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ARMOR PLATE BALLISTIC TESTING

OBJECT

To establish a rational basis for the ballistic acceptance testing of armor.

SUMMARY

The fundamentals are presented for a rational system of armor plate ballistic testing. The desirable properties of armor are first discussed. These are (1) high resistance to penetration, (2) freedom from back spalls, (3) freedom from cracking (shock failure). The theory of the ballistic methods by means of which these properties may be tested is then presented, and the relation of these methods to the non-ballistic methods is discussed. Finally, a criticism is given of the present ballistic specifications which are employed to test for these properties.

It is found that the ballistic acceptance test could be improved by certain changes. These changes are for

a. Resistance to Penetration Test

1. Change from the "Army" to the "Navy" criterion of complete penetration.
2. Raise the range of plate thickness tested by a given caliber projectile.

b. Resistance to Back Spall Test

1. Introduce special cal. .30 and cal. .50 test projectiles with blunter ogives.

2. Introduce a shorter 20 mm AP test projectile which would have less tendency to fracture during impact than the present 20 mm AP test projectile.

c. Resistance to Shock Failure

1. Eliminate the present H.E. projectile tests, together with

2. Substituting special 20 mm test slugs for plates now tested with H.E. projectiles.

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INTRODUCTION

Considerable progress has been made during this war in an improvement of armor quality and also in an understanding of the mechanics of how armor functions. It is believed that still further improvement in armor quality may be obtained if this understanding of the mechanics of armor is utilized in establishing a rational basis for the ballistic specifications of armor. In the present report an attempt is made to establish such a basis.

The primary function of armor on armored vehicles and artillery is to protect, as far as possible, the personnel and materiel which are sheltered behind it from injury by the effects of enemy fire of all kinds. In order to do this satisfactorily the armor must

a. resist to the greatest possible extent penetration by projectiles of all kinds and by fragments and gas jets or the like produced by the explosion of high explosive shells, grenades, mines, etc.

b. resist to the greatest extent possible the detachment and projection from its back of pieces of itself when it is penetrated or struck by projectiles or fragments or when subjected to other effects of the explosion of high explosive shells, grenades, mines, etc., and

c. resist to the greatest possible extent being broken up or cracked by the impact of projectiles and fragments or other effects of the explosion of high explosive shells, grenades, mines, etc.

The ability of armor to perform these functions is called, respectively,

a. resistance to penetration.

b. resistance to back spalling, and

c. resistance to shock.

Measures of these three types of resistances are obtained by both direct and indirect methods. In the direct method samples of armor are shot at; in the indirect method physical tests are made on small test specimens. Each method has its own inherent advantages and disadvantages.

The direct method has the great advantage that in it service conditions are closely approximated. On the other hand, it has certain disadvantages which severely limit its use. These are

a. the tests destroy or at least seriously damage the pieces of armor to which they are applied and hence can only be applied to representative samples.

b. samples have to be comparatively large; usually 36" x 36" x thickness of armor.

c. it is difficult and troublesome to carry out the tests under the low temperature conditions encountered in service, namely -40° to -65° F.

d. the tests can only be conducted at a proving ground which is provided with rather elaborate facilities and the cost of conducting them is relatively high.

e. owing to the necessity for shipping the samples to a proving ground for test there must be a considerable time lag between the production and selection of the samples and the completion of the test.

The indirect method has the great advantage of destroying only a small test sample, of rapidity, and of low cost. Its great disadvantage is that common to all indirect tests, namely, the correlation is not perfect between its results and those of the direct tests.

In general, ballistic tests are conducted for one of three purposes, as follows:

a. Experimental or development tests are conducted to determine directly the ballistic characteristics of new steels, experimental heat treatments, or, simulating combat conditions, the optimum armor characteristics to resist an anticipated type of attack.

This type of firing also is conducted to obtain information upon which design improvements or alterations are based.

b. Qualification tests are conducted for the purpose of qualifying a manufacturer's process. Such tests may be of comparative complexity and when employed are designed to establish the ability of a manufacturer to produce a satisfactory product, after which indirect tests are largely depended upon to control the uniformity of the product.

c. Acceptance ballistic tests are conducted on samples, representing distinct lots of armor, which are presented by the manufacturer for test. Such tests must necessarily be augmented by indirect tests because of the impossibility of controlling uniformity by ballistic tests alone.

The subsequent discussions are concerned primarily with the acceptance testing problem. However, the principles outlined apply equally effectively to all types of ballistic testing conducted at normal impact. Irrespective of the fact that it appears possible to eliminate acceptance ballistic testing and rely practically entirely upon the indirect tests after suitable qualification ballistic tests have been performed, it may always be psychologically necessary to conduct ballistic acceptance tests.

Ballistic acceptance tests must satisfy two general requirements demanded of all acceptance tests, reproducibility and simplicity. Thus on the one hand the test must be so designed as to involve a minimum number of variables in the testing procedure itself in order that the results obtained in the test can unmistakably be attributed to the characteristics of the armor being tested. On the other hand, the test must be of such a nature that it can be carried out with a maximum economy in time, equipment and manpower. These two requirements, reproducibility and simplicity, dictate that all acceptance tests should be conducted at normal impact. Obliquity testing immediately introduces inherent variables such as the true angle of incidence as affected by deviations from the specified obliquity and projectile yaw and the likelihood of projectile deformation and fracture. With respect to simplicity, normal impact firing is considerably easier with regard to the mounting of the plates and the interpretation of the ballistic impacts.

DISCUSSION

I Resistance to penetration.

a. Mechanics of penetration.

Armor may resist penetration of projectiles by and/or <u>i</u> dissipating the kinetic energy of the projectile,

<u>ii</u> itself absorbing the kinetic energy.

The dissipation of kinetic energy may occur either through the plastic deformation of the projectile, or by the deflection of the projectile in one or in several pieces. Face hardened armor is designed to resist penetration principally by this method.

The plate may absorb the kinetic energy of the projectile only through plastic deformation of its own material. It is primarily through such absorption that homogeneous armor resists penetration. The characteristics of the plate material which affect its capacity to absorb energy through plastic deformation are

<u>i</u> Resistance to plastic deformation.

<u>ii</u> Resistance to instability of homogeneous deformation.

<u>iii</u> Freedom from laminations.

<u>iv</u> Ductility.

The hardness of the plate material is one measure of its resistance to plastic deformation. It cannot however be uniquely correlated with the resistance to plastic deformation which the plate offers when it is resisting penetration by a projectile. This may be seen from the observation that the resistance to deformation is dependent upon the amount of prior deformation, and the amount of deformation of the plate material in the vicinity of a penetrating projectile is much greater than that in the vicinity of a hardness reading indentor. Since the variation of resistance to deformation with amount of deformation is dependent upon the composition (particularly carbon content) and metallographic structure of the material, plates arranged in order of resistance to indentation by a hardness machine are not necessarily arranged in order of resistance to penetration by a projectile.

When a projectile penetrates armor, it is necessary that it induce plastic deformation in the armor in order that a hole may thereby be made through which it may pass. The general nature of this deformation, and therefore the resistance to penetration, depends upon whether, and at what stage of the penetration, homogeneous deformation becomes unstable.[1,2] Once such instability has set in, a mass of plate material in front of the projectile becomes detached from the plate, thereby allowing the projectile to pass through more freely. Since such detachment requires only a slight absorption of energy, the occurrence of such instability lowers the resistance to penetration of the plate material. All the factors which affect the tendency for homogeneous deformation in

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[1] C. Zener and J. H. Hollomon: "Plastic Flow and Rupture of Metals," Trans. A.S.M. vol. 33, 163 (1944).

[2] C. Zener and J. H. Hollomon: Journal of Applied Physics, vol. 15, 22 (1944).

a material to become unstable are not fully understood. No adequate test may therefore be made for this quality, other than through its effect upon resistance to penetration.

The presence of laminations and the absence of ductility lower the resistance to penetration of the plate by permitting the plate material to make room for the projectile without undergoing the normal amount of plastic deformation. Since these two qualities are examined in special tests (back-spalling and shock tests, respectively), they need not be further discussed here.

From the above it may be seen that the indirect test (Brinell hardness) is not an infallible indicator of resistance to penetration characteristics. However, it is one of the most important factors involved, and when the type of steel, its soundness and its metallographic structure are either constant or controlled within narrow limits, the control of hardness provides a satisfactory measure of the qualities which affect resistance to penetration. It is an ideal control test because of its non-destructive and economical aspects which permit the testing of all plates produced.

b. Theory of Test for Resistance to Penetration.

The concept of resistance to penetration is not without ambiguity, and therefore any test which is devised to measure it is somewhat arbitrary. It is necessary to remain cognisant of the arbitrary nature of this test and not to use it in comparing radically different types of plates, such as steel and Dural. Such a comparison can be made only by examining both types under a wide range of conditions.

The ambiguity in the concept of resistance to penetration arises from the wide variety of conditions of attack to which armor is subjected. That combination of qualities which enables armor best to resist penetration under one type of attack is not necessarily the same combination which enables it best to resist penetration under another set of conditions. The most that can be expected of a single method of testing for resistance to penetration is that the test be sufficiently sensitive to all four resistance qualities so that any gross failings in any one quality will be reflected in the test. Since the qualities iii and iv, (freedom from laminations, and ductility) have special ballistic tests, it is desirable that the resistance to penetration test be especially sensitive to the first two qualities.

The resistance to penetration test is limited, as are all ballistic tests, to firings at normal incidence by the requirements of reproducibility and of simplicity, as noted in the introduction.

The criterion as to what to call a complete penetration is not unique. Three are in common use, the "Army criterion", the "Navy criterion" and the "Protection criterion". The last-named criterion is especially adapted to high obliquity firings and need not be further considered here. The first criterion specifies a penetration as complete when from the back side may be seen either the tip of the projectile when the projectile remains in the plate, or a pinhole of light when the projectile has been ejected. The second criterion specifies a penetration as complete when the projectile has passed clear through the plate. That criterion should be adopted as standard which is most sensitive to the various plate qualities, in particular the first two. Upon this basis the Navy criterion is by far the better. This is because

- <u>i</u> the resistance to plastic deformation of the material near the back of the plate affects the "Navy" ballistic limit much more than the "Army" ballistic limit,
- <u>ii</u> the tendency for instability of homogeneous deformation does not appreciably affect the "Army" ballistic limit, while it greatly modifies the "Navy" limit, and
- <u>iii</u> an increase in hardness lowers the ductility of the back fibres of the plate, thereby lowering the bulging at the back of the surface before light is transmitted or the nose of the projectile

appears, and therefore such an increase in hardness has greater effect upon the "Army" than upon the "Navy" limit.

After deciding the obliquity at which the plate is to be set, and the criterion as to what is to be called a complete penetration, next a decision must be made as to the type and calibre of projectile which is to be fired against the plate. For the sake of reproducibility, it is desirable that the projectile be a monobloc, i.e., that it have no AP cap. Such a cap would introduce a variable factor over which the test range could exercise no control. The calibre of the projectile should be so chosen that the ballistic test for resistance to penetration is actually testing, as closely as possible, for that combination of qualities which gives best resistance to penetration under combat conditions. Present combat conditions may be described, roughly, as velocities over 2000 f/s and obliquities over 30°. Under such conditions the resistance to penetration of a series of plates increases with increasing hardness well past 320 BHN, provided the differences in hardness were obtained only by differences in time and temperature of the temper (i.e. assuming constant metallurgical quality). Such a response to conditions of temper are also found in the resistance to penetration at normal incidence, provided the striking velocities are over 2000 f/s, or, in other words, provided the projectile's caliber is less than the plate thickness. Combat conditions might change so that our armor would be called upon to defeat greatly overmatching projectiles at low velocities, under perhaps 1500 f/s. Such projectiles would no doubt be designed so as most efficiently to penetrate undermatching plate, that is, they would have a nearly flat nose.[1] For protection against such projectiles another type of armor, subject to another type of specification, would have to be used, since softer plate offers more resistance to the penetration of such projectiles than harder plate.[2]

Finally, the resistance to penetration test must be so established as to control the minimum hardness level. The tests for resistance-to-spalling and resistance-to-shock effectively control the upper limit of hardness. Thus the resistance-to-penetration test, when applied, can be effectively employed to evaluate the validity of the controlling hardness test. The accumulation of such data permits the development of improved indirect control tests. The undermatching projectile test at normal impact is clearly required to effect the desired control of minimum hardness.

In the determination of the specification acceptance

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1. "Penetration of Homogeneous Plate by 3" Flat Nosed Projectiles," Naval Proving Ground, Report Nos. 7-43, 12-44.
2. C. Zener and R. E. Peterson: "Mechanism of Armor Penetration, Second Partial Report", Report Number WAL 710/492.

ballistic limits it is convenient to have an interpolation formula for the variation of ballistic limit with plate thickness. Of the many formulae which have been used, the following ballistic formula proposed by the Navy[1] has been found to give most accurately the BL(N) over a very wide range of e/d (plate thickness/projectile caliber):

$$V = C(e/d - \Delta)^{1/2} .$$

The physical interpretation of this formula is that every layer in the plate absorbs an amount of energy from the projectile which is proportional to the thickness of the layer, except the outer layers, which effectively absorb no energy. A formula which agrees with the above to within 0.3% over a range of e/d of two fold and which is much easier to plot, is[2]

$$V = V_1 \ (e/d)^{\alpha} .$$

The ease in plotting arises from the circumstance that this formula gives a straight line on log paper. The constant V_1 is equal to the BL(N) of matching plate (e/d = 1). The precise value of the exponent α will depend upon the ogive shape of the test projectile, but

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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.

[2] C. Zener: "Principles of Armor Protection, Third Partial Report", Report Number WAL 710/607-2.

is always slightly greater than 1/2.

c. Critique of Present Specifications.

The following six projectiles are at present used as test projectiles: cal. .30 AP M2, cal. .50 AP M2, 20 mm. AP M75, 37 mm. AP M74, 57 mm. AP M70, 75 mm. AP M72. All six projectiles are suitable as test projectiles, for normal incidence specifications, except the 20 mm. AP M75. This projectile is undesirable both because it has a tendency to fracture even at normal incidence, presumably because of its large yaw, and because of its rounded ogive which gives rise to shatter even at comparatively low velocities, as is illustrated in Figure 1. It would therefore be desirable to have a new 20 mm. test projectile designed along the lines of the 57 mm. AP M70 or of the 75 mm. AP M72.

In the present specifications the "Army" criterion for success is used in the resistance to penetration test. As discussed in the previous section, the "Navy" criterion would be more significant.

The present philosophy of resistance to penetration tests is that the plate should be tested by as nearly as possible matching projectiles. Such a philosophy has led to test velocities, in the case of plates of 3/4" thickness and over, between 1100 and 1650 f/s. Under these test conditions the ballistic limits are relatively insensitive to plate hardness, even decreasing with plate hardness in the lower velocity ranges ($e < d$). (See Figure 2). It would therefore be advisable to choose test projectiles of such a caliber that the ballistic limits would lie above the present range, say from 2000 to 2400 f/s. The test velocities must not, however, be so high that the inertial forces[1] of the plate material induce plastic deformation in the projectile. The extent of such plastic deformation would be very sensitive to the projectile hardness, and therefore the observed performance of the plate would be subject to conditions very difficult to control. Fortunately all the test projectiles have a sharper ogive than have the capped projectiles used in service. Higher velocities may therefore be used without the projectiles suffering plastic deformation than in the case of service projectiles with caps removed.

Suggested projectile calibers and the ranges of plate thicknesses to which they apply are shown in Table I.

II Resistance to Back-Spalling.

a. Occurrence of Back-Spalling.

Two distinct types of plate fragments frequently come off the back of a plate during impact. One type of fragment is caused by the localization of shear deformation

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[1] C. Zener: "Mechanism of Armor Penetration, Third Partial Report", Report Number WAL 710/492-1.

TABLE I

RESISTANCE TO PENETRATION TESTS, NORMAL IMPACT, "NAVY" LIMIT CRITERION

PROJECTILE CALIBER	THICKNESSES OF PLATE TESTED
Caliber .30 AP M2	Up to 7/16" inclusive
Caliber .50 AP M2	Over 7/16" to 7/8" inclusive
20 mm AP (Improved projectile)	Over 7/8" to 1 1/4" inclusive
37 mm AP M74	Over 1 1/4" to 2 1/4" inclusive
57 mm AP M70	Over 2 1/4" to 3 1/4" inclusive
75 mm AP M72	Over 3 1/4" to 4" inclusive
90 mm AP M77	Over 4" to 5" inclusive

about certain internal surfaces. Such a localization of shear deformation is caused by the instability of homogeneous shear deformation which always arises after a slight deformation. The mechanism of this type of failure has been recently discussed in detail.[1] It gives rise to the formation of punches, and to the wiping off of petals, both on the front and back faces. Fragments of this type form the more readily the harder the plate. In order to reduce the tendency for their formation, a plate would therefore have to be softened, and its resistance to penetration in the high velocity range would have to be reduced. The avoidance of such fragments is therefore incompatible with a high resistance to penetration in the high velocity range.

The second common type of plate fragment is associated with a lack of cohesion across certain planes parallel to the plate surface. The presence of such weak surfaces can in no way aid the plate in resisting penetration, while the fragments, called "back-spalls", which they may occasion during impact can be of great danger. It is therefore desirable that the specifications contain a test which will exclude plates having internal surfaces across which the cohesion is especially weak.

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[1] C. Zener and J. H. Hollomon: Ibid.

Other less frequent types of plate fragments are associated with a general lack of ductility throughout the plate as a whole, or upon its face or back surface. Such a lack of ductility is generally the cause of failure in the shock test, and therefore a special test need not be made for the tendency to form such fragments.

The ballistic test in current use for testing the presence of internal weak surfaces is the projectile-through-plate (PTP) test. In this test a projectile is fired at normal incidence with a velocity considerably above the ballistic limit. If a spall exceeding a certain diameter is ejected from the back of the plate, the plate fails the test.

The majority of ballistic failures occurring in homogeneous rolled armor over the past three years has been due to back spalling, even though the testing criteria have been extremely mild in many cases. For this reason it became necessary to develop an additional test for the characteristic in rolled armor (steel soundness) and cast armor (solidity of the section) which largely controlled this factor, not hitherto controlled by other specification tests. The <u>Fracture Test for Steel Soundness</u> was thus developed and has at present been applied to Specification AXS-488, Revision 2 covering the procurement of rolled homogeneous armor for combat vehicles. The test is simple and can be applied to the critical areas of a heat of steel so that a satisfactory indication of overall steel soundness characteristics is obtained. It efficiently determines steel soundness characteristics but does not sufficiently distinguish between unsoundness which causes back-spalling and that which may be comparatively harmless. If it were economically feasible to set the soundness rejection limit sufficiently high, the test could be absolute in its control. However, this is not possible and it is unreasonable to reject steel from a soundness standpoint which from all considerations is not inferior ballistically.

Similarly radiographic inspection has been applied to control the soundness characteristics of cast armor. These two tests are extremely useful in rejecting obviously poor material before time and effort have been expended in its heat treatment and further processing. These control tests must periodically be supplanted and verified by efficient direct ballistic tests, and, it thus appears, that the back-spalling test (PTP tests) must be developed to its utmost efficiency. The direct test again supplies the evidence and data necessary to effect improvements in the control tests.

b. Theory of Test for Back-Spalling.

An analysis of the formation of shear spalls must begin with a description of the state of stress in the plate material surrounding the projectile. Due to the high temperature of the material right next to the projectile, the projectile can exert no shearing traction upon the plate material, only a normal pressure. When a normal pressure acts upon a surface, the shearing stresses engendered thereby are a maximum across planes meeting the surface at an angle of 45°. These surfaces of maximum shearing stress are indicated in illustration a of Figure 3.

At the surface of the projectile the shearing stress is equal across the two mutually perpendicular planes of maximum shearing stress. In an isotropic material, shear failure will therefore occur first across that plane of maximum shear stress across which slip is least impeded by the plate material further away from the hole. Thus in illustration a of Figure 3, slip can occur across the whole of the plane AB, and A'B', but slip across the planes AC and A'C' is hindered by the plate material away from the hole. One would therefore expect face spalls by slipping along A'B', back spalls by slipping along the surface AB. This is just what happens in plate of good quality and of sufficiently high hardness to produce spalls.

On the other hand, if the plate material is not isotropic, but if the surfaces originally parallel to the plane of the plate are planes of weakness, then shear failure may occur across these planes when they are nearly oriented parallel to a surface of maximum shear stress. This is the case when the plate is said to be excessively "laminated".

Once shear failure occurs in the immediate vicinity of the hole, it will propagate a certain distance, by means of stress concentration, as is indicated in illustration b of Figure 3. This propagation will continue along a surface of weakness, i.e., along a surface originally parallel to face of plate. The distance the shear failure will propagate depends to some extent upon the weakness of the "laminations".

The shear failure is accompanied by a redistribution of stress which in turn may give rise to a new type of failure. During shear failure, all shearing stress is relieved across the surface of shear failure, e.g., AC in illustration b of Figure 3. The only stress then acting across the surface of failure is a normal pressure. This normal pressure gives rise to a bending moment across the surface CD, and therefore to tension along the lower part of this surface, in the vicinity of C, as indicated in illustration c of Figure 1. This tensile stress may reach a high value, as may be seen from the fact that the torque about C produced by the normal pressure along AC must be balanced by the stress across the comparatively short plane CD. When the tensile stress reaches a sufficiently high value, the material fractures along CD with little or no plastic deformation. The deformation is hindered by the restraints imposed by the plate material to the right of CD.

The movement of the incipient spall occasioned by the initiation of the crack along CD will reduce to some extent the pressure along AC. This may result in the cessation of the crack along CD. On the other hand, the crack may continue clear to the surface, resulting in a spall being thrown off.

Several factors influence the tendency of the crack along CD to continue clear to the surface. The greater the velocity of the projectile, the greater is the tendency of the spall to be thrown off. This is illustrated in Figure 4 in which are shown the backs of the holes produced at various velocities by projectiles with an ogive similar to that of the cal. .50 core. The effect of velocity is understood by considering that the moment across BC must not only cancel the moment due to the pressure along AB, but also the moment due to the deacceleration forces associated with the inertia of the incipient spall.

The propagation of the crack to the back surface is also favored by a blunt ogive. This effect of the ogive shape may be seen by a comparison of Figures 4 and 5, which illustrate the spalling produced upon the same plate by projectiles of two types of ogive. The projectile with the sharp ogive does not produce a complete back-spall at 2000 f/s, while a complete back-spall is produced by the blunter projectile below 1400 f/s.

c. Critique of Present Specifications.

The present projectile-through-plate test for back spalls is conducted at zero obliquity. This is in conformity with the general principle, already cited, that all tests of plates must be made at normal incidence in order to avoid the variability introduced by the fracture of projectiles.

Plates of thickness 1/8" to 7/16" are tested with either cal. .30 AP or cal. .50 AP bullets. These bullets are especially unsuitable for projectile-through-plate tests. On the one hand, the unusually long pointed ogives of their cores require a high striking velocity in order to subject the plate to a severe back-spalling test. On the other hand, their jacket produces a type of punching at high velocities[1,2] which may disqualify the plate on the criterion of exit diameter, but which is in no way an indication of surfaces of weak cohesion in the plate. The only possible solution to this dilemma is to use special test projectiles with cores of a blunter ogive. These

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1. N. A. Matthews: Rolled Armor Report No. 44.
2. C. Zener and J. H. Hollomon: "Mechanism of Armor Penetration, First Partial Report", Report Number WAL 710/454, Figure 6A.

would then need to be shot at only a comparatively low velocity, say 1600 f/s, in order to differentiate between plates which are good and bad with respect to spalling characteristics.

Plates in the thickness range 7/16" to 11/16" are tested with 20 mm. AP M75 projectiles. These are fired at each of the two velocities 1500 f/s and 2500 f/s. These two velocities are used because plates which pass the PTP test at the higher velocity frequently fail at the lower velocity. This occurrence of failure at the lower and not at the higher velocity is in contradiction to the mechanism of failure described in the previous section. It is believed that this anomaly is associated with the extreme length of the M75 projectile. Because of this length the stability factor is unusually low, and consequently the projectile is apt to have a considerable yaw when it strikes the plate. Such a yaw is increased by the turning moment exerted by the plate upon the first instant of impact.[1] The increase in yaw is greater the lower the velocity. Such an increase in yaw may cause the plate to fail the test in two distinct ways. Firstly, a yawed projectile is apt to produce a larger hole than an unyawed projectile. Secondly, the increase in yaw is accompanied by an increase in bending moment,

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1. C. Zener and R. E. Peterson: Ibid.

which moment may cause the projectile to fracture, and therefore to produce a larger hole. The failure of a plate at the lower velocity is therefore likely to be due solely to defects of the projectile itself. Since such defects cannot be reproducible, the test at 1500 f/s is not satisfactory.

The test at the higher velocity of 2500 f/s also has its difficulties. The M75 projectile has a blunt nose. Such blunt noses invariably shatter at comparatively low velocities.[1,2] An example of such shatter against a 1/2" plate at 2500 f/s is shown in Figure 1. The nose of the projectile first sheared symmetrically so as to leave a conical ogive with a 45° angle. Shear then proceeded along a new 45° plane. The M75 projectile is therefore unsatisfactory as a test projectile both in the low and also in the high velocity range.

The 3/4" to 1 1/8" plates are tested with the 37 mm. AP M74 projectile at the two velocities 1500 f/s and 2500 f/s. It is not believed that plates ever fail at the lower velocity and at the same time pass at the higher velocity. The lower test velocity could therefore be eliminated.

1 1/4" to 3 1/8" thick plate are tested at 1500 f/s.

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1. C. Zener: "Mechanism of Armor Penetration, Third Partial Report", Report Number WAL 710/492-1.
2. C. Zener and J. Sullivan: "Principles of Projectile Design, Second Partial Report", Report Number WAL 762/231-2.

It is believed that service conditions would be more closely approximated if a higher striking velocity were used, e.g. 2000 f/s.

III Resistance to Shock Failure.

a. Occurrence of Shock Failure.

Resistance to penetration, at least in the high velocity range, is determined primarily by the resistance of the plate material to plastic deformation. The fracture stress of the material is not important since the principal stresses in the plate attain large positive values during penetration only in unusual circumstances.

When a plate resists the penetration of an overmatching projectile at a high obliquity, it does so by deflecting the projectile. The various stages in the deflection are illustrated schematically in Figure 6. Within wide limits, the response of the plate is determined primarily by the initial normal component of the projectile's velocity, V_n. Thus when a plate resists penetration at obliquities of 30° or higher, the ballistic limit, V, depends upon angle of impact θ over a wide range of angles according to the formula.[1]

$$V \cos\theta = \text{constant.}$$

In other words, the reaction of the plate is independent

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[1] Bruce Ward; "Principles of Armor Protection, Second Partial Report", Memorandum Report WAL 710/607-1.

of the initial tangential component of velocity V_t over a wide range. The plate therefore reacts essentially as if it were struck normally by a projectile with a 90° yaw.

Suppose a plate is struck normally by an overmatching projectile with a 90° yaw. The plate is then subjected to a bending moment which tends to wrap the plate around one side of the projectile. This bending moment induces a tensile stress on the back of the plate along a direction transverse to the projectile. This tensile stress will cause the back of the plate to yield plastically, to fracture, or first to yield plastically and then to fracture. The nature of the response will depend upon the metallurgical structure of the steel, upon its hardness, and finally upon the care taken in the manufacture of the plate.

In order to understand how the response of the plate to shock is affected by various factors, it is most convenient to use the concept of flow stress and of fracture stress first introduced by Ludwig. The flow stress is the stress necessary to make the material flow plastically. It depends both upon the transverse components of stress and upon the previous strain in the material. The fracture stress is the stress at which the material would fracture if no plastic deformation were to occur. The fracture stress appears not to depend upon the transverse components of stress, but it is, like the flow stress, in general a function of the previous strain. The material will flow plastically if the flow stress is below the fracture stress; it will fracture if the reverse is the case.

The metallurgical structure has little effect upon the flow stress of steels at the same hardness level. It does however have a marked effect upon the fracture stress. The two extreme cases of a pearlitic and of a tempered martensitic steel are presented as Figure 7. In the former steel the initial fracture stress is only slightly higher, from 10% to 20%, than the initial flow stress for the case of uniaxial tension. In the latter steel the fracture stress is essentially independent of strain. In the example given, the pearlitic and the tempered martensitic steel have identical properties as measured in the conventional tensile test or by the conventional hardness machines. They no longer behave identically when a transverse constraint is imposed which prevents any change in dimensions along one transverse direction, as is the case when an overmatching projectile strikes a plate normally with a 90° yaw. Such a restraint raises the flow stress. According to the Von Mises theory, the rise will be 16%. The fracture stress remains essentially unaltered by this restraint. As may be seen by reference to Figure 7, this 16% rise in flow stress, which has only a minor effect upon the strain-to-fracture of the tempered martensitic steel, has, on the other hand, a drastic effect upon the strain-to-fracture of the pearlitic steel. In the latter steel, the flow stress is raised above, or nearly to, the fracture stress at zero strain, depending upon the precise conditions, such as strain rate and temperature. If the strain rate is sufficiently high, or the temperature is sufficiently low, the transverse restraint will raise the flow stress of the pearlitic steel above the fracture stress at zero strain, so the steel will fracture brittlely with no plastic deformation whatsoever.

From the above discussion it is clear that armor can successfully withstand severe shock conditions only if it contains no pearlite. The effect of the presence of intermediate structures, such as bainite, is complicated and is not well understood.

For a given composition, both the flow stress and the fracture stress curve of a tempered martensitic steel rise with an increase in hardness. The flow stress curve rises faster than the fracture stress curve, however, so the strain to fracture diminishes with an increase in hardness. The harder a steel plate, the less able it is to withstand shock conditions.

In addition to the metallurgical structure and hardness level, the casting and forging practice also may affect the fracture stress. Thus non-metallic inclusions in a rolled plate always lower the fracture stress along an axis transverse to the principal direction of rolling.

The shock resistance of armor, or its ability to deform plastically at high rates of strain, may be greatly affected by temperature of test, dependent upon its metallographic structure. Thus satisfactory ballistic test behavior at normal temperatures does not provide assurance that the armor will resist brittle failure at low temperatures or under conditions of restraint which may be set up by incorporation into a completed vehicle. The Fibre Fracture Test has therefore been developed[1] as an inspection device to control the characteristics of the armor which affect its ability to deform plastically at high rates of strain and at low temperatures. This test is more critical with respect to the inherent ability of the material to deform plastically than are ballistic shock tests. However, there are other aspects of armor, particularly rolled, which affect its ability to resist cracking, and the principal one is directionality which, of course, cannot be controlled effectively by the indirect test.

The Fibre Fracture Test has a very useful application since it is simple enough to apply with sufficient frequency

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1. A. Hurlich: "Armor - Development of a Fracture Test to Indicate the Degree of Hardening of Armor Steels Upon Quenching", Report Number WAL 710/532.

to control those characteristics of armor which to a large extent determine its shock resistance. The direct ballistic test is needed, however, since it so stresses the armor as to integrate the many variables which affect shock resistance, such as hardness, heat treated condition, steel soundness and directional characteristics.

b. Theory of Test for Shock.

The shock test must be so designed as to simulate closely a bending of the plate with the back of the plate subjected to tension. It is therefore necessary to apply to the face of the plate an impulsive force of sufficient magnitude to produce bending.

The force on the face of the plate must not be so localized that its associated energy is dissipated in pushing aside the plate material to form partial or complete holes, as are produced by A.P. projectiles and by Munroe explosive jets. The pressure must be distributed over an area with a diameter equal to at least the plate thickness. In order that such a pressure distribution be obtained, it is desirable that the testing projectile have a flat ogive. However, the use of a flat ogive projectile introduces the possibility of a new type of plate reaction which must be avoided, namely, the formation of a punching. This new problem may be best visualized by reference to Figure 8 which illustrates the stress system in a plate being subjected to a shock test by a flat ogived projectile.

Suppose, as illustrated in this figure, that a uniform pressure p acts inside a circle of diameter d. This pressure gives rise to two types of stress systems in the plate. In the region in the vicinity of the projectile, these stresses are tensile near the back surface, compressive near the face. The problem in the shock test is to keep the shearing stress below the shear yield stress, at the same time raising the tensile stress in the back of the plate above the tensile yield stress.

As indicated in Figure 8, the shearing stress may be computed in terms of the pressure acting upon the face. After the initial acceleration of the plate material just ahead of the projectile, the equilibrium conditions may be applied to the material lying within the cylindrical surface of diameter d. The equation of equilibrium gives for the shearing stress S acting across this surface

$$S = \frac{1}{4} \cdot \frac{d}{e} \cdot p \quad .$$

The bending moment, and therefore the tensile stresses near the back of the plate cannot be computed from equilibrium considerations as was the shearing stress. As long as the response of the plate remains elastic, the velocity of the plate just ahead of the projectile is strictly proportional[1] to the pressure p, and therefore remains constant, with no acceleration, once p has reached a constant value. Equilibrium considerations may therefore be applied to the material just ahead of the projectile. On the other hand, the bending moment produced by the pressure p depends upon the diameter D of the region which is being bent. In fact, the bending moment is proportional[2] to the logarithm of the ratio (D/d). As the elastic wave travels radially outwards, the diameter D increases, and hence also the bending moment and the tensile stresses. The exact analysis of the manner in which the tensile stress depends upon the various parameters is given in a current report.[3] For the purpose of the present discussion it is necessary to know only that the bending moment, and hence T, increases with time as the pressure p is maintained constant.

From the above described difference in the factors which determine the magnitudes of the shearing stress and of the bending moments, it is evident that the latter will be increased relative to the former if the projectile is sufficiently soft to mushroom. Such a projectile will exert a nearly constant force for an appreciable time, and during this time the bending moment

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1. C. Zener: "The Intrinsic Inelasticity of Large Plates", Physical Review, 59 669 (1941).
2. See S. Timoshenko, Theory of Plates and Shells, (McGraw-Hill, 1940), p. 69.
3. C. Zener: "Mechanism of Armor Penetration, Fourth Partial Report", Report Number WAL 710/492-2.

will steadily rise, while the shearing stress remains constant. Such projectiles are in fact now in use for shock tests.

The physical picture of shock testing is now sufficiently complete so that a formula may be constructed which relates all the parameters of a shock test. The fundamental principle of such a formula is that the test projectile should be fired just under the velocity which will give rise to a punching. The formula will therefore equate the force with which the projectile acts upon the plate to the force necessary to push out a punching. In the derivation of the formula reference will be made to Figure 8. If the projectile were pushed slowly against the plate the maximum pressure it could exert would be nearly equal to the tensile strength of the projectile material. On the other hand, if the projectile steel had zero resistance to plastic deformation, the pressure exerted by a moving projectile would be ρV^2, where ρ is the density of the steel, and V is the incident velocity. The pressure exerted by an actual projectile in a test will be approximately the sum of the two terms, $(T.S.)_{proj.} + \rho V^2$. Upon referring to Figure 8, and upon utilizing the approximate relation

$$\text{Shear strength} \simeq (1/2)\ \text{tensile strength},$$

we obtain the formula

$$\rho V^2 + (T.S.)_{proj.} = \beta (T.S.)_{plate} (e/d) \quad (1)$$

where β is a numerical constant. When cognizance is taken of the fact that the mushrooming of the projectile will cause only about one half of the projectile's force to be exerted within a circle of radius <u>d</u>, it is to be expected that the constant β will have a value of approximately 4.

<u>c.</u> <u>Critique of Present Specification</u>.

The shock tests for plates under 7/16" thickness is by means of an H.E. shell. In view of the extreme sensitivity of the effect of such shocks upon the time of initiation of explosion, such tests are unsatisfactory. For plates in the thickness range 1/8" - 7/32", cal. .50 slugs should be developed; for plates in the thickness range 1/4" - 7/16", 20 mm. slugs should be developed to apply over the total thickness range 1/8" to 7/16".

The shock test for plates thicker than 7/16" is of a satisfactory type, namely with slugs designed for shock testing. A comparison is given in Figures 9 and 10 of the shock specifications now in use with the theoretical equation (1). In the first figure the ordinate is $\rho V^2 + (T.S.)_{proj.}$, where V is the specification striking velocity, and the abscissa is the plate thickness. Corresponding to a slug maximum hardness of 140 BHN the tensile strength of the projectile material has been taken as 70,000 psi. The value of ρV^2 as a function of velocity may be read from a graph in a current report.[1] Corresponding to the linear relation given in Equation (1) between $\rho V^2 + (T.S.)_{proj.}$ and plate thickness, the points on the logarithmic paper of Figure 9 should lie upon straight lines having a slope of unity (45°). This they are seen to do. In Figure 10 the quantity $\rho V^2 + (T.S.)_{proj.}$ is plotted against e/d. If the plates of all thickness groups had the same hardness level, all the points should lie upon the same straight line. Actually, the larger the test projectile, the lower the associated straight line. In order to check whether this lowering could be attributed to the decrease in plate hardness with increasing plate thickness, the numerical constant β of Equation (1) was so chosen as to fit the line associated with the 37 mm. slug with the tensile strength of the plate at 180,000 psi, corresponding to a BHN of 340. This value was 3.8, in agreement with the theoretical discussion of the previous section. Having fixed β from the 37 mm. data, that tensile strength of the two other groups of plates was found which best brought the data into agreement with Equation (1). These tensile strengths were 145,000 psi and 139,000 psi,

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[1] C. Zener and R. E. Peterson: "Mechanism of Armor Penetration, Second Partial Report", Figure 6, Report Number WAL 710/492.

corresponding to 290 BHN and 278 BHN, respectively. These hardness levels are consistent with those of plates in the associated thickness range. Equation (1) may therefore be used with confidence to establish the appropriate velocity for shock testing of plate of a given hardness and thickness with slugs having a given caliber and maximum hardness.

At the present time, the slug type of shock test has not been developed to apply to armor thicknesses greater than 2 1/2", because large caliber projectiles (155 mm.) would be required for 3" and greater thicknesses of plate. However, it must be realized that such heavier armor thicknesses are not likely to be severely shocked under combat conditions, and it is probable that the present types of obliquity tests with matching and overmatching projectiles constitute an adequate control of shock resistant characteristics.

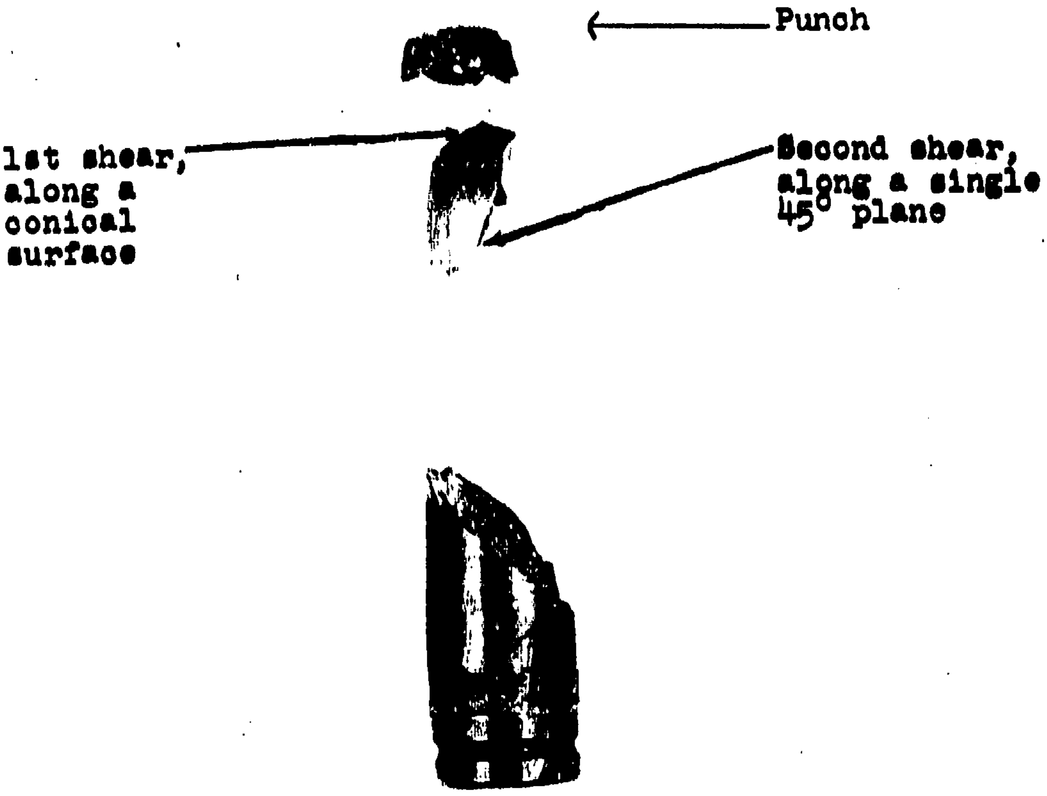
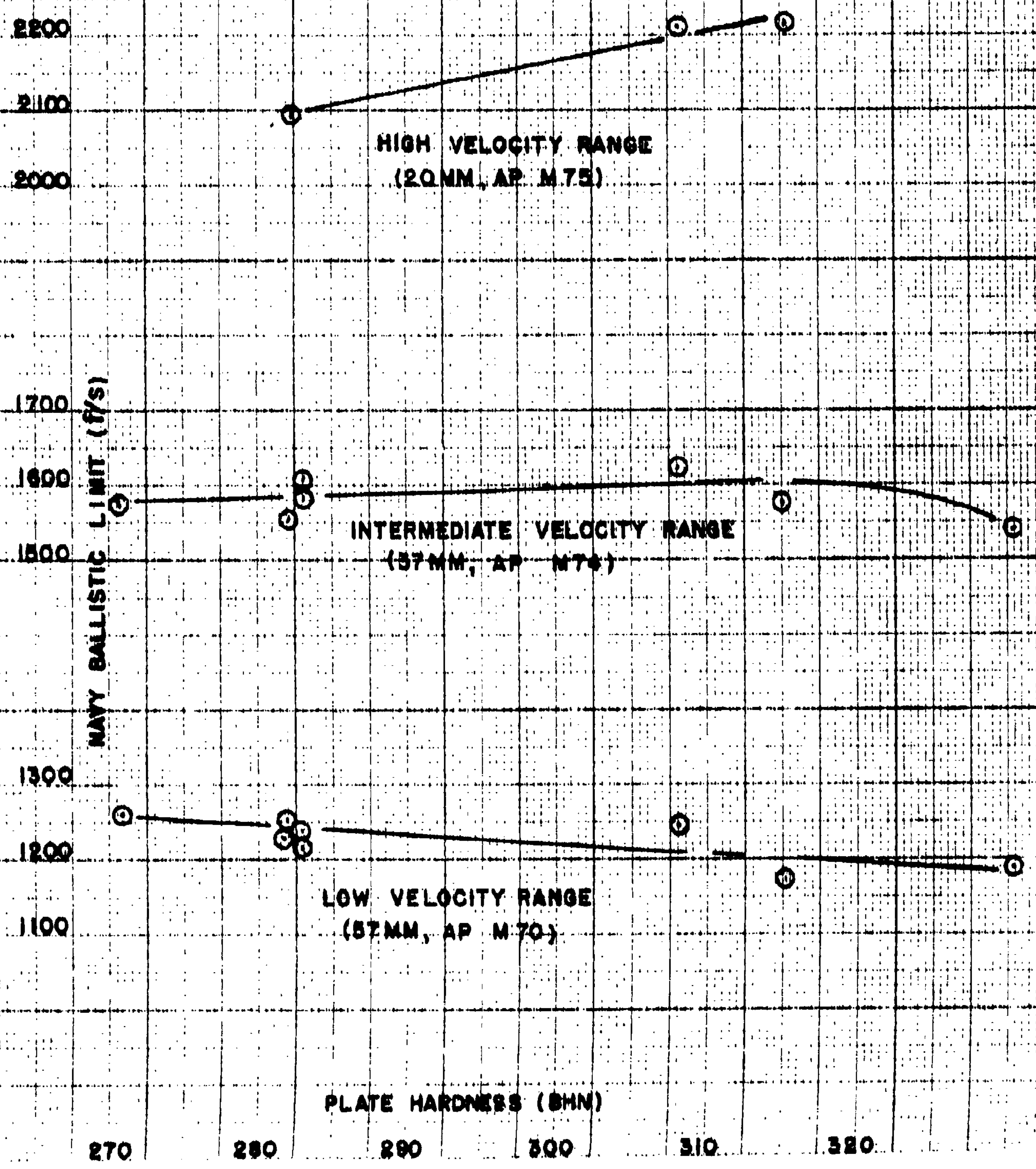


FIGURE 1

Example of shatter of 20 mm. AP M75 projectile (2500 f/s striking velocity, zero obliquity, 1/2" 330/350 BHN plate)

FIGURE 2

HARDNESS DEPENDENCE OF BALLISTIC LIMITS
IN VARIOUS VELOCITY RANGES
(ABERDEEN REPORT AD-586)
PLATE THICKNESS = 1.5"



RD 249
1765 f/s
no petals off

RD 240
1770 f/s
1 petal off

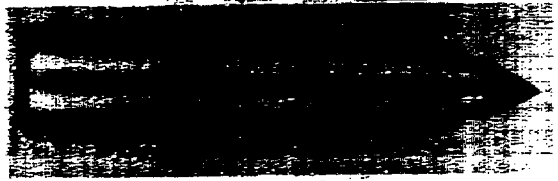
RD 235
2010 f/s
2 petals off

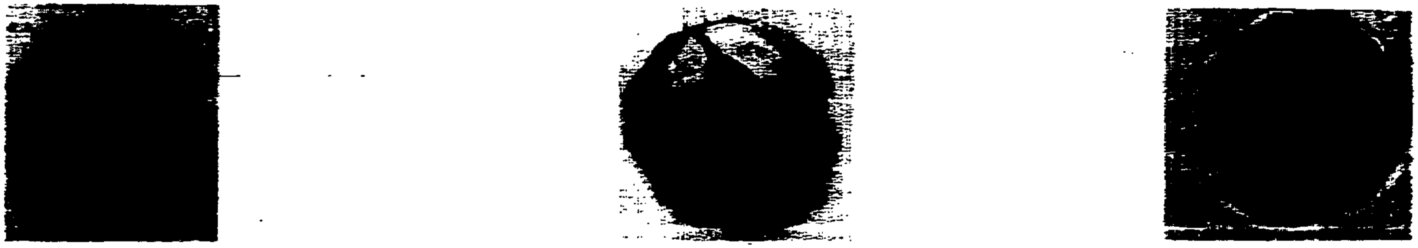
[illegible] 2
2[illegible] f/s
all petals off

FIGURE 4

Effect of velocity upon spalling-
caliber .50 type ogive.

Caliber [illegible]
used in [illegible]





[redacted]

13[illegible] f/s
incomplete penetration

RD 244

1370 f/s
complete penetration
no petals off

[redacted]

1375 f/s
complete penetration
all petals off

FIGURE 5

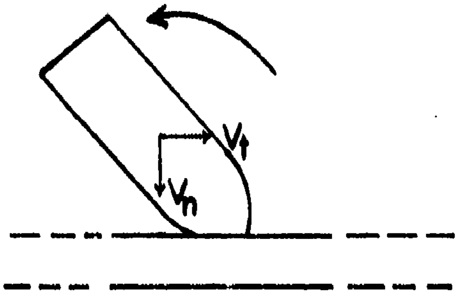
[redacted] upon spalling-
[redacted] ogive.

[redacted] projectile
[redacted] experiments

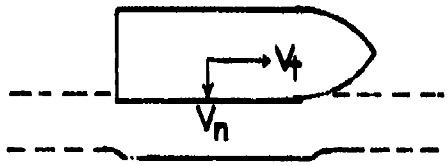
[redacted]

FIGURE 6

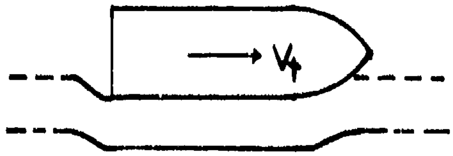
ILLUSTRATION OF APPROXIMATE MANNER IN WHICH UNDERMATCHING PLATE RESISTS PENETRATION AT HIGH OBLIQUITIES



a. THE INITIAL REACTION FORCE EXERTS A COUPLE WHICH TURNS THE PROJECTILE SO AS TO LIE PARALLEL TO PLATE.



b. THE PROJECTILE PRESSES SIDEWISE AGAINST THE PLATE.



c. ALL THE ENERGY ASSOCIATED WITH THE VELOCITY COMPONENT NORMAL TO THE PLATE IS ABSORBED AS PLASTIC DEFORMATION.

FIGURE 7

INTERPRETATION OF DIFFERENCE BETWEEN BEHAVIOR OF TEMPERED MARTENSITIC AND PEARLITIC STEELS UNDER SHOCK CONDITIONS.

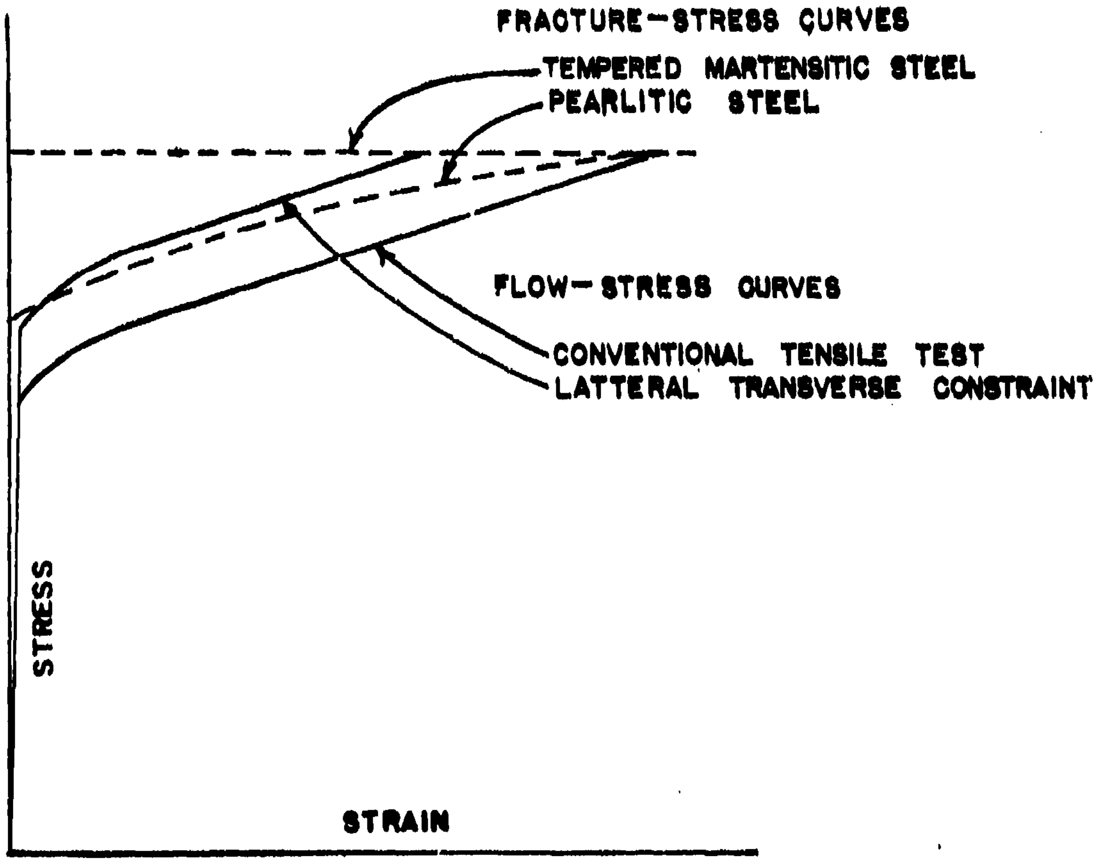
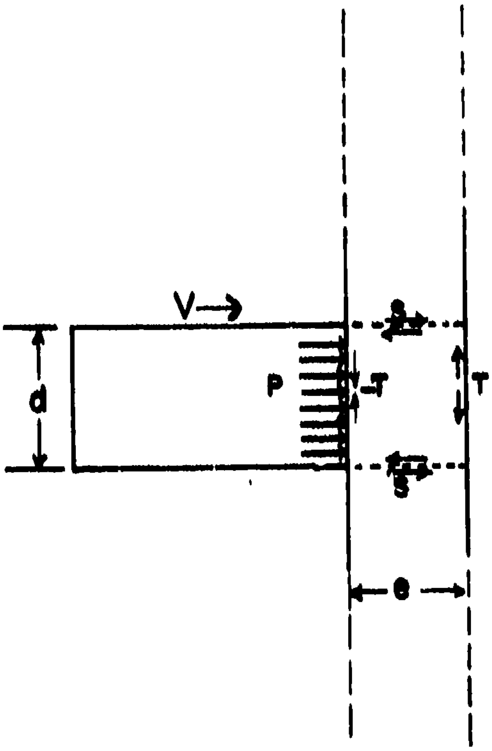


FIGURE 8

STRESS SYSTEM IN PLATE SUBJECTED TO IMPACT BY A FLAT NOSED PROJECTILE



EQUATION OF EQUILIBRIUM

$$1/4 \pi d^2 p = \pi d e S$$

SHEAR STRESS

$$S = 1/4 . e/d . P$$

FIGURE 10

EFFECT OF PLATE HARDNESS UPON SHOCK VELOCITY

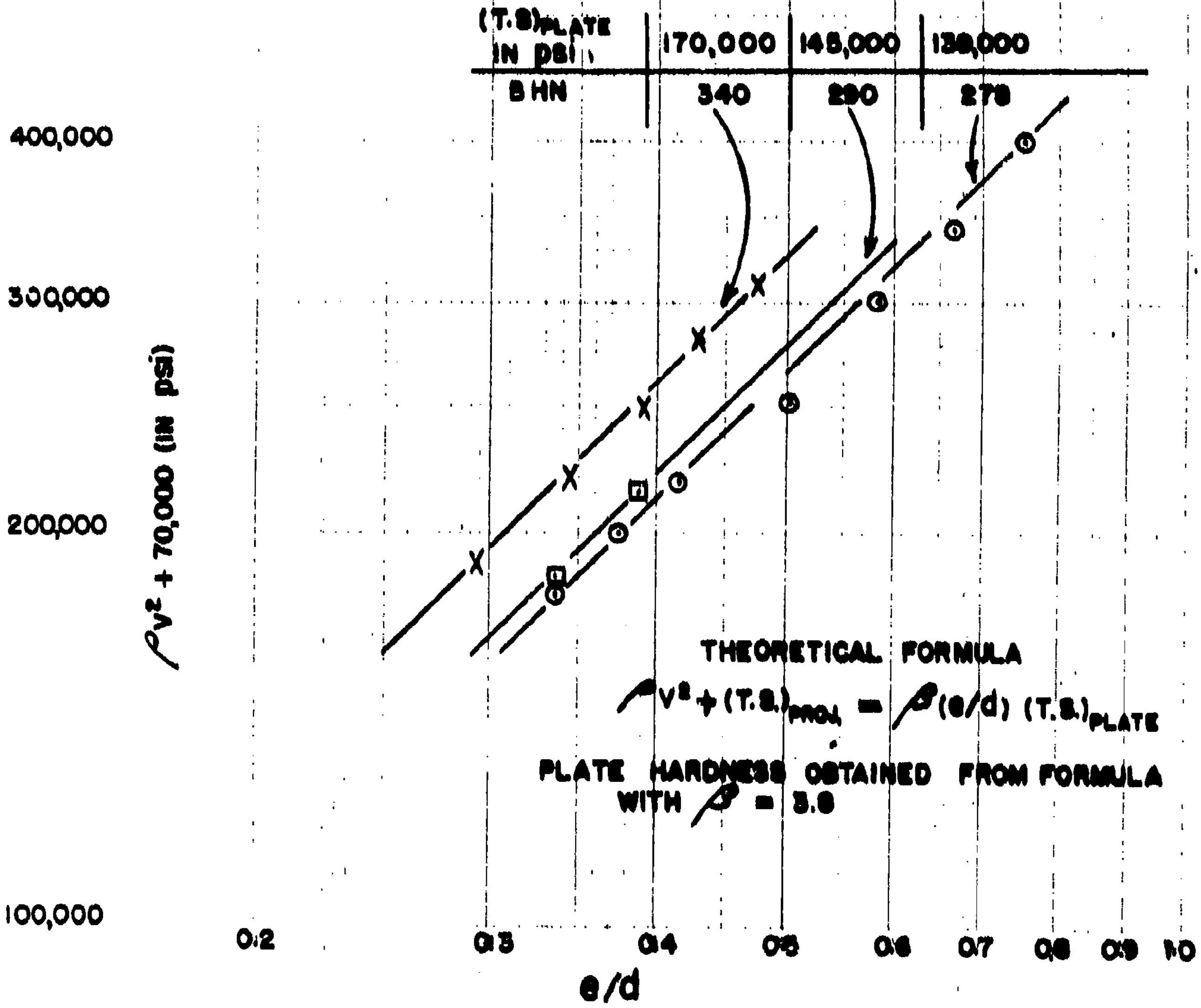


FIGURE 9

TEST OF THEORETICAL SHOCK TEST FORMULA