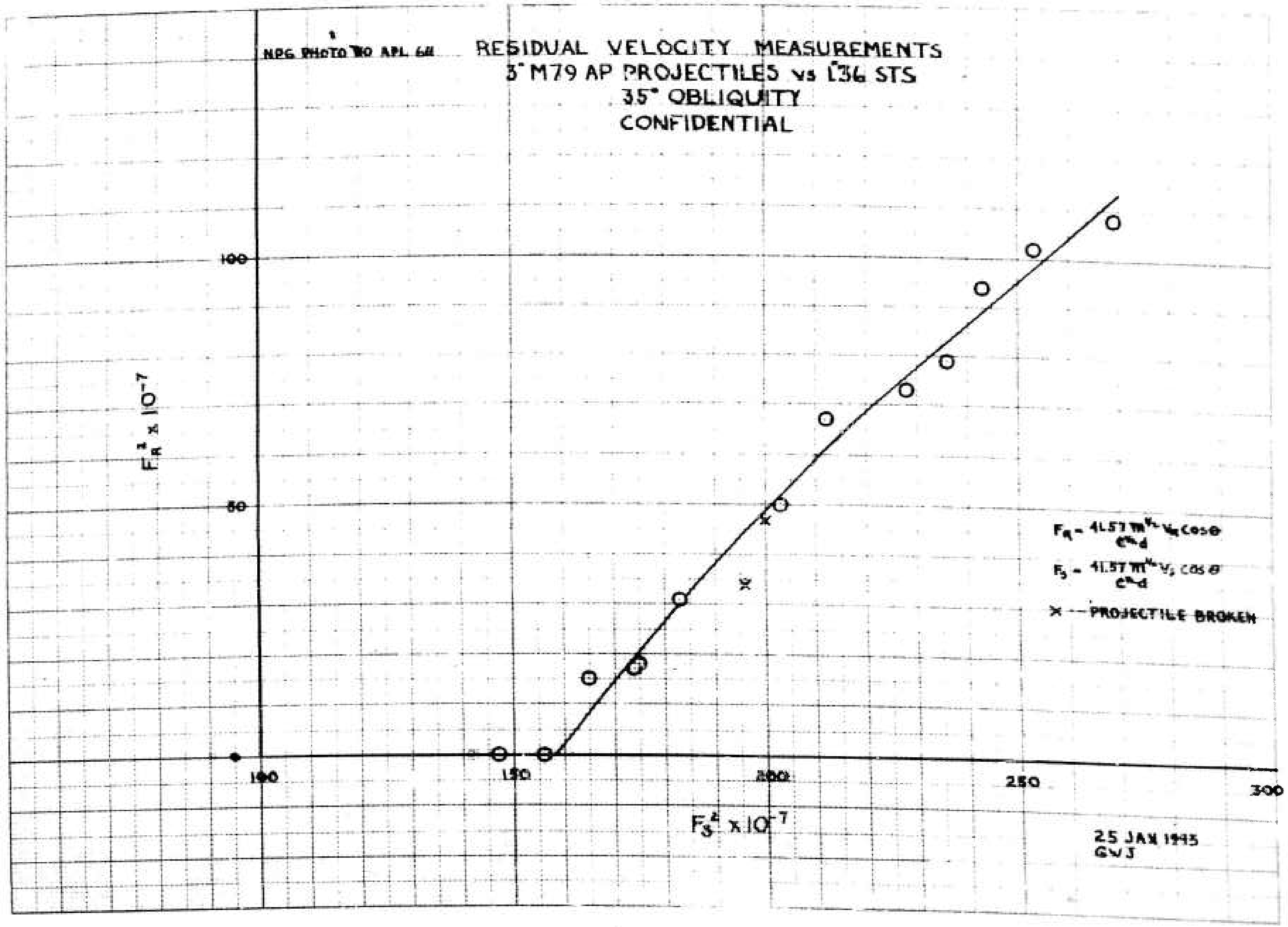

NPG PHOTO NO APL 6II
RESIDUAL VELOCITY MEASUREMENTS
3" M79 AP PROJECTILES vs 1.36" STS
35° OBLIQUITY
CONFIDENTIAL
$F_R^2 \times 10^{-7}$
100
50
100
150
200
250
300
$F_S^2 \times 10^{-7}$
X -- PROJECTILE BROKEN
25 JAN 1945
GVJ

Fig. 3.

It is well known that at 0° obliquity, the residual energy of the projectile after a complete penetration is a linear function of the striking energy.

$$E_R = S(E_S - E_L), \ldots\ldots \quad (1)$$

where the slope ranges from about 0.90 for plate of somewhat over caliber thickness to about 1.10 for the thinnest plates. The theoretical implications of this law are developed in reference (4); additional material is given in reference (1).

In the case of oblique impacts, the relation between residual and striking energy is more complicated than at 0°. Figure 4 displays a typical plot, for a 3" A.P. projectile vs. 1.36 STS at 35° obliquity. To eliminate partially the effect of small variations in plate thickness projectile mass, and obliquity from round to round, the plot is actually one of F_R^2 vs. F_S^2, where

$$F_S = (12)^{3/2} m^{1/2} V_S \cos \theta / e^{1/2} d$$

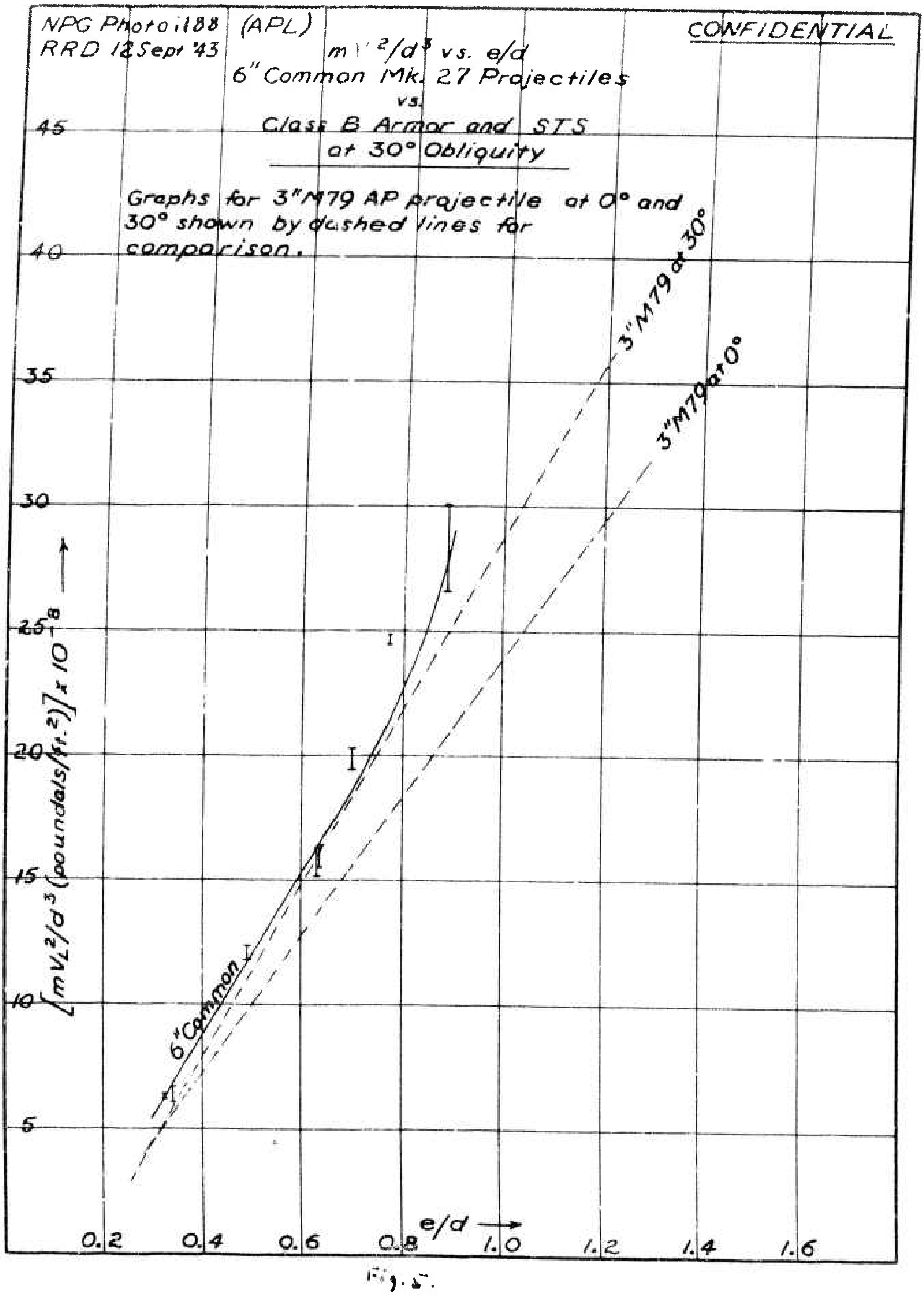
and

$$F_R = (12)^{3/2} m^{1/2} V_R \cos \theta / e^{1/2} d.$$

For constant e, m, and θ it is clear that F_S^2 and F_R^2 will be strictly proportional to E_S and E_R respectively. It will be observed that, starting at the limit F^2 of 158×10^7, the graph has a slope of about 1.24; the curve is then slightly concave downward, until it becomes a straight line of slope 0.88 at about 1.36 times the limit F^2.

At points where a residual energy graph has a slope greater than unity, energy absorption decreases with increased striking energy, and vice versa where the slope of the graph is less than unity. Thus, it is clear that in the case illustrated in Figure 3 energy absorption by the plate decreases at first as the striking velocity is raised above the limit velocity; this phenomenon is associated with the decreasing amplitude of the yawing motion of the projectile as it passes through the plate at higher and higher striking velocities. A minimum energy absorption occurs at the point where the slope of the graph is unity - i.e., at about $F_S^2 = 205 \times 10^7$.

A complete set of empirical data on the variation of the F-coefficient with obliquity is reserved for a subsequent report. As stated in reference (1), it has been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RRD 12 Sept '43
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mV^2/d^3 vs. e/d
6" Common Mk. 27 Projectiles
vs.
Class B Armor and STS
at 30° Obliquity
Graphs for 3" M79 AP projectile at 0° and 30° shown by dashed lines for comparison.
3" M79 at 30°
3" M79 at 0°
6" Common
$[mV_L^2/d^3 (\text{poundals}/\text{ft.}^2)] \times 10^{-8}$
e/d
45
40
35
30
25
20
15
10
5
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6

Fig. 5.

established that the limit energy is a linear function of plate thickness at obliquities up to about 30°. As an illustration of this, Figure 4 is presented showing a plot of mV_L^2/d^3 vs. e/d for the 3" APM79 solid shot at 30° obliquity. The 0° line is shwon for comparison. The M-79, being a solid shot, experiences comparatively little body deformation in oblique impacts; common shell suffer more body deformation at the higher values of e/d, with a consequent rise in the limit energy, as illustrated by Figure 5, which is a graph of mV_L^2/d^3 vs. e/d for the 6" Common Mk. 27 at 30° obliquity. It will be noted that while the graph is reasonably straight up to about e/d = 0.6, it curves up sharply beyond that value of e/d.

On the assumption that the increased resistance of a plate in an oblique impact is due merely to the increased thickness of metal measured along the initial trajectory of the projectile, the limit energy at 30° would be obtained from that at 0° by multiplying the 0° energy (for each e/d) by sec 30°. Line A of Figure 4 shows the result of such a multiplication; it is clear that at 30° the M-79 does not obey this simplest possible law for oblique impacts. Line B corresponds to an F-coefficient constant with θ. Inspection of Figure 4 is sufficient to show that the limit energy is not proportional to any simple power of sec θ, and that the mode of variation of the limit energy with θ varies with e/d.

2. <u>Theory of low-obliquity penetration.</u> The theoretical considerations set forth here are of a preliminary nature, the complexity of the problem precluding anything like a complete solution at this time.

If the projectile passed undeviated through the plate, it would be reasonable to expect the limit energy at obliquity θ to be to the limit energy at 0° as sec θ. The complicated yawing motion of the projectile during penetration causes marked deviations from this rule, as suggested by Figure 4. As noted above, the yawing motion is decreased in amplitude by increasing the striking velocity above the limit velocity, with an accompanying decrease in the energy absorbed by the plate. This can be understood if it can be shown that the yawing torque does not increase too rapidly with increased striking velocity, so that any increase in torque is more than offset by a decrease in the time during which it acts, with a consequent reduction in the total yaw developed.

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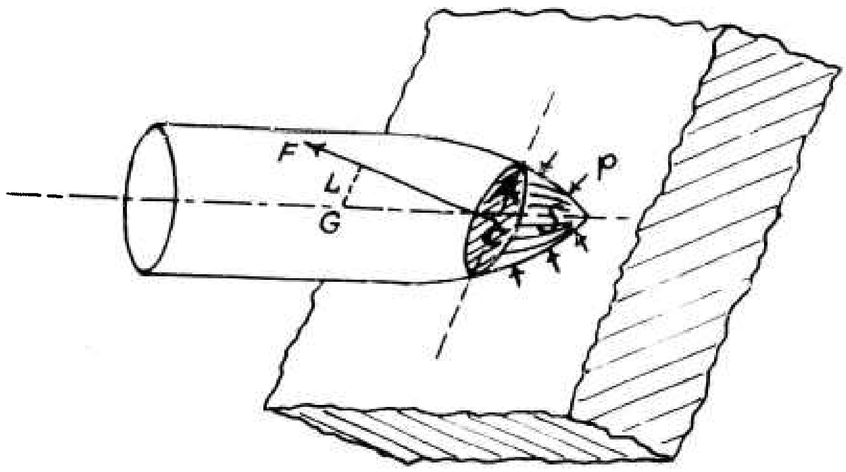

Fig. 6A. A uniform pressure over the embedded portion of the ogive is equivalent to the same pressure acting normal to the section "A" of the projectile by the plane of the plate.

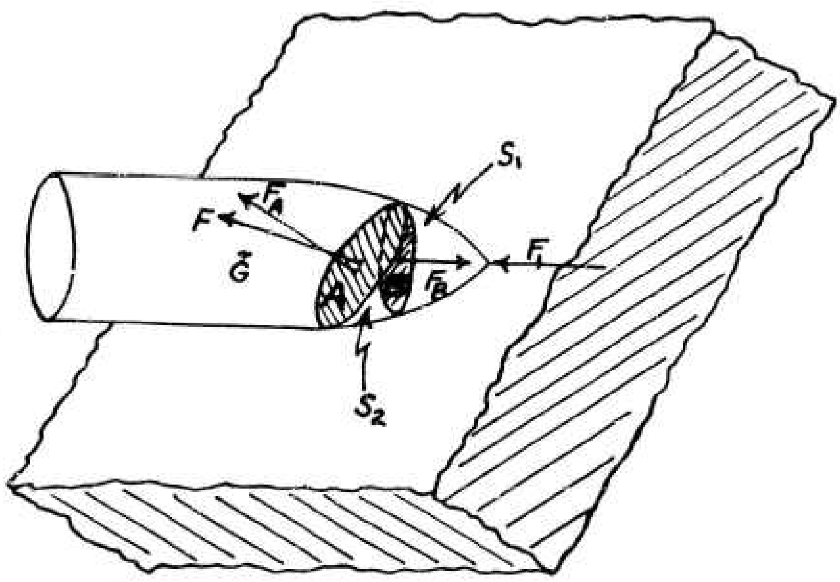

Fig. 6B. To illustrate the case of non-uniform pressure.

Calculation of the yawing torque is simplified by our knowledge of the fact that as friction is negligible, the forces over the plate-projectile boundary are everywhere normal to the surface of the projectile. The calculation is complicated, however, by our knowledge of the fact that the kinetic nature of armor penetration with its consequent inertial effects will result in a non-uniform distribution of pressure over the nose of the projectile.

The elements that enter into a calculation of the yawing torque may be presented by considering first a highly idealized penetration, and modifying it step by step to bring it into closer relation with an actual penetration. Imagine first a projectile entering a thick plate without yaw, with no extrusion occurring around the nose of the advancing projectile, so that the plate surface remains plane (Figure 6A). Judging by hardness patterns for incomplete penetrations (reference (2)) the material in immediate contact with the projectile nose will have a practically uniform yield-stress, so that disregarding inertial effects for the moment, the pressure on the ogive should be about the same at all points. As in a problem in hydrostatics, then, the uniform pressure P over the surface of the projectile-nose embedded in the plate (S) is equivalent in its effects to the same pressure acting normal to the area A of the section of the projectile by the plane of the face of the plate. The resultant force F is thus of magnitude pA, is normal to the plane of the plate, and passes through the center of area of A. The torque-arm L of the force F about G, the center of mass of the projectile, will evidently vary as sin θ, and will decrease almost linearly with depth of penetration, while A will increase with depth of penetration, first very rapidly, and then more slowly, the exact details depending upon the shape of the ogive.

As the projectile yaws under the influence of the torque due to the force F, as shown in Figure 2, the angle θ between the plate normal and the projectile axis will tend to increase, and as A and L increase with θ, the yaw is, so to speak, self-generating.

Several considerations enter the picture to modify this process. The upward motion of the point of the projectile will plow up a spur from the face of the plate, as well as producing some extrusion of plate material all around the impact. As is apparent from Figure 2B, the extrusion of material around the projectile tends to restore the symmetry of the forces acting upon the projectile. This symmetrical extrusion will tend to offset the increase in torque due to the developing yaw of the projectile.

If the path of the point of the projectile makes a considerable angle with the projectile axis, the inertial terms in the expression for the pressure on the projectile will be unsymmetrical, giving greater pressures above the nose than below.

The pressure over the ogive will certainly not be uniform in any case, being, because of the inertial terms, greatest at the point and falling off aft along the projectile nose. This fact will modify the theorem previously advanced on the calculation of the yawing torque. To deal with the case of non-uniform pressure, it will be convenient to divide the embedded surface of the projectile nose into two parts, S_1 and S_2 (Figure 6B), separated by the section B, which is normal to the axis of the projectile. S_1 is then symmetrical about the axis of the projectile, and the pressure upon it, if symmetrical, will produce an axial force F_1 which, passing through the center of mass G of the projectile, produces no torque. The sections A and B and the Surface S_2 together comprise a closed surface, whose vector representative is zero. Thus, the <u>resultant</u> of the vector representatives of A and B (taken in the <u>inward</u> sense) is the <u>equilibrant</u> of the vector representing the surface S_2. Therefore, if a uniform pressure P acts over S_2, the resultant of the <u>outward</u> vectors F_A and F_B is the resultant force on S_2, where $\overline{F_A = PA}$ and $F_B = PB$. As F_B is an axial force, it contributes nothing to the torque on the projectile. If the variation of pressure over S_2 is negligible, we are led to the same method for calculating the yawing torques as in the case of uniform pressure, except that the pressure P is not now the pressure over the entire embedded part of the ogive, but the average pressure on S_2, which is smaller than the mean pressure over the S_1 and S_2 together.

Now, if one considers a particular striking velocity, while the pressure is concentrated near the point of the projectile, the point is ineffective in producing yawing torque because of the small embedded area; the pressure used in calculating the torque falls off with depth of penetration, but the rapid growth in area A presumably offsets this. Next, suppose the striking velocity to be increased; the pressure will be still further concentrated at the point of the projectile, but this increased pressure will be, as before, relatively ineffective in producing torque. On the other hand, the pressure will be still further reduced farther back along the ogive, where it is most important in producing torque. There seems to be no reason to expect any important increase in mean torque with increased striking velocity, and as the torque will act for a shorter time at the higher velocity, a decrease in the yaw developed is to be expected.

It has been noted that when conditions of impace are severe, failure of projectiles to penetrate may be associated with projectile breakage, and that a small increase in velocity will prevent projectile breakage and insure penetration. As the projectile evidently fails due to bending stresses induced by the torque-producing forces on the nose, and a small increase in velocity can prevent breakage, it is concluded that the yawing torque is decreased by an increase in striking velocity.

In practice the pressure will probably not be uniform over S_2, being on the average less below the axis of the projectile than above, due to the asymmetry of the area, so that in Figure 6B the torque-producing force is better represented by F than by F_A. Note that F does not originate at the geometrical center of A, but at the center of area determined by weighting the elements of area in accordance with the distribution of pressure on S_2.

To recapitulate: In the initial stages of an oblique impact the torque on the projectile at any instant is approximately equal to that which would be produced by a uniform pressure over the section of the projectile by the plane of the plate. The orientation and area of the section will be modified by extrusion of material from the face of the plate around the advancing projectile. Furthermore, the pressure will depart somewhat from uniformity, so that the torque-producing force has a line of action lying between the plate normal and the projectile axis (cf. F in Figure 6B), and does not pass through the geometrical center of the section. The pressure is greatest around the point of the projectile and falls off aft, and in calculating the torque the significant pressure on the projectile is that around the entrance of the hole in the plate, so that this pressure falls off as the depth of penetration increases, and has a distribution over depth of penetration which varies with the striking velocity. The phenomena of projectile breakage suggest a decrease in maximum torque (and presumably in mean torque) with increased striking velocity. The decrease in amplitude of yaw which occurs as the striking velocity is increased above the limit velocity is correlated with the shortened time during which the yawing torque can act, and possibly with the decrease in mean torque suggested by the study of projectile breakage.

It is a striking fact that against plates which at normal obliquity give an <u>increase</u> in energy absorption with an increase in striking velocity above the limit, the energy absorption <u>decreases</u> with an increase in striking velocity at any considerable obliquity. This decrease in energy absorption is, as previously noted, associated with the decrease in yawing motion at velocities above the limit. Presumably the yawing motion executed by passage of the projectile through the plate results in the working of a greater volume of metal than in a simple unyawed penetration. It follows that any alteration in projectile design which would result in a decrease in the yaw generated during penetration should decrease the limit energy, other things being equal. This is a point to which further reference will be made in the section on high obliquity impact.

The discussion given here deals primarily with the case of a plate thick enough not to dish appreciably upon impact. As pointed out in connection with Figure 1, unsymmetrical dishing of a thin plate around the impact will have an effect equivalent to lowering the obliquity, so that the energy required for the penetration of a thin plate should increase more slowly with obliquity than for a thick plate. This is an agreement with Figure 4, where the limit energy graph determined experimentally crosses the line A. Another difference between the penetration of thick and of thin plates lies in the fact that with thin plates, the point of the projectile will emerge from the back before the bourrelet enters the face of the plate, bringing into play a set of torque-producing forces tending to counteract those which operate at the face of the plate.

From the many factors which enter in to the problem, it is clear that the calculation of the yawing torques and of the yaw generated in any given penetration is an exceedingly intricate problem. As an illustration of the influence of some of the factors involved, an idealized case is given in Appendix B, where the yawing torque is calculated for a projectile with a conical nose experiencing a uniform pressure as it penetrates into a thick plate whose face remains plane.

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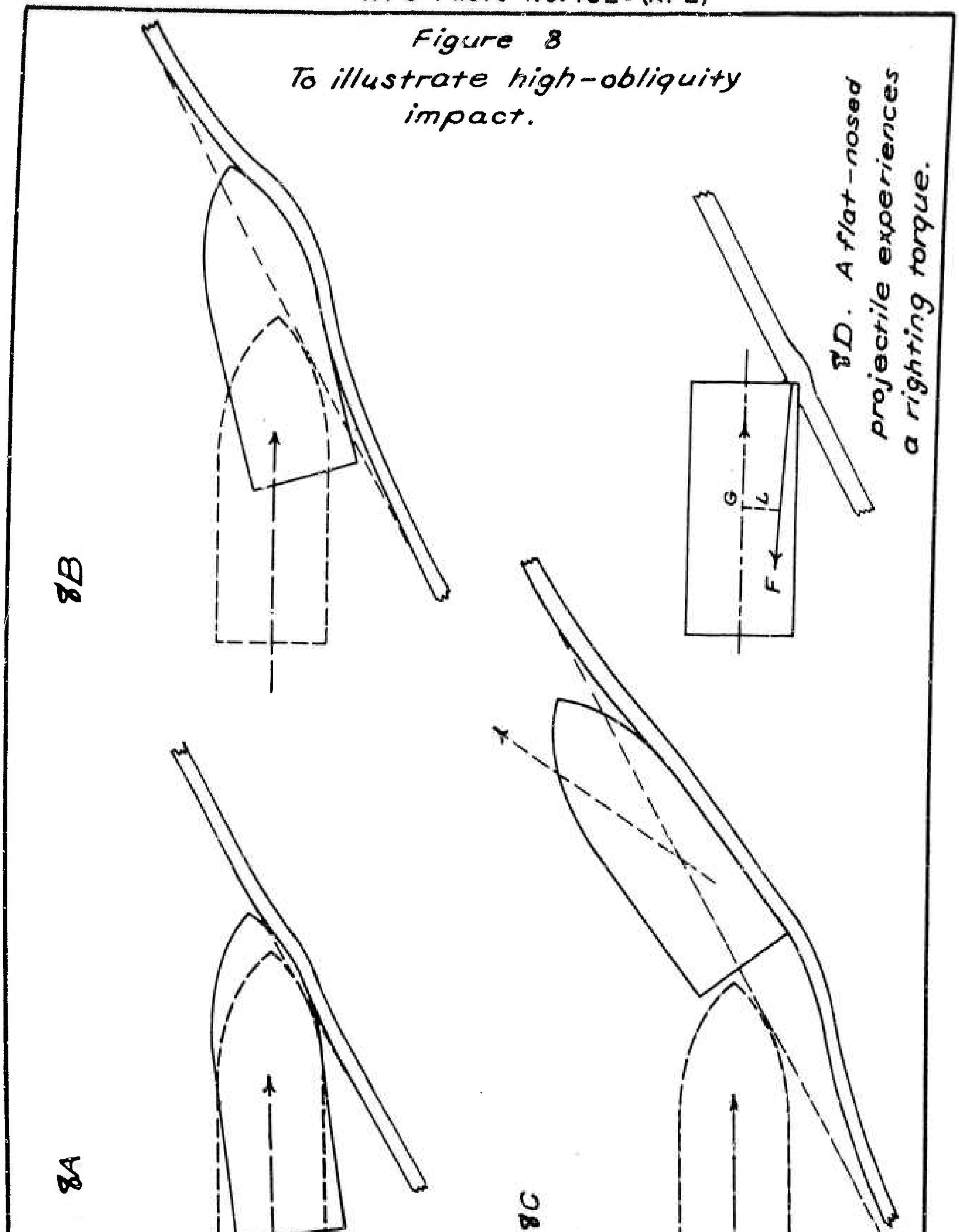

Figure 8
To illustrate high-obliquity impact.

NPG Photo 1055 (APL) Fig. 7.

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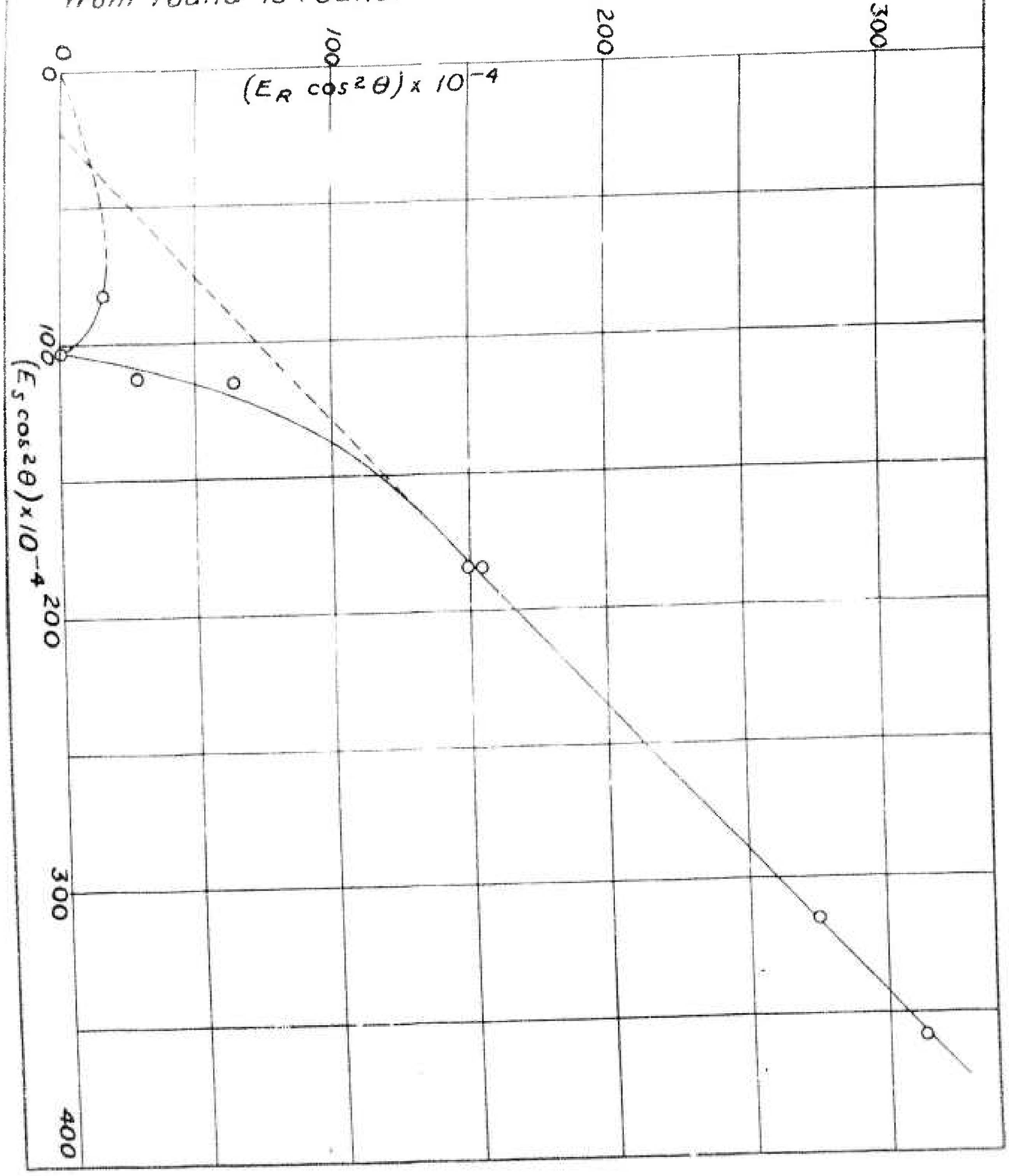
RESIDUAL ENERGY vs. STRIKING ENERGY

3" AP Type A Projectiles (uncapped) vs. 3/8" modified STS at 45°

The energies in ft.-poundals are multiplied by $\cos^2\theta$ to smooth out the effect of small variations in obliquity from round to round.



III HIGH OBLIQUITY

The values of e/d which are of interest in what is considered the high-obliquity range are relatively low. When a relatively thin plate is struck at a high obliquity (e.g., $e/d = 0.125$, $\theta = 45°$) the mechanism of impact appears to be entirely different from the mechanism at lower obliquities ($\theta < 35°$). Roughly speaking, over the greater part of the velocity range one of two things will happen, namely either (1) the projectile passes through the plate with a high residual velocity and in almost the original direction or (2) the projectile ricochets from the plate with a high residual velocity, the angle of departure from the plate being roughly equal to the obliquity of impact. Figure 7 is a graph of residual energy vs. striking energy for a rather round-nosed 3" projectile (the uncapped 3" AP Type A) vs. 3/8" modified STS at 45°; because of the nose shape, this projectile ricochets at a somewhat lower obliquity than more pointed projectiles. It will be observed that there is a narrow range of striking energies where the energy absorption is high, and in which the limit velocity is found. This type of graph is typical of all high-obliquity studies.

At this obliquity a lucky shot may stick in the plate. At higher obliquities (e.g., 60° and 75°), it is very unusual to have a projectile stick in the plate. In a near-limit ricochet the projectile plows deeply into the plate, gradually yawing so as to turn with its axis parallel to the plate; the plate may be split open along a line parallel to the axis of the projectile. Sometimes this split continues to open up after the projectile has passed by even opening up to a width of more than a caliber, although the projectile has ricocheted. There is considerable evidence to show that at the limit, the projectile is likely to penetrate the plate base first, and plow a long hole in the plate, before dropping through.

It is possible that the existence of a limit is in a certain sense fortuitous -- that the main mechanism is due to a normal force, tending to deflect the projectile; if this force is insufficient, the projectile breaks through with little deflection, and makes a small hole. In the ricochet region, the projectile gradually revolves about a transverse axis parallel to the plane of the plate, sliding along the surface in such a way as to remain parallel to the surface, which is deformed as the projectile slides on it (Figure 8). In the intermediate zone, where the <u>base</u> breaks through, the projectile plows through the plate sideways, and is gradually brought to rest. It is only in this case that a force is applied of the necessary amount and direction to bring the projectile to rest; in the other cases the force is either insufficient or acts in the wrong direction to stop the projectile.

When a projectile strikes a thin plate, pushing forward the material with which it is in contact, the plastic deformation is propagated outward from the impact. The rate of propagation of this plastic deformation is much less than that of an elastic wave, and may be comparable with that of the projectile. At the low velocities necessary to penetrate thin armor at high obliquities, it is possible that the velocity of propagation of the plastic deformation may exceed that of the projectile.

Assuming this to be the case, there would be a certain critical striking velocity for the projectile; below this striking velocity, the deformation of the plate would travel along the plate ahead of the projectile, in such a way as to maintain a high obliquity at the point of contact. Above this striking velocity, the projectile would be traveling faster than the deformation, so that the dishing of the plate would lower the effective obliquity at the point of contact, and the projectile will "bite". Investigation of this hypothesis would seem to offer a promising field for photographic study. If the hypothesis should be verified, it might be desirable to investigate those properties which control the rate of propagation of plastic deformations, for an increase in that rate obtained without loss of other essential properties in the armor should serve to raise the limit velocity.

The shape of the projectile is an exceedingly important factor in determining its effectiveness at high obliquities, although this is a factor as yet only partially explored. To take the most extreme case, a flat-nosed projectile will penetrate a plate of quarter caliber thickness at an obliquity of 60° at velocity less than half that required for a projectile with a conventional 5/3 - caliber ogive (reference (5)). In this case the projectile neatly punches a clean hole in the plate, producing a negligible deformation in the material around the hole. As compared with more conventional projectiles, the reduction in the volume of metal plastically worked (because of the elimination of the dished area) accounts for the great reduction in the limit energy.

To take a less extreme case, a capped projectile with a broad cap having a sharp shoulder on it is more effective than a capped projectile with a small cap or with a rounded cap (reference (6)). Data with uncapped projectiles at high obliquities are unfortunately too meager to permit a full analysis of the effect of nose shape, but similar relations seem to hold - broad, angular noses "bite" better and result in lower limits at high obliquities than do the nose shapes usually used on uncapped projectiles.

Inspection of complete penetrations at high obliquity indicates that, as at low obliquity, the projectile experiences as initial yawing torque tending to increase the obliquity. The boundary between ricochet and penetration is probably determined by a delicate balance between the rate of yaw and the rate of deformation of the plate. A nose shape tending to decrease the rate of yaw in the initial stages of oblique impact would favor "biting" of the plate, and (other things being equal) should result in a lower limit velocity. To give the most extreme example again, the flat-nosed projectile very probably experiences an initial righting torque - i.e., a torque tending to turn it towards the plate normal, rather than away from it (Figure 8D).

APPENDIX A.

1. SUMMARY OF NPG REPORT NO. 1-43 (Reference 1)

Certain experimental laws of penetration of homogeneous armor at 0° obliquity are presented, and theoretical interpretations are derived. In particular:

(a) In the penetration of thick plates (e/d 0.3) the quantity mV_L^2/d^3 is a linear function of e/d. This law is explained by Bethe's expanding-hole theory, modified to take account of the formation of petals on the back of the plate.

(b) In the penetration of thick plates, if the residual energy E_R is plotted as a function of the striking energy E_S, a straight line results with a slope of about one. For a thick plate the slope of this line is less than unity; trials against a series of progressively thinner plates give slopes increasing as e/d decreases. These observations are explained when one considers the dynamic nature of projectile penetration; if the force with which the plate resists the projectile increases linearly with the projectile energy, the observed results follow. The slopes may be calculated quantitatively by an extension of Robertson's version of the Poncelet-Morin theory.

(c) In the penetration of thin plates (e/d 0.3), the predominant mechanism of failure is the bending back of plate material around the hole, comparable to the bending of the petals on the back of a thicker plate. This mechanism leads to a quadratic variation of mV_L^2/d^3 with e/d, which is in fair agreement with experiment. In this thin-plate theory, stretching and dishing are not included; they are relatively unimportant at the upper end of the thin plate range, but contribute the bulk of the energy absorption in the thinnest plates, which lack the stiffness to abosrb much energy by bending.

(d) Additional qualitative results are given, including explanations of shatter at velocities well above the limit, shatter against thick plates, and the effect of projectile form on projectile breakage and on the phenomenon of punching.

2. SUMMARY OF NPG REPORT NO. 3-44 (Reference 2)

The penetration of homogeneous plate by uncapped projectiles at 0° obliquity was discussed in Naval Proving Ground Report No. 1-43. The present report supplements Report No. 1-43 with comments on four secondary features of penetrations of the same classification. They are:

(a) The effect of velocity on impact dimensions, - an analysis of the energy absorption by the armor material as shown by the enlargement of the hole produced by completely penetrating projectiles of various velocities.

(b) A measurement of the energy expended in deforming projectiles obtained by observation of the rise in temperature of the projectile.

(c) An analysis of the energy consumed in overcoming friction between the projectiles and plate by observation of the retardation in rotation as well as velocity.

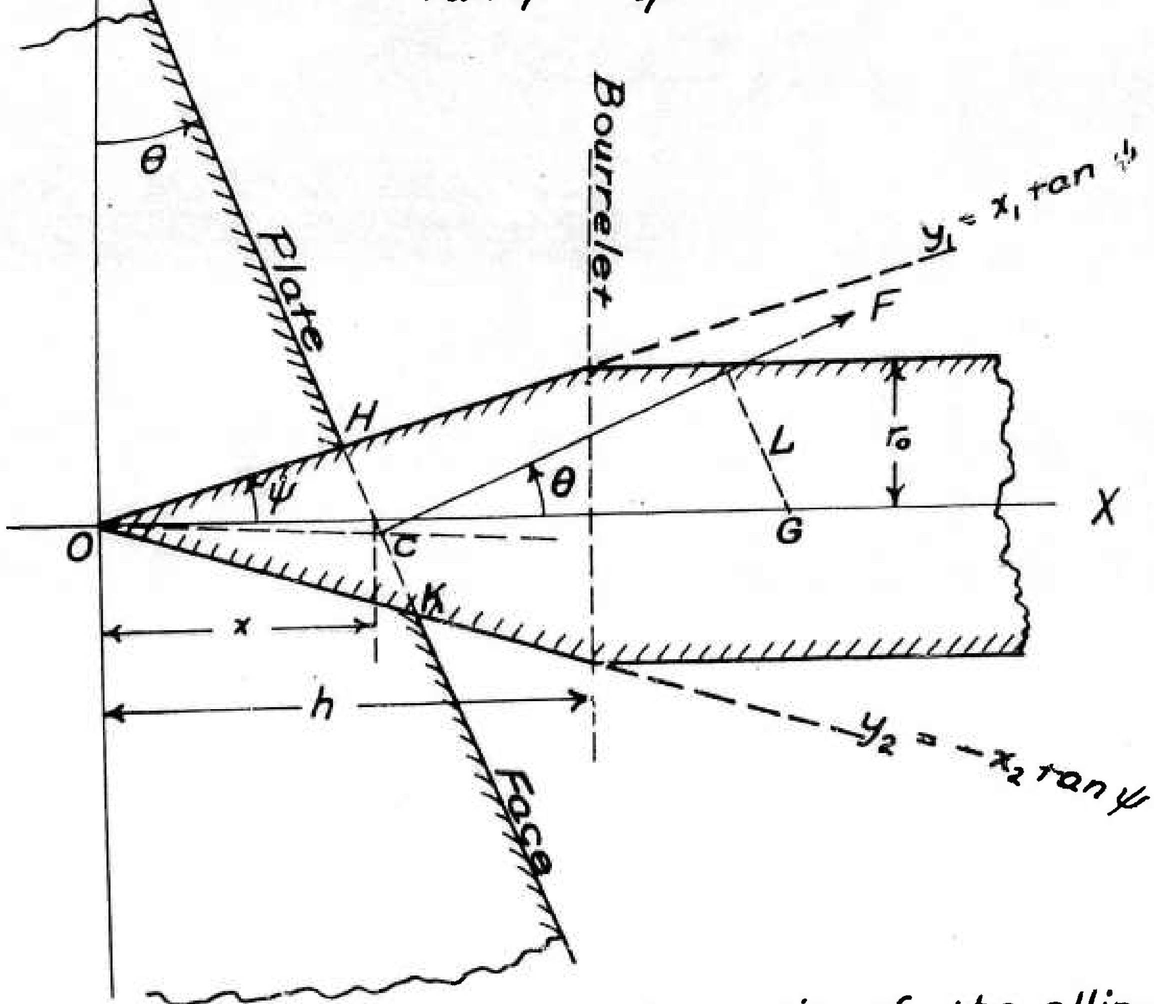
(d) A survey of the hardness distribution in sliced sections of armor surrounding partial and complete penetrations.

NPG Photo No. 1529(APL)

Figure 9
Ideal Penetration of a thick Plate by a Conical Projectile.

A uniform pressure p over the nose is assumed, and the plate-face is assumed to remain plane.

$$\tan\psi = r_0/h$$



The major axis of the elliptical section of the projectile by the plane of the plate is HK, of length

$$2x\tan\psi\sec\theta/(1-\tan^2\psi\tan^2\theta).$$

The length of the minor axis is

$$2x\tan\psi/\sqrt{1-\tan^2\theta\tan^2\psi}$$

The force F is therefore

$$\pi p x^2\tan^2\psi\sec\theta/(1-\tan^2\theta\tan^2\psi)^{3/2}$$

APPENDIX B.

YAWING TORQUE IN AN IDEAL CASE

Consider a projectile of radius r_0, with a conical nose of length $\underline{k}$, so that the nose has a semi-aperture ψ given by $\tan\psi = r_0/h$. Let this projectile make an ideal penetration at obliquity θ into a very thick plate, the face of which is assumed to remain plane. Imagine the pressure to be uniform over the embedded protion of the nose. Then the theorem developed in part II (2) (See Figure 6A) applies, i.e., the force on the projectile is the same as that due to a uniform pressure normal to the section of the projectile nose by the plane of the plate.

If $\underline{x}$ is the depth of penetration measured from the point of the projectile along the projectile axis (Figure 9), it is found by elementary geometry that the area of the elliptical section is:

$$A = \frac{\pi x^2 \sec\theta \tan^2\psi}{(1 - \tan^2\psi \tan^2\theta)^{3/2}} \quad - - - - - (B1)$$

The center of this section will rot lie on the axis of the projectile, but upon a straight line passing somewhat below the axis, as shown in Figure 9. For a cone of small aperture, this discrepancy may be neglected. Then, if $\underline{k}$ is the distance forn the point of the projectile to G, its center of mass, the torque-arm L of the force F is given by

$$L = (k-x) \sin\theta.$$

If the pressure on the projectile nose is $\underline{P}$, the force on the projectile is $F = PA$, and the torque about G is

$$M = \frac{\pi P x^2 (k-x) \tan^2\psi \tan\theta}{(1 - \tan^2\psi \tan^2\theta)^{3/2}} \quad - - - (B2)$$

Even in this simplified case it is clear that calculation of the equations of motion would be exceedingly intricate, although useful approximate calculations would be fesible for small values of θ.

This result may be compared with Part V of reference (3), where the torque is proportional to the resistance function R and to sin θ. In equation (B2) above, the resistance to the projectile is PA, where A is obtained from (B1). The principal difference between the result given here and that of reference (3) is the introduction of an explicit form for A and of the variable factor (k-x).

Under the simplified conditions assumed in this calculation, equation (B2), together with the two force equations,

$$\left.\begin{aligned} F_x &= -PA\cos\theta, \\ F_y &= +PA\sin\theta, \end{aligned}\right\} \quad ---- \quad (B3)$$

could be used to determine the motion.

It is to be noted that the formula (B2) will fail at the instant when the bourrelet enters the plate.

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