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WATERTOWN ARSENAL LABORATORY

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MECHANISM OF ARMOR PENETRATION

Third Partial Report

BY

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Senior Physicist

DATE 30 March 1944

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MECHANISM OF ARMOR PENETRATION

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OBJECT

To analyse the principles of shatter.

SUMMARY

Examples of shatter are presented, and the mechanism of the phenomenon is analysed.

It is shown that a projectile striking a plate at normal incidence could fracture under tensile stresses with no prior plastic deformation if the fracture stress of the projectile transverse to its axis were sufficiently low. It is observed however, that plastic deformation usually precedes shatter. A detailed quantitative study has been made of the plastic deformation at the bourrelet. It has been possible to correlate, by means of the stress-strain curves of the projectile steel, the expansion of the bourrelet with the hardness of plate, the striking velocity, and the hardness of the projectile.

In the absence of tensile fracture, it is concluded that the fragmentation of the front portion of the projectile during shatter is associated with the instability of homogeneous adiabatic shear deformation which appears

[redacted]

after a slight prior plastic deformation. The process of fragmentation cannot be described in detail, as the orientation of the fragmentation surfaces will be sensitive to the conditions at impact.

C. Zener
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APPROVED:

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INTRODUCTION

It has long been known that projectiles deform or fracture when the conditions of impact with armor are sufficiently severe. A type of projectile breakage, not previously reported in the literature, was discovered by the British during their reverses on the Libyan battlefields. They found that their projectiles would not completely penetrate the opposing armor at close range, although they could completely penetrate at moderate ranges. This anomalous behavior was traced to the breaking up of the projectiles at high velocities, and to the nonpenetration of the resulting fragments. The velocities at which this fragmentation occurred happened to be above the ballistic limit of the plate. This phenomenon of the fragmentation and nonpenetration of a projectile at a velocity above the ballistic limit of a plate has been called "shatter". The purpose of the present report is to analyse the physical basis of shatter.

RESULTS AND DISCUSSION

GENERAL DESCRIPTION OF SHATTER

In order to illustrate in a qualitative manner how a projectile responds to an increase in the velocity of impact, projectiles of a uniform hardness of 65 RC were fired normally against a greatly overmatching plate at a series of increasing velocities. These projectiles are reproduced in Figure 1. No appreciable deformation is observed at the two lowest velocities. The bourrelet is slightly expanded at 2500 f/s, while at 2900 f/s the front portion of the ogive has become separated from the rest of the projectile. At a velocity of 3200 f/s the projectile fractured into several pieces, while at 3500 f/s the projectile apparently disintegrated into many pieces and could not be recovered. The partial penetrations in the plate are all of the normal petalling type except at the highest velocity. Here the penetration was less deep than for those corresponding to lower velocities, and the petals have been scooped out.

In order to illustrate how the type of penetration is affected by an increase in velocity of impact, sections of penetrations are reproduced in Figure 2. Complete penetration is obtained at 2685 f/s, while the projectile does not pass through the plate at the higher velocity of 2935 f/s.

The conditions for the occurrence of shatter were first described by Milne in a British Ordnance Board Proceedings, and are presented in Figure 3. The plate thickness - velocity space in this Figure is separated into four regions by three types of lines. One line, the dashed line EBCF, is the projectile shatter line. This divides the plate thickness - velocity space into two regions, one corresponding to the projectile remaining intact, the other corresponding to the projectile shattering. Another line, AB, gives the critical velocity for perforation for a projectile which remains intact. A third line, CD, gives the critical velocity for perforation in the case of projectiles which shatter.

Several examples will be given of the use of this diagram. Suppose that the plate thickness is at level #1, and that the incident velocity of the projectile is gradually increased from a very low value. First the projectile does not penetrate, then it penetrates, with increasingly higher residual velocity until it shatters. The projectile shatters however only at such a high velocity that it succeeds, in spite of shatter, in perforating the plate. Now suppose the plate thickness is at the higher level #2. As the velocity of the projectile is now gradually increased, it also at first does not penetrate, then it passes intact through the plate with increasingly higher velocities. At this higher plate thickness, however, when the shatter velocity is reached the projectile is not going fast enough to penetrate the plate at this velocity, and does not again penetrate until a considerably higher velocity is reached. Finally, suppose the plate thickness is at level #3. As the velocity is now gradually increased, the projectile shatters before passing through the plate. It therefore cannot penetrate intact. Penetration, with projectile shatter, is then only attained at very high velocities. From the above considerations it follows that for a given projectile and plate hardness shatter can occur only in a certain range of plate thickness.

It is expected that the general features of Figure 3 will be valid at normal incidence for all types of projectiles and plates. The exact location of the boundaries between the four regions will however depend considerably upon the shape of the projectile's ogive, and upon the relative hardness of the projectile's ogive and bourrelet with respect to the plate. The general features of shatter depicted in Figure 3 are not applicable to all types of projectiles at oblique incidences. Certain projectiles, in particular the small calibre projectiles currently used by the U.S. Army, fracture at obliquities of 20° and over. Such fracture is of an entirely different nature from that which occurs at normal incidences, being associated with tensile stresses accompanying bending moments. At small angles of obliquity, such fracture occurs in fact more readily the lower the velocity. This behavior arises from the fact that when a projectile strikes a plate at an angle, the obliquity initially increases, and that this increase in obliquity is greater the lower the velocity.[1]

ANALYSIS OF UNBALANCED COMPRESSIVE STRESS

The front portion of a projectile is subjected to extremely large pressures. In the Appendix it is shown, both from theoretical considerations and from experimental observations, that these pressures may become as high as 600,000 psi. Such large pressures would by themselves cause no damage provided they were uniformly distributed over the projectile, for such a distribution would give rise only to a hydrostatic pressure, and a hydrostatic pressure can deform metals only elastically. Actually the pressure is not uniform. As the projectile is entering the plate, the pressure is a maximum at the tip of the ogive,[1,2] and decreases gradually therefrom to zero over those portions of the projectile which are outside the plate. This nonuniformity in pressure results in the axial pressure being larger than

1. C. Zener and R. E. Peterson: "Mechanism of Armor Penetration, Second Partial Report", WAL 710/492, pp. 24-29.
2. "Penetration Mechanisms II. Supplementary Report on the Penetration of Homogeneous Plate by Uncapped Projectiles at 0° Obliquity", U. S. Naval Proving Ground Report No. 3-44.

the radial pressure, as is illustrated in Figure 4. It is the difference in these two pressures, which will be called the unbalanced pressure, that is effective in producing plastic deformation.

The various manners in which a projectile may respond to the unbalanced pressure may best be seen by a consideration of a solid cylinder subjected to an unbalanced pressure, e.g., to a pressure over its two ends. The deformation will initially be uniform throughout the cylinder. Any deviation from uniform deformation is unstable. Thus suppose the cylinder starts to bulge locally. The material in the local bulge will become stronger than the surrounding material due to strain hardening. Further, it will be subjected to a smaller stress than the surrounding material due to the increase in cross section. Deformation in the bulge would therefore cease until the remaining portion of the bar had deformed the same amount. Again, suppose the shear deformation is slightly greater in a certain band inclined 45° to the axis than in all other bands. The increased strength which accompanies deformation will then cause further deformation in this band to cease until the surrounding regions have become equally strong. If the deformation proceeded isothermally, the deformation would continue to be uniform since strain-hardening always accompanies isothermal strain. If, however, the deformation is adiabatic, as in the case of a projectile, a strain is reached at which strain-hardening ceases. Further strain actually weakens the material.[1,2,3] Uniform deformation becomes unstable at this strain. For if the bar now begins to shear across a 45° plane, the material in this plane becomes weakened thereby, and the shear will therefore continue. Instability due to local bulging cannot occur, since the decreased strength of the material will be more than compensated for by the decrease in stress due to the increase in cross section.

If the deformation is not sufficient to give rise to unstable shear deformation, the amount of the deformation for a given material depends only upon the magnitude of the unbalanced pressure. The dependence is discussed in the following part of this section. When the uniform deformation becomes unstable, the precise manner in which the nonuniform deformation proceeds depends upon the precise manner in which the pressure is distributed over the projectile. The nonuniform deformation is discussed in the following section.

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1. C. Zener and J. H. Hollomon: "Plastic Flow and Rupture of Metals, First Partial Report", WAL 732/10.
2. C. Zener and J. H. Hollomon: "Plastic Flow and Rupture of Metals", Trans. A.S.M. 33 163 (1944).
3. C. Zener and J. H. Hollomon: "Effect of Strain Rate Upon Plastic Flow of Steel", Journal of Applied Physics, 15 22 (1944).

An increase in projectile velocity may increase the unbalanced compressive stress acting upon the parallel portion of the bourrelet in two distinct ways; (1) by increasing the longitudinal pressure, (2) by decreasing the lateral pressure. The lateral pressure is reduced if the radial momentum of the plate material is sufficiently great to push the plate material plastically aside further than it would have been pushed by the quasi-static forces of the projectile alone. This relaxation of the lateral pressure has been discussed in a previous report,[1] and occurs at a lower velocity the smaller the radius of curvature of the ogive, expressed in calibres, and the softer the plate material.

In order to subject the above ideas to a quantitative test, projectiles of uniform hardness were fired against a thick plate (2.5 calibres) at various velocities, and the resulting permanent expansion of the bourrelet observed. From the expansion the compressive strain at the bourrelet was computed, and upon assuming a reasonable stress-strain relation, the maximum unbalanced compressive stress was calculated. The observations and calculations are given in Table I, and are presented graphically in Figure 5.

The curves in the right hand portion of this Figure represent the stress-strain curves of the projectile steel at several hardness levels, as taken from the work

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

of Hollomon.[1] A strain hardening exponent of 0.06 was assumed, which seems to be the best guess for a steel with a carbon content of .65/.75, and a yield stress of about 300,000. The yield strength of the steel (Manganese-Molybdenum, FXS-318) at the hardness level of 60 RC was taken as 310,000 psi from a recent report.[2] The yield stress was taken to increase 7,000 psi for every point RC.[3] The curves in the left hand portion of Figure 5 represent the maximum unbalanced pressure acting upon the bourrelets of projectiles when fired at different velocities. Each curve corresponds to a definite plate hardness. Those curves corresponding to a plate hardness of 306 and of 269 BHN respectively were obtained as follows. The maximum diameter of the bourrelet was measured before and after firing. If d_i and d_f are these diameters, respectively, the plastic natural strain suffered at the bourrelet is calculated from the formula

$$\text{Strain} = \ln \frac{(\text{area})_f}{(\text{area})_i} = 2 \ln (d_f/d_i) \quad .$$

To obtain the maximum strain at the bourrelet during impact, one must add the elastic to the plastic strain. This elastic strain will be nearly the same as the elastic strain at the yield point, and may be taken, for

1. J. H. Hollomon: "Tensile Stress-Strain Curves", WAL 630/7-1.
2. D. Van Winkle and C. Zener: "Development of Projectile Steels, First Partial Report", WAL 321/4.
3. Metals Handbook (1939) p. 127.

the steel in the bourrelet, as 0.01. From the maximum strain at the bourrelet during impact, the experimental data for which is given in Table I, one can then read from the appropriate stress-strain curve the maximum unbalanced pressure during impact. Although the projectile hardness will affect the maximum strain, it should not affect the maximum unbalanced pressure. This invariancy of maximum unbalanced pressure upon projectile hardness is illustrated by the data for projectiles of 60 and 65 RC hardness. The method used in constructing the curves for 360 and 230 BHN is described below.

The curves of Figure 5 may be used in reverse to give the deformation produced in a projectile of any hardness when fired against a plate of arbitrary hardness with an arbitrary velocity. The method will be illustrated for the case of an incident velocity of 2500 f/s, a plate hardness of 306, and a projectile hardness of 60 RC. One goes up vertically along the 2500 f/s line until one meets the curve corresponding to the 306 BHN, at 380,000 psi, then goes horizontally to the right until meeting the line for the 60 RC hardness, then goes vertically down to the strain axis and reads the strain 0.30 which the bourrelet would suffer under these conditions.

The curves of maximum unbalanced compressive stress vs. velocity may be further interpreted. It is expected that the maximum unbalanced compressive stress may be represented as the sum of two terms. The first term, S_o, is essentially the maximum unbalanced compressive stress at the bourrelet if it were pushed through statically. The second term represents the effect of the inertia of the plate material, and may be written as $\alpha \rho V^2$, where α is a numerical constant of the order of magnitude of, but less than, unity, ρ is the density of the plate material, and V the incident velocity. It is expected that the curves may therefore be represented as

$$\text{Max. Unbalanced Stress} = S_o + \alpha \rho V^2 \quad .$$

The curves which pass through the experimental points in Figure 5, have in fact been drawn to conform to this equation. The coefficient α for both curves is the same, namely 0.12. This value of α is identical to the value of α corresponding to the inertial pressure of air, at velocities below that of sound, for a similarly shaped ogive.[1] (Semi-angle of ogive used in present experiments, 57°; semi-angle of ogive used in experiments on air resistance, 48°). The constant S_o for the plates of 269 and 306 BHN is 290,000 and 310,000 psi, respectively. Estimated curves have been drawn for 230 and 350 BHN plates. In

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1. C. Zener and R. Peterson: Ibid, Table III

drawing these it was assumed that the coefficient α was the same as above, namely 0.12 and that a linear relation exists between the BHN and the constant S_o, the constant S_o increasing 1,000 psi for every two points BHN.

DISINTEGRATION OF PROJECTILE

When projectiles are fired at increasingly higher velocities, the deformation does not just increase uniformly. A velocity is finally reached at which the projectile separates into two or more pieces, generally into a great many pieces. The surfaces of these pieces may be fused together so as to form one conglomerate mass. The separation into individual pieces can conceivably occur either by fracture due to tensile stresses, or by shearing across discontinuous surfaces due to an instability of homogeneous adiabatic shear deformation. Such instability arises from the adiabatic stress-strain curves having a maximum rather than continuing to rise. The occurrence of such instability is well known in the case of armor plate.[1]

It is well known[2,3,4] that tensile stresses may be produced inside a solid body by localized forces applied normally to its surface. Thus if a solid sphere is

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1. C. Zener and J. H. Hollomon: "Mechanism of Armor Penetration, First Partial Report." WAL 710/454
2. A. E. H. Love: Mathematical Theory of Elasticity (Cambridge, 1927) p. 198.
3. E. G. Coker and L. N. G. Filon: Photoelasticity (Cambridge 1931) pp. 410-413.
4. S. Fuchs: Physikalische Zeits p. 1282 (1913).

pressed against a semi-infinite solid, the three principle stresses in the semi-infinite medium directly beneath the sphere are all compressive. Further in, one is compressive, two are tensile. This case is illustrated in Figure 6. As the velocity of a projectile increases, the force acting upon the ogive becomes concentrated about its tip. If the fracture stress of the steel in the ogive is sufficiently low relative to its flow stress, brittle fracture will therefore result. At the high hardness level of the ogive the fracture stress with respect to the longitudinal axis is at best only slightly above the flow stress of the steel. The tensile stresses occur, however, along directions normal to the axis of the projectile, and therefore normal to the direction of rolling. Due to the elongation of the impurities along this axis during the process of rolling, the fracture stress transverse to the axis is certainly smaller than that parallel to the axis. The ratio of the two fracture stresses depends of course upon the cleanliness of the steel and upon the amount of forging. Experience has shown that clean steels, as ordinarily forged, have a ratio not less than 0.7. A ratio of 0.7 for the fracture stress to the yield stress is however not sufficiently low to allow brittle fracture in a projectile under conditions of normal impact. An examination has been made of the numerical solutions for the stresses produced by a localized pressure. From this examination it appears that the ratio of fracture stress to yield stress would have to be as low as one fourth to allow brittle fracture at normal impact.

The only other method by which a projectile may separate into pieces at normal impact is through inhomogeneous shear. As has been discussed on page 6c, once instability is reached all further deformation is confined to certain surfaces across which the shear strain becomes very large. To a first approximation the initial plastic deformation of the ogive may be thought of as a simple homogeneous compression. Such a deformation can be represented as a simultaneous shear across four or more planes inclined 45° to the axis. No one 45° plane is favored over the others. The first approximation to the deformation is therefore not sufficient to determine the orientation of the surfaces of high localized shear which attend instability. These can be determined only by the next approximation, that is, by the deviation from simple compression.

One type of deviation may be produced by a slight asymmetry such as may arise from a slight yaw. Such an asymmetry would automatically select one 45° plane for discontinuous shear. Examples of this type of failure are shown as Figure 7, including a 16" projectile from H. H. Zornig.[1]

A second type of deviation may result from the concentration of the pressure about the tip of the ogive, mentioned above. Such a distribution of pressure will tend to produc a discontinuous shear across a cone, with the apex of the cone pointed towards the base of the projectile. This cone then acts as a wedge which tends to spread the body of the projectile. If the body is not sufficiently ductile, it will fracture longitudinally into two or more pieces. Examples of such cones and fractured bodies are shown as Figure 8. An example shown to the authors by Dr. T. A. Read of the Frankford Arsenal appears to have failed along a series of concentric cones.

While the initial discontinuous shear may be confined to a single surface, many intersecting surfaces may become operative as deformation proceeds. The ogive may in this manner become separated into many pieces.

Discontinuous shear takes place across the surfaces above discussed. Another type of discontinuous plastic

1. H. H. Zornig: "Lecture On Armor Piercing Projectiles", WAL 762/16.

deformation is possible. This occurs along the planes passing through the region of maximum shearing stress. In contrast to the planes previously discussed, the orientation of these planes is not necessarily identical to that of the surfaces across which the shearing stress is a maximum. Familiar examples of such surfaces have previously been shown in armor plate,[1] where they give rise to "trapped" punches. The physical basis for trapped punches is well understood. The region immediately below a distributed pressure is subject only to hydrostatic pressure, the surface of maximum shearing stress lies beneath the surface at a distance comparable to the linear dimensions of the region over which the surface pressure is distributed. Just as the force with which the projectile acts upon the plate may give rise to a trapped punching in the plate, so likewise the opposite force with which the plate acts upon the projectile may produce a trapped punching in the projectile. Such trapped punchings have been observed in all the projectiles of the type fired for this report having a RC hardness of 65, and fired under conditions which give at least a 5% expansion at the bourrelet. Examples are shown in Figure 7. If the velocity of the projectile is sufficiently high, the trapped punching is broken

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

away from the projectile when the projectile is recovered. Otherwise it remains attached to the projectile by its outer rim. Since the stress across the central portion of the surface of maximum shear stress was a pressure during the plastic deformation, the residual stress is also a pressure. The perimeter of the trapped punching, along which it remains attached to the projectile, is therefore subject to a tensile load. If the perimeter fractures under this tensile load, the trapped punching will therefore be thrown off. This has been observed to happen from one hour to several days after firing.

APPENDIX

Compressive Stresses in Projectiles

An estimate of the retarding force f acting upon the projectile during armor penetration at normal incidence may be obtained by equating the energy necessary for complete perforation to the force times the plate thickness e. Thus

$$1/2(W/g)\ V^2 = f \cdot e \qquad (1)$$

This equation is strictly applicable only when the length of the ogive is less than the plate thickness. Otherwise the distance over which a force acts is considerably in excess of e, with a resultant lowering of the force f. The average pressure P acting across a section at the bourrelet is then given very nearly by

$$(\pi/4)\ d^2\ P = f \cdot e. \qquad (2)$$

Eq. (2) would be a closer approximation if in Eq. (1) W referred to the weight of the projectile back of the bourrelet.

In any particular case the pressure P may be computed directly from the ballistic data. In those cases where the ballistic data have already been analyzed in terms of the Thompson coefficient F, the pressure P can most readily be obtained in terms of this coefficient. This coefficient is defined, for normal incidence, by the equation

$$W V^2 = F^2 e d^2 , \qquad (3)$$

with W expressed in lbs, V in ft/sec, and e and d in ft. Upon combining Eqs. (1), (2) and (3), one obtains

$$P = 1.37 \times 10^{-4} F^2 \text{ psi} \qquad (4)$$

A plot of this relation is given in Figure 10.

The F coefficient of cal. .50 projectiles with respect to homogeneous armor in the hardness range 340-380 BHN approaches 65,000 for large values of e/d. From Figure 10 it may be seen that this F coefficient corresponds to a pressure of 600,000 psi.

The above high pressure is in accord with a theoretical analysis of the pressure acting upon the bourrelet. The plate material flows plastically not when the pressure reaches a critical value, but rather when the flow stress reaches a critical value. The flow stress is effectively the difference between the maximum and minimum pressure. In the neighborhood of the projectile's ogive, all three principle stresses in the plate are compressive stresses. The maximum compressive stress is therefore considerably larger than the flow stress. According to Bethe's analysis, the maximum compressive stress, the stress acting normal to the surface of the projectile, is from two to three times as large as the flow stress. The flow stress itself is larger than the flow stress of the undeformed material due to strain hardening. This increase in flow stress is in the neighborhood of 100,000 psi, corresponding to a strain of about unity. Taking the initial flow stress of a 360 BHN plate to be 160,000 psi, the effective flow stress will be about 260,000 psi, and therefore the pressure normal to the ogive of the projectile will be from 520,000 to 780,000 psi.

TABLE I

DATA ON STRAIN AT BOURRELET

Plate BHN	Projectile RC	Velocity (ft/sec)	Expansion of bourrelet (inches)	Total Nat. Strain
306	65	2000	.001	0.015
		2200	.002	.025
		2500	.006	.050
		2800	.021	.13
		3000	.028	.17
	60	1900	.006	.050
		2000	.014	.098
		2100	.019	.12
		2300	.032	.21
		2400	.040	.24
		2700	.062	.38
269	60	2000	.003	.030
		2300	.007	.057
		2700	.039	.24
		2800	.054	.33

ACKNOWLEDGMENT

The author is glad of this opportunity to acknowledge the assistance of Mr. Bruce Ward, whose keenness of observation in the firing range has initiated some of the ideas in this report.

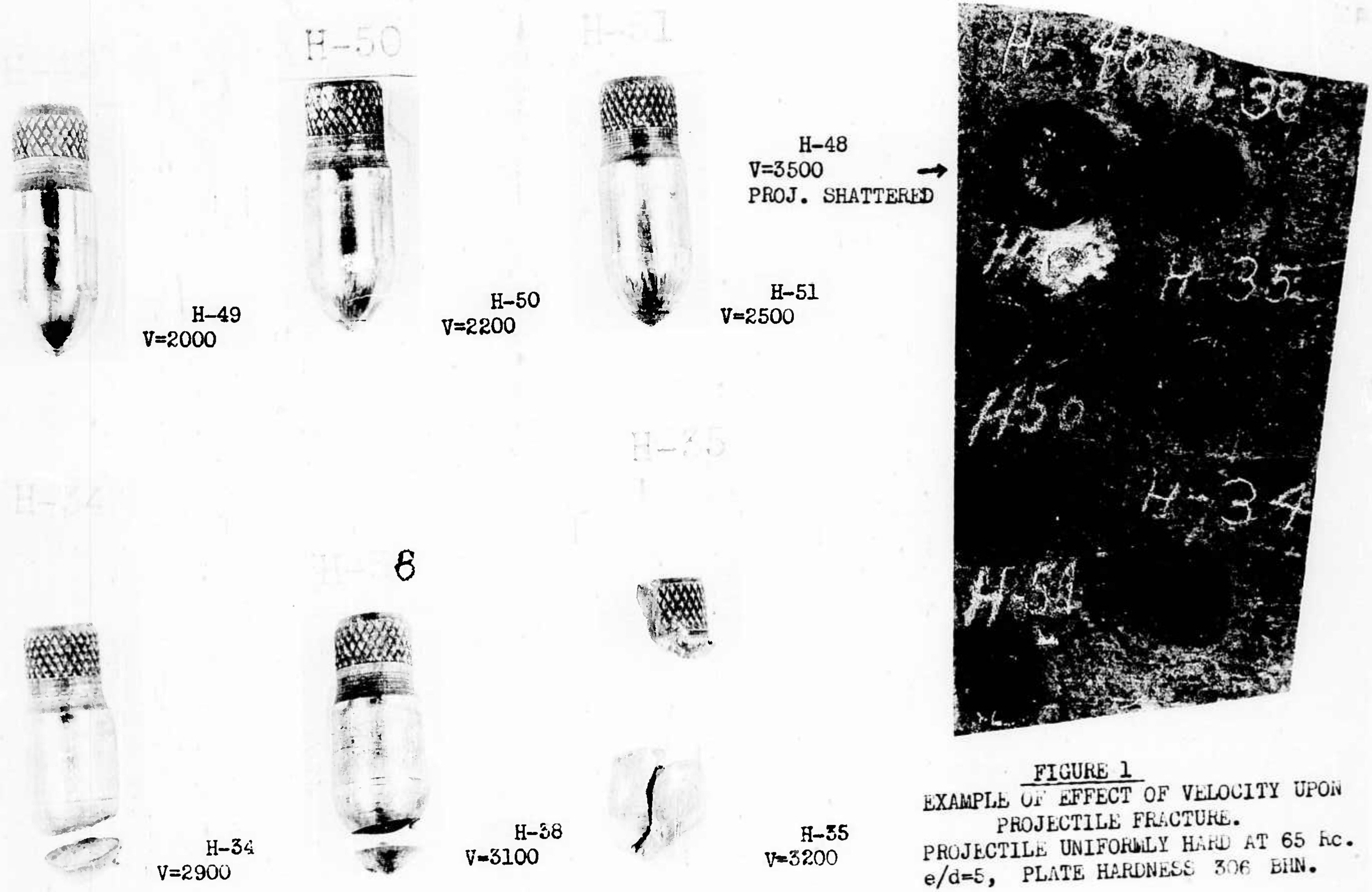
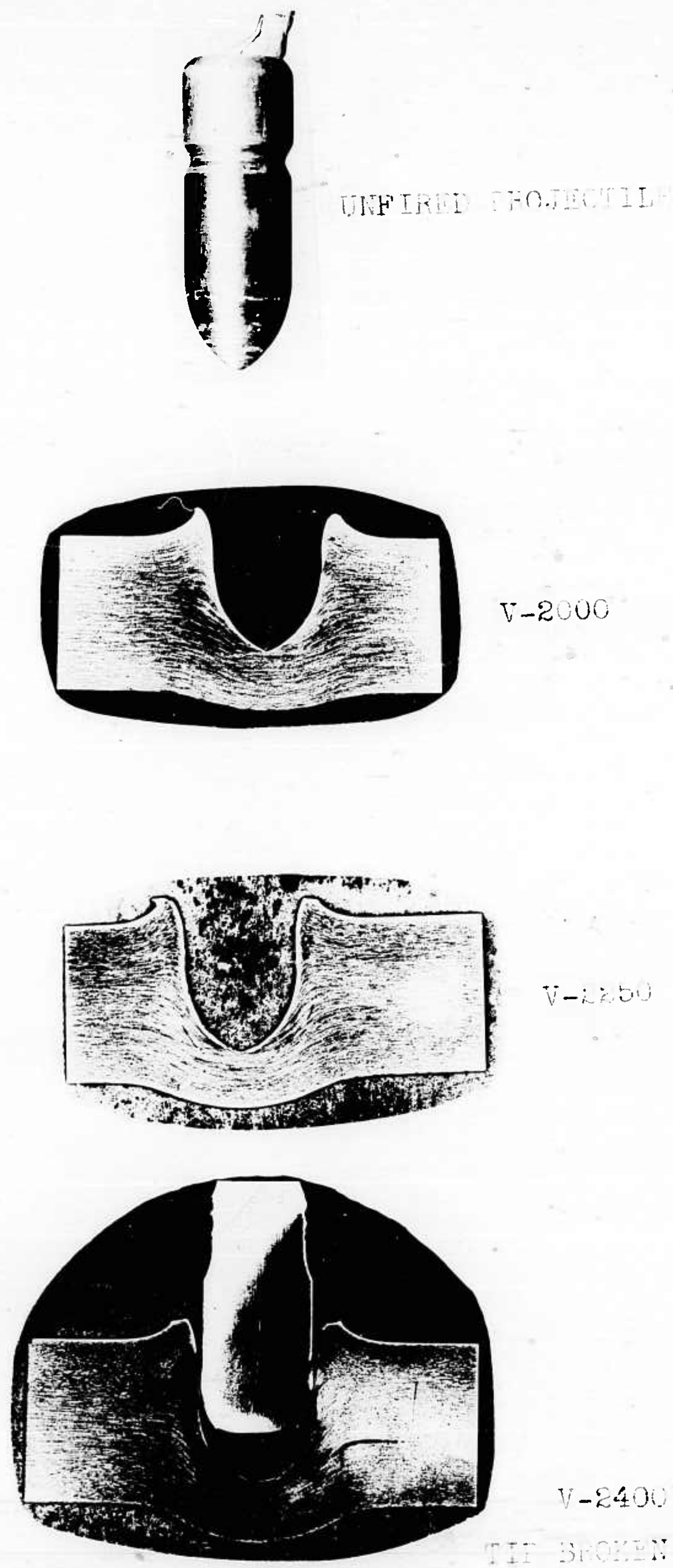


FIGURE 1
EXAMPLE OF EFFECT OF VELOCITY UPON PROJECTILE FRACTURE.
PROJECTILE UNIFORMLY HARD AT 65 Rc. e/d=5, PLATE HARDNESS 306 BHN.



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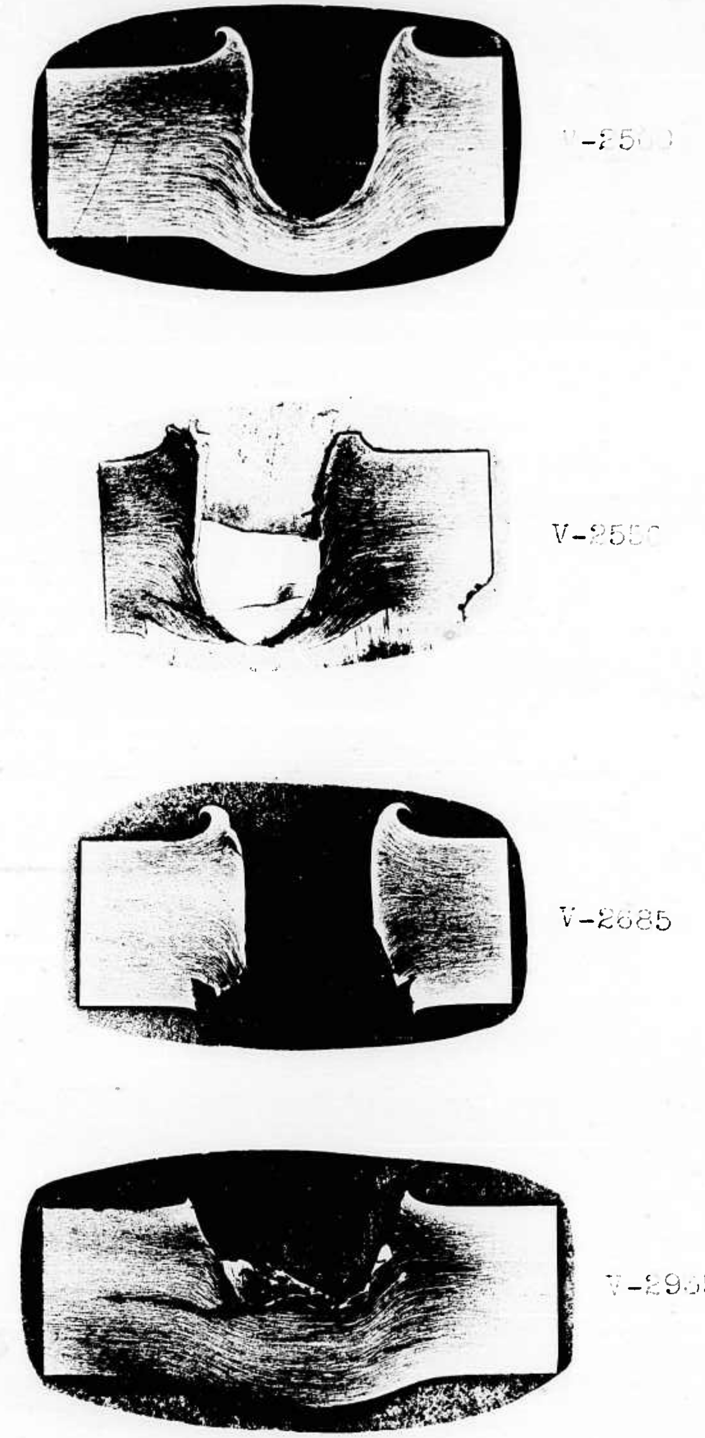

FIGURE 2

EXAMPLE OF SHATTER
SECTIONS OF PENETRATIONS
e/d=1.5, 418 BHN PLATE
65 Rc PROJECTILE

WTN.639-6395

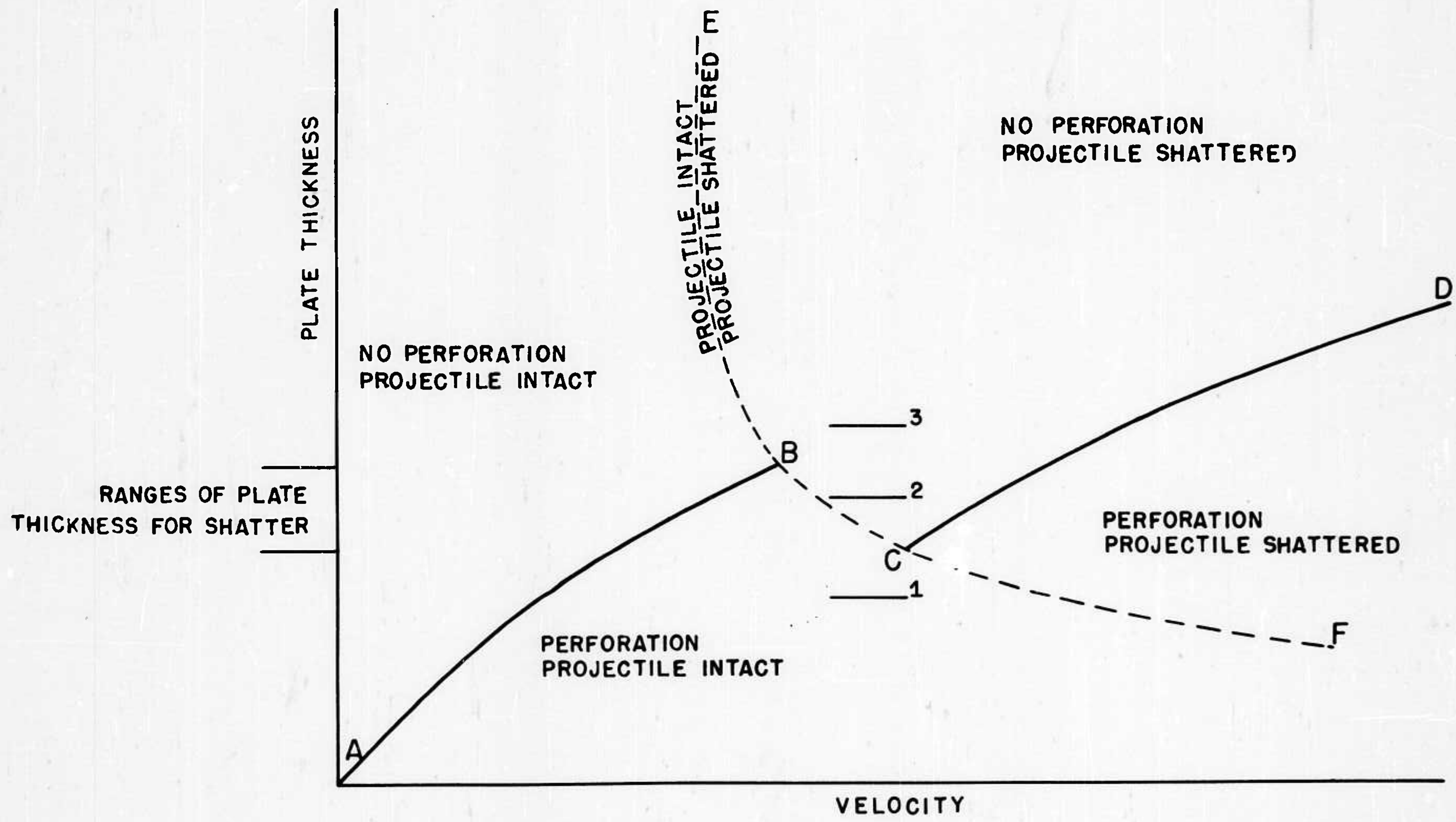

FIG. 3

GENERAL CONDITIONS FOR SHATTER

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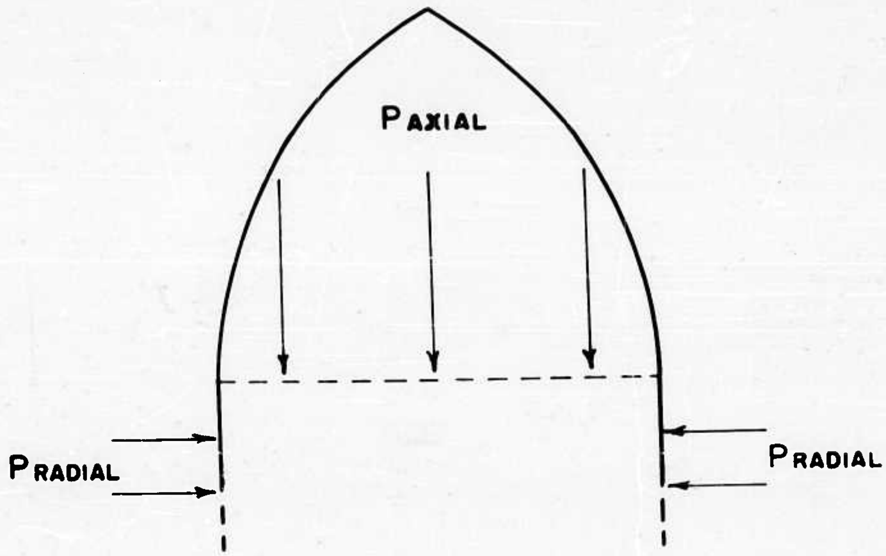

FIG. 4

EXAMPLE OF UNBALANCED PRESSURE
ACTING UPON BOURRELET

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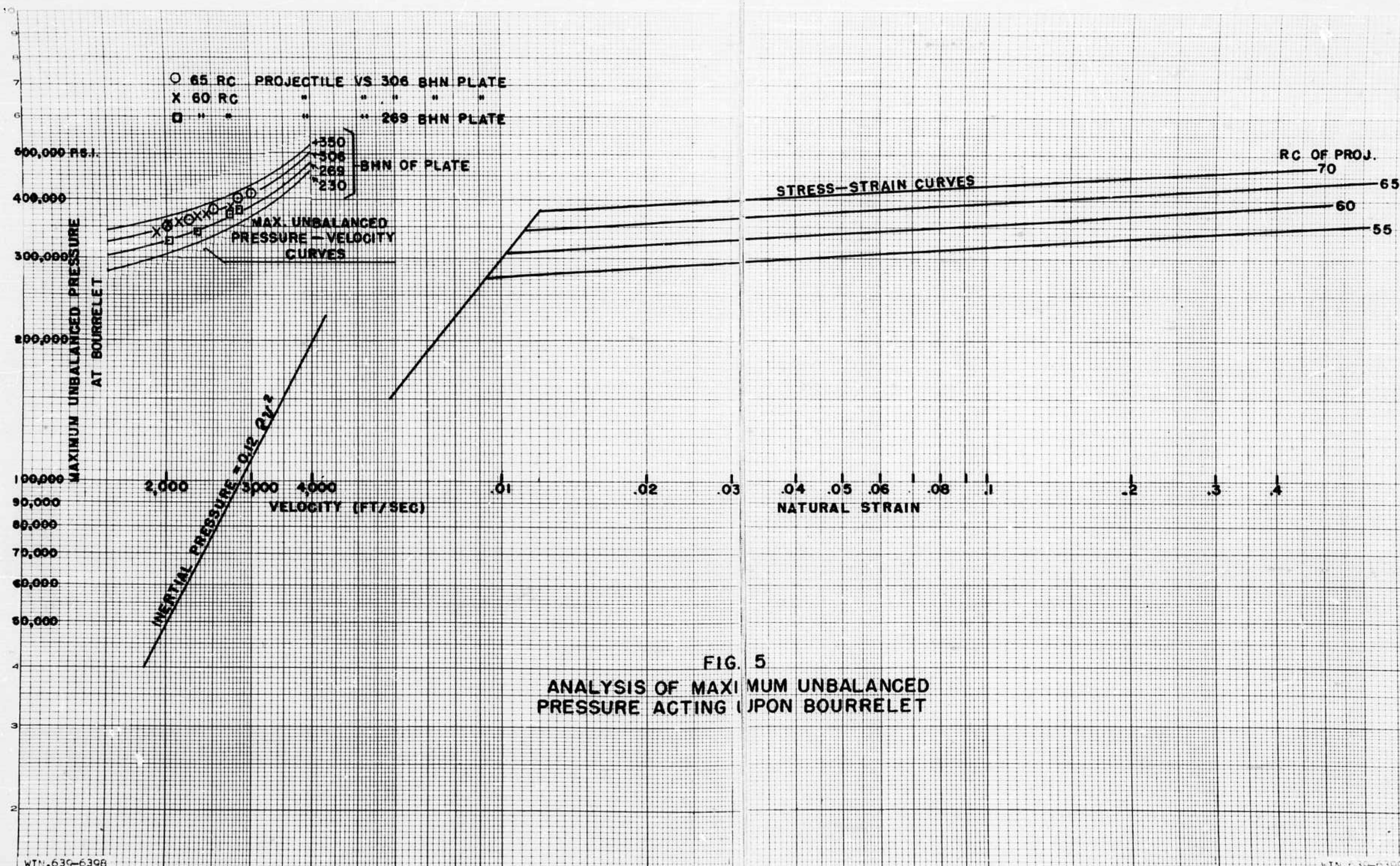


FIG. 5
ANALYSIS OF MAXIMUM UNBALANCED PRESSURE ACTING UPON BOURRELET

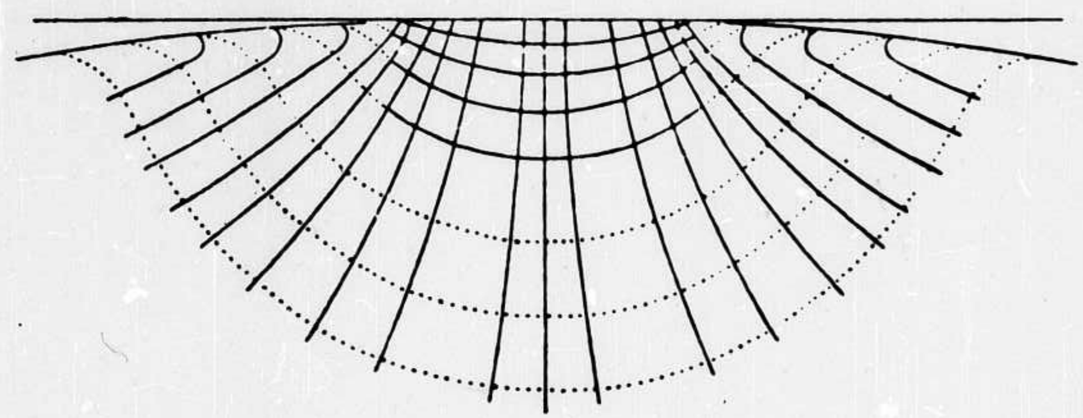
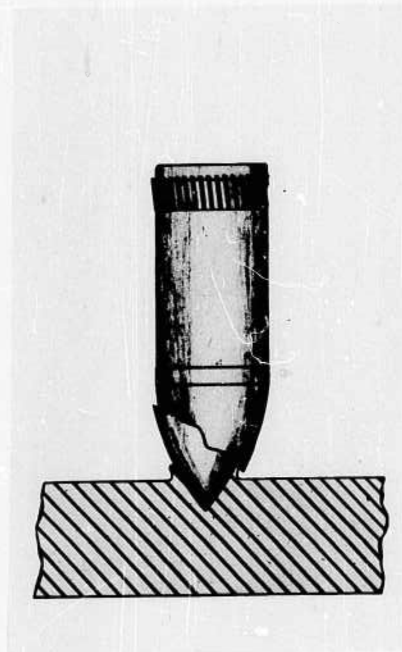


FIGURE 6

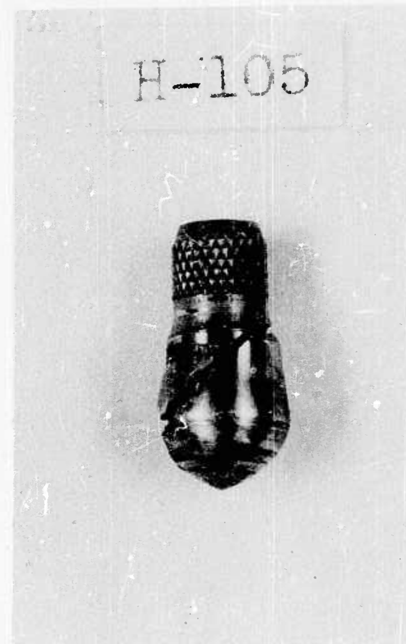
ILLUSTRATION OF STRESS PATTERN UNDER SURFACE DUE TO LOCALIZED PRESSURE.
SOLID LINES: COMPRESSIVE PRINCIPAL STRESS
DOTTED LINES: TENSILE PRINCIPAL STRESS.
AFTER FUCHS.

WTN.639-6400

16" PROJECTILE
(AFTER COL. H.H. ZORNIG)



SCHEMATIC DIAGRAM
(AFTER COL. H. H. ZORNIG)



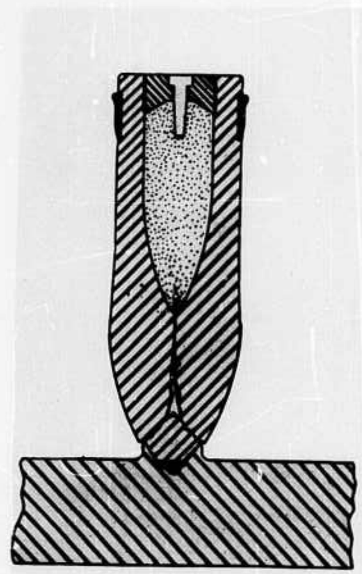
CAL..30 PROJECTILE
(PROJECTILE UNIFORMLY HARD AT 60 Rc, e/d=5, PLATE HARDNESS 306 BHN, VELOCITY 2700 f/s)

FIGURE 7

EXAMPLES OF FAILURE BY SHEARING OFF OF OGIVE TIP

WTN.639-64C1

16" PROJECTILE
(AFTER COL. H. H. ZORNIG)



SCHEMATIC DIAGRAM
(AFTER COL. H.H.ZORNIG)

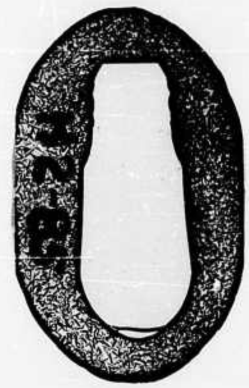
CAL. .30 PROJECTILE
(PROJECTILE 65 Rc AT OGIVE,
F.H. PLATE, VELOCITY 1300 f/s)

FIGURE 8

EXAMPLES OF FAILURE BY FRACTURE
OF BODY BY TRAPPED PUNCHING.

WTN.639-6402

A
PUNCHING SEPARATED FROM
PROJECTILE



B
SECTION THROUGH INTACT PROJECTILE
SHOWING TRAPPED PUNCHING STILL ATTACHED

FIGURE 9
ILLUSTRATION OF TRAPPED
PUNCHING OF PROJECTILES.
(PROJECTILE 65 Rc.)

WTN.639-6403

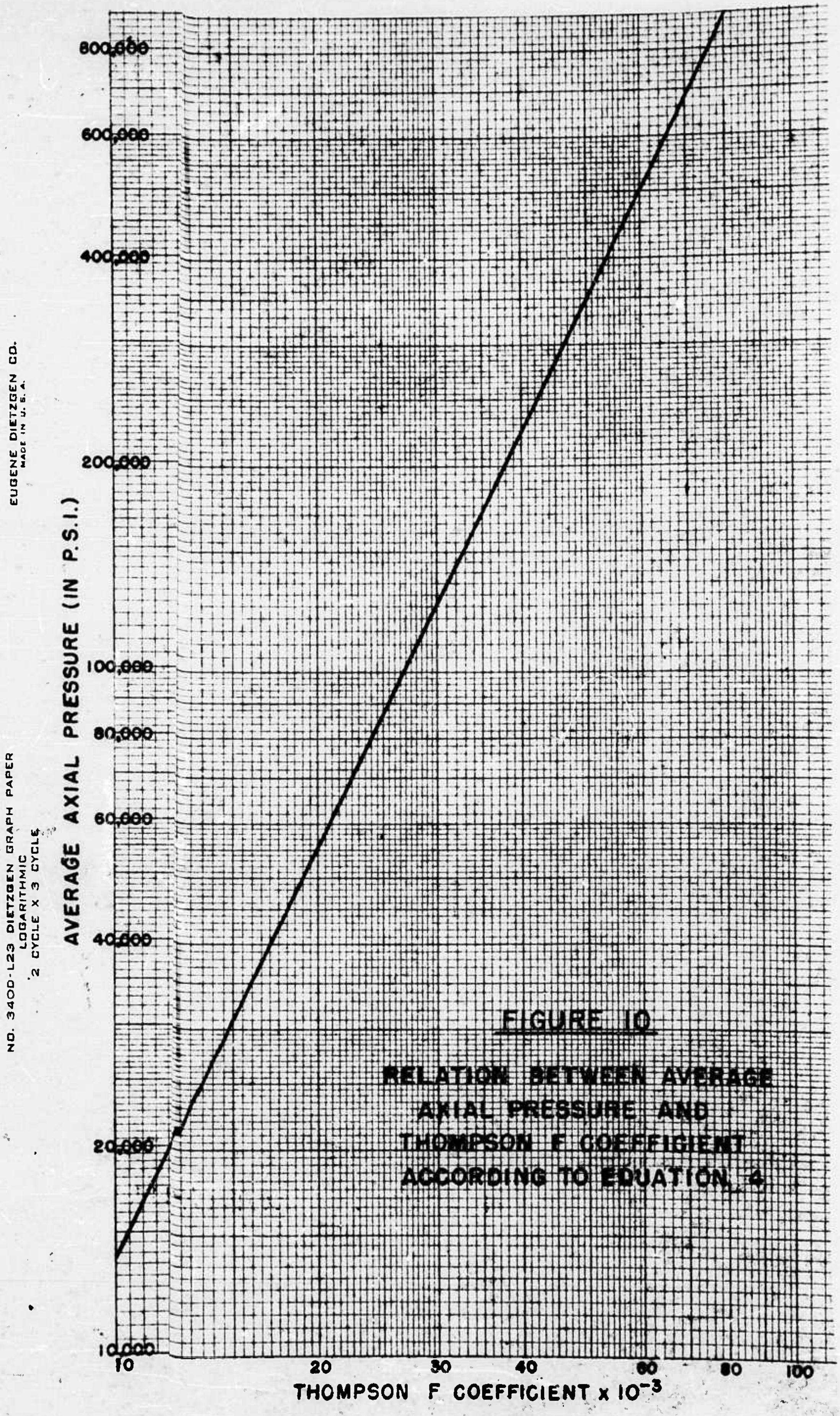


FIGURE 10

RELATION BETWEEN AVERAGE AXIAL PRESSURE AND THOMPSON F COEFFICIENT ACCORDING TO EQUATION 4