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U. S. NAVAL PROVING GROUND
DAHLGREN, VIRGINIA

REPORT NO. 584

11955

LIGHT ARMOR, TITANIUM

1st Partial Report

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BALLISTIC TEST OF
5/8" TITANIUM ARMOR
INCLUDING FIVE PLATES FROM
THE REMINGTON ARMS COMPANY AND
ONE PLATE FORGED BY THE NAVAL GUN FACTORY
FROM A duPONT INGOT

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METALLURGICAL EXAMINATION OF
REMINGTON TITANIUM PLATE 1R

C-59355

FINAL Report
Copy No. 15

Task Assignment NPG-41-Re3a-128-1
Classification CONFIDENTIAL

Ballistic Test of 5/8" Titanium Armor Plates
and Metallurgical Examination of Plate 1R

## PART A

## SYNOPSIS

1. This test was conducted to determine the comparative ballistic properties of five 5/8" Remington titanium armor plates and one experimental 5/8" titanium plate forged by the Naval Gun Factory from a duPont ingot and finished by rolling. The metallurgical properties are reported on the initial plate submitted by the Remington Arms Company.

2. Against Caliber .30 APM2 and Caliber .50 APM2 projectiles at 0° obliquity, the titanium plates tested at an equivalent steel thickness from 0.350 to 0.370 inches were superior in ballistic performance to homogeneous aircraft steel armor, equal to 24S-T4 aluminum-alloy armor, and inferior to face-hardened steel armor.

3. Against 20mm HE loaded and fused projectiles at 20° obliquity, the titanium plates tested, at an equivalent steel thickness from 0.350 to 0.360 inches were inferior to homogeneous and face-hardened steel armor. The overall shock properties were equal to those of 24S-T4 aluminum-alloy armor in regard to protection afforded, but slightly inferior in regard to tendency to crack.

4. Titanium is suitable for use as an armor material insofar as ballistic properties are concerned but applications will depend upon reductions in the present high cost per pound of armor and upon the possibility of improving the present ballistic quality.

5. A metallurgical examination of one of the better titanium armor plates showed a characteristic equi-axed grain structure which also had a preferred crystal orientation developed in the process of rolling and annealing. The preferred orientation produces maximum hardness in a direction across the thickness of the plate and should help penetration resistance.

6. The oriented structure was less effective ballistically when the plate was finished in the maximum cold-worked condition but subsequent experimental annealing restored some of the lost ballistic quality.

7. When the orientation was removed by transforming the structure at high temperature, the resultant structure was deficient in strength with indications of poorer ballistic quality.

Ballistic Test of 5/8" Titanium Armor Plates
and Metallurgical Examination of Plate 1R

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Ballistic Test of 5/8" Titanium Armor Plates
and Metallurgical Examination of Plate 1R

PART B

INTRODUCTION

1. AUTHORITY:

This test was authorized by references (a) and (b).

2. REFERENCES:

a. BUORD ltr NP9 (Re3a-128) to NAVPROV of 27 April 1949.
b. BUORD ltr L4-3(11)(Re3a-128) to NAVPROV of 27 June 1949.
c. Naval Research Laboratory - First Preliminary Report on Ballistic Studies of Metallic Titanium, Advance Copy, March 1, 1949.
d. Remington Arms Co. ltr to BUORD of 20 December 1949.
e. Titanium, Report of Symposium, Office of Naval Research, 16 December 1948.
f. Titanium Symposium, Industrial and Engineering Chemistry, February 1950.
g. Remington Arms Co. ltr to BUORD of 6 January 1950.

3. BACKGROUND:

Since titanium is a relatively new metal, some of its properties which might influence the ballistic quality are listed below.

Titanium is intermediate in density between 24S-T4 aluminum armor and steel armor. The metal has a high melting point, low thermal expansion and low heat conductivity. In common with zirconium it has a strong tendency to seize other metals in frictional contact. The crystal structure of titanium is close-packed hexagonal in contrast to the body-centered cubic crystal arrangement in steel. Titanium has an allotropic modification at high temperature - beta titanium - which has a body-centered cubic structure and which develops in the pure metal near 1615°F. Carbon, as titanium carbide, is found in significant amounts in commercial titanium. The carbide is relatively insoluble in both the low temperature alpha and high temperature beta modifications and therefore does not have a hardening function as it does in steel.

Ballistic Test of 5/8" Titanium Armor Plates
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Although very pure titanium is available in small amounts for laboratory uses, the prospective metal for commercial use contains small amounts of other elements which modify its properties. Remington Arms Company vacuum-arc-melted titanium has a nominal composition of 99+% titanium, 0.3% carbon and smaller amounts of oxygen, nitrogen, iron and other elements (reference (d)). The E. I. duPont de Nemours & Company also produces titanium metal ingots by induction melting in graphite which have a higher range of carbon content (0.3 to 1.0%). The commercial metal can be forged and rolled to plates such as might be used for armor.

Two recent symposiums on titanium metal, one conducted by the Office of Naval Research (reference (e)) and the other by the American Chemical Society (reference (f)) have provided information which is used in this report.

A conference on the production of the Remington titanium armor plates described in this report was held at the Naval Proving Ground on 10 November 1949 and was attended by the following representatives from other activities: W. L. Finlay and C. I. Bradford, Remington Arms Company; W. George and E. J. Chapin, Naval Research Laboratory; H. W. Freeman, Bureau of Ordnance (Re3a). At this conference the ballistic results on Plate 1R were reviewed and it was decided that the most feasible experimental variations in the manufacture of the remaining plates were to increase the amount of kneading during forging and to reduce the extent of annealing after rolling. Some of the material was left as forged billets which could be rolled into plates later. Because of the pioneer nature of this work, a chemical and metallurgical examination of each plate was decided upon to establish basic information on titanium armor plates.

4. OBJECT OF TEST:

The test was conducted to determine the comparative ballistic properties of five 5/8" Remington titanium armor plates and one experimental 5/8" titanium plate forged by the Naval Gun Factory from a duPont ingot and finished by rolling. The metallurgical properties are reported on the initial plate submitted by the Remington Arms Company.

Ballistic Test of 5/8" Titanium Armor Plates
and Metallurgical Examination of Plate 1R

5. PERIOD OF TEST:

| | | |
|---|---|---|
| a. | Date Project Letters | 27 April 1949 and 27 June 1949 |
| b. | Date Necessary Material Received | 18 October 1949 to February 1950 |
| c. | Date Commenced Test | 10 November 1949 |
| d. | Ballistic Test Completed | March 1950 |
| e. | Partial Metallurgical Examination Completed | March 1950 |

## PART C

## DETAILS OF TEST

6. DESCRIPTION OF ITEMS UNDER TEST:

A total of eleven plates have been rec[redacted]e Naval Proving Ground. The table below identifies [redacted]es as to manufacturer, method of fabrication, size, an[redacted] state of ballistic testing.

| NPG No. | Manufacturer | Mfrs. Plate No. | Size | Forging | Rolling | Ballistic Test |
|---|---|---|---|---|---|---|
| 1R | Remington | 364 | 5/8x20x20" | Standard-A | Standard-D | Fired |
| 2R | " | 414 | 5/8x20x20" | Standard-A | Standard-D | Part Fired |
| 3R | " | 415 | 5/8x20x20" | Standard-A | Max.cold work-E | Fired |
| 4R | " | 407 | 5/8x20x20" | Max.Kneading-B | Max.cold work-E | Fired |
| 5R | " | 428 | 5/8x20x20" | Max.Kneading-B | Max.cold work-E | Part Fired |
| 6R | " | 445 | 3/8x22x29" | Max.Kneading-B | Max.cold work-E | Held |
| 7R | " | 443 | 3/8x22x29" | Max.Kneading-B | Max.cold work-E | Held |
| 8R | " | 514 | 1-1/2x13x13" | Max.Kneading-B | F | Sold |
| 9R | " | 448 | 1-1/2x13x13" | Max.Kneading-B | F | Held |
| 10R | " | 540 | 1-1/2x13x13" | Max.Kneading-B | F | Held |
| 1D | duPont & NGF | No data | 5/8x24x28" | C | G | Fired |

Notes on Forging and Rolling Treatments:

A - Standard Remington forging practice: forged under a 1200 lb. hammer to a billet 1-1/2 x 14 x 14" with seven heatings to 1750°F, billet ground before rolling.

B - Forging for maximum kneading: same as A except approximately 50% more kneading during the forging operations.

C - Forged at the Naval Gun Factory, using an 8000-lb. drop hammer, to a billet 1-3/4" thick, forging temperature 1875°F.

D - Standard Remington rolling practice: rolled on hot jobbing mills to 5/8" thickness, with three heatings to 1750°F and six passes per heating, annealed 1-1/2 hours at 1450°F, air cooled, roller leveled for flatness.

E - Rolling for maximum cold work: similar to D except rolled with as little heat as possible and with no anneal after the rolling operation.

F - Left in "as forged" condition.

G - Rolled by Allegheny-Ludlum to 5/8" thickness. Plate was flattened at the Naval Gun Factory by heating to about 1300°F and pressing, air cooled.

Much of the above information on Remington forging and rolling treatments was obtained from representatives of the Remington Arms Company at the Naval Proving Ground conference. Most of this information is probably classed as a "trade secret" by Remington. The information which was specifically exempted from the trade secret classification was given in the following statement by the Remington Arms Company from reference (d).

"The material being shipped to you was produced by vacuum arc melting and casting of an ingot from commercially pure titanium sponge, the ingot then being forged into a billet and subsequently hot-rolled to present dimensions. Neither physical nor chemical properties have been analyzed. The nominal composition of commercially pure titanium is:

| | |
|---|---|
| Titanium | 99+% |
| Carbon | 0.3%, approximate |
| Oxygen<br>Nitrogen<br>Iron | Few one hundredths to a few tenths percent each. |
| Other Elements | Trace". |

The following analytical data on three of the Remington plates was given in reference (g).

| Plate Number | Carbon % | Nitrogen (%) |
|---|---|---|
| 414 (NPG No. 2R) | 0.28 | 0.013 |
| 415 (NPG No. 3R) | 0.43 | 0.010 |
| 407 (NPG No. 4R) | 0.30 | 0.013 |

Plate No. 1D was forged from a duPont ingot which had a carbon content of about 0.75%. The plate was returned to the Naval Gun Factory in a buckled condition after rolling and was flattened by heating to forging temperature and pressing.

7. **RESULTS AND DISCUSSION:**

a. **Ballistic Test**

The details of the ballistic results on each plate are given in Appendix (D) and the results are summarized in Table I, Appendix (B). Photographs of the plates after ballistic testing are included in Appendix (A) as Figures 1 to 10, inclusive. The testing procedure is described in Appendix (E).

The table given below lists the average ballistic limit coefficient for the best titanium plates and, for comparison, the average ballistic limit coefficient of other light armor materials. These limit coefficients have been calculated using the Vp50 limits. The Vpmin limits or specification requirements against 20mm HE loaded and fuzed projectiles for the various materials are also listed. The values represent performance for a given equivalent steel thickness e' to facilitate comparison between alloys of different density.

Ballistic Test of 5/8" Titanium Armor Plates
and Metallurgical Examination of Plate 1R

| Material | Equivalent Steel Thickness e' | Cal. .50 APM2-0° Limit Coefficient F(e'/d,θ) | Cal. .30 APM2-0° Limit Coefficient F(e'/d,θ) | "Vpmin" Limit 20mm HE 20° |
|---|---|---|---|---|
| Titanium (Av. of Plates NPG Nos. 1R and 2R) | 0"355 | 65,300 [1] | 70,800 [1] | 2394 f/s [1] |
| Face-Hardened Armor | 0"313 | -- | 75,800 [2] | 2265 f/s [3] |
| Face-Hardened Armor | 0"380 | 76,000 [4] | -- | 2617 f/s [3] |
| Homogeneous Aircraft Armor | 0"393 | 59,600 [4] | 65,600 [5] | 2694 f/s [3] |
| 24S-T4 Aluminum Alloy | 0"355 | 65,000 [6] | 66,200 [6] | 2320 f/s [7] |

Notes:

(1) Average of plates 1R and 2R, considered the best overall plates.

(2) Average limit coefficient for 61 acceptance plates.

(3) Minimum requirements of applicable armor specifications.

(4) Average of plates reported in NPG Report No. 478 of 19 January 1950.

(5) Average of 10 acceptance plates.

(6) From average performance curve based on all 24S-T4 aluminum alloy plates tested between 1943 and 1 February 1950.

(7) As predicted by the performance curve (NPG Photo No. 21190) contained in NPG Report 13-43 of 10 August 1943.

Ballistic Test of 5/8" Titanium Armor Plates
and Metallurgical Examination of Plate 1R

Plates 1R and 2R, manufactured in a similar manner by standard Remington practice, exhibited the best overall ballistic performance of the titanium plates. This was based primarily on the fact that these two plates gave the highest penetration limits against Caliber .50 APM2 projectiles at 0° obliquity, although some of the other plates were slightly better against Caliber .30 APM2 projectiles. The performance against Caliber .50 ammunition is considered to be of prime importance because this type of attack is considered likely to occur in service and also because armor of this weight (approximately 14.5 pounds per square foot) is generally employed for protection against Caliber .50 ammunition.

A graphic comparison of titanium with other types of light armor is given in Figure 11 using the Vp50 limit criterion.

From the table and Figure 11, the following comparisons with other types of light armor currently in use by the Navy are indicated.

(1) The average performance against Caliber .50 APM2 projectiles at 0° obliquity of the two best titanium plates (1R and 2R) is superior to that of homogeneous aircraft steel armor, equivalent of 24S-T4 aluminum alloy armor and inferior to face-hardened steel armor.

(2) The average performance against Caliber .30 APM2 projectiles at 0° obliquity of the titanium plates is superior to homogeneous aircraft steel armor and 24S-T4 aluminum alloy armor and inferior to face-hardened steel armor.

(3) The combination of strength and ductility present in the titanium plates 1R and 2R gave higher penetration resistance against Caliber .50 APM2 projectiles and slightly lower Caliber .30 APM2 resistance than did the combination of properties present in the other titanium plates tested with both calibers - 3R, 4R, and 1D. After annealing (1-1/2 hours at 1450°F) plate 3R was equivalent to 1R and 2R against Caliber .50 APM2 projectiles. Annealing plate 4R resulted in some improvement but not as much as in 3R. Plate 1D when annealed (slow cool from 1300°F) did not show any improvement.

(4) The shock properties of plate 1R against 20mm HE fuzed projectiles at 20° obliquity were inferior to those of homogeneous aircraft and face-hardened steel armor and superior to 24S-T4 aluminum alloy armor. This statement is based on the minimum protection limit "Vpmin" and the fact that cracking was not excessive. The shock performance of the other two titanium plates tested (3R and 4R, rolled with maximum cold work) was inferior to that of plate 1R in that the "Vpmin" limits were lower (Table 1) and the degree of cracking was greater (Figures 2, 4 and 6). Annealing 3R and 4R probably would have effected an improvement in shock resistance but sufficient material was not available for testing.

The results reported herein show the ballistic limit coefficient, F(e'/d,θ), of the best plate (4R) tested against Caliber .30 APM2 to be 72,800 at 0° obliquity. The ballistic limit coefficient calculated from earlier Naval Research Laboratory results on small samples (plate V4, reference (c)) is 78,600. The difference in ballistic performance reported may have been due to uncertainty from the limited number of impacts obtained on the small sample available for test in reference (c). Some differences in metallurgical properties were also observed. According to the tensile test data discussed later, the material in plate V4 had a slightly better combination of strength and ductility than plate 1R which had an F value of 69,600 against Caliber .30 ammunition.

The Remington titanium plates made by standard practice had the best all-around ballistic properties. Plates in which a certain amount of cold work was left in order to increase hardness were deficient against the Caliber .50 APM2 projectiles, apparently because of the accompanying decrease in ductility. The progress of metallurgical work so far has indicated that a final anneal applied to these work-hardened plates will improve their Caliber .50 penetration resistance.

The duPont plate 1D was slightly inferior in Caliber .50 penetration resistance to the work-hardened Remington plates but annealing did not improve the duPont plate, so that the cause of the deficiency apparently was not work hardening.

b. Penetration Mechanism

The hardness pattern of cold-worked metal surrounding an incomplete penetration of a Caliber .50 APM2 core is represented in Figure 12. A considerable volume of metal was work hardened in absorbing the projectile energy. This impact was one of a comparatively few in which the base of the projectile core cracked off during penetration. The longitudinal etched section of this same impact illustrated in Figure 13 revealed the veins and cracks resulting from shear stress and also the formation of petals at the back of the plate. A transverse etched section of another Caliber .50 impact in Figure 14(a) showed veins running out from the core. There did not seem to be any significant mode of formation of these veins other than an obvious concentration of shear deformation surrounded by comparatively undisturbed metal. The veins were a location for incipient cracks as shown by the path of rupture in Figure 15(b).

Examination of some of the complete penetrations showed that the lead plug over the nose of the APM2 cores tended to coat the inside of the hole in the plate with a film of metallic lead. This effect is illustrated in Figure 14(b). The film obviously would prevent direct frictional contact between the steel core and the titanium during penetration. Some caliber .50 API rounds which had no lead plug were fired against plate 1D but the results were the same as with the APM2 rounds. Based on these results, it would seem that the tendency of titanium to "seize" other metals in frictional contact is not a significant factor in its penetration resistance.

Heating of the contact surfaces during projectile penetration seemed to have occurred in sufficient amount to draw the temper slightly in the outer surface of the hardened steel dart. This condition is illustrated in Figures 16 and 17.

From the above observations on projectile damage, it is concluded that commercial titanium has only a little more effect on the Caliber .50 APM2 core than 24S-T4 aluminum, which practically never damages the projectile at 0° obliquity.

c. Chemical Analysis

Data obtained on the composition of plate 1R are given in Table II. The carbon content varies somewhat because of local segregation but it is believed that the average value for the plate is between 0.40 and 0.50%. The nitrogen and iron contents are low and in line with the expected values for Remington titanium. Samples for oxygen determination have been sent to the Naval Research Laboratory. There is as yet insufficient data to permit a correlation of composition with ballistic properties. If good ductility is desired in commercial titanium, the carbon and nitrogen should be kept relatively low, according to reference (f).

d. Microstructure

The form of the insoluble carbide particles probably has an effect on ballistic performance. A uniform dispersion of small rounded particles generally is considered to be the preferred structure in other materials. The typical carbide distribution in plate 1R is illustrated in Figures 18 and 19. Although fairly well dispersed, the carbides are somewhat elongated in the direction of rolling and flattened on the sides parallel to the plate surface. A substantial amount of kneading to break up the carbides appears to be desirable in the manufacture of titanium for ballistic plates.

The microstructure developed in the manufacture of plate 1R was composed of rather large equi-axed grains of alpha titanium.

Grain structures of longitudinal sections and of sections parallel to the surface are shown in Figures 20 and 21.

The alpha-beta transformation series in Figure 22 illustrated another type of alpha titanium grain structure produced by experimental heat treatment. By heating at increasing temperatures above 1600° F, the beta transformation was found to start at the boundaries of the equi-axed alpha grains, then begin at isolated spots within the grains and finally extend completely through the structure at 1750°F or above. On cooling, the beta phase apparently reverted completely to alpha since the density remained constant. The alpha phase now had an angular structure characterized by groups of parallel elements. This is a characteristic structure observed when transformation occurs along crystallographic planes and is named "Widmanstätten" after the discoverer. For simplification in this report, the equi-axed alpha and Widmanstätten alpha will be abbreviated as E-alpha and W-alpha respectively. The parallel pattern in W-alpha is more closely spaced in quickly cooled metal but evidence of the pattern is retained in more slowly cooled specimens as shown in Figures 23(b) and 25(a). Metallographic work on plate 1R led to the discovery of a combination etching technique ("C" and "B" solutions) which proved very sensitive to the lamellar structure in W-alpha titanium. The example in Figure 24(b) shows the dark "ribs" brought out by this technique.

The ribs presumably represented boundaries between different crystallographic orientations although there was some possibility that a rejected constituent might have been present. A summary of the methods used in preparing specimens for metallographic examination is given in Appendix (C).

Widmanstätten structures are also found under suitable conditions in many other metals and alloys including steel. The structure generally is associated with poor mechanical properties.

When a hexagonal close-packed crystal structure like that in alpha titanium is cold worked, the deformation produces mechanical twins within the grains. This is a ductile type of deformation with considerable capacity for energy absorption. A typical twinned structure of equi-axed alpha titanium in the vicinity of a projectile penetration through plate 1R is shown in Figure 25(b). Although the twins appear as parallel lines, this structure has no relation to the Widmanstätten pattern obtained by heating in the alpha-beta transformation range.

e. Mechanical Properties

The location of test samples is given in Figure 26. Tensile test data on plate 1R in the condition as received from the manufacturer are given in Table III. A comparison of the average values with plate V4 of reference (c) is given below:

| Plate | Source of Data | Tensile Strength (psi) | Yield Strength (psi) | Elongation in 4D (%) | Reduction of Area (%) | Reduction of Diameter Major Axis (%) | Reduction of Diameter Minor Axis (%) |
|---|---|---|---|---|---|---|---|
| 1R | NPG | 85,500 | 77,700 | 21.4 | 40.2 | 8.7 | 34.5 |
| V4 | HRL | 93,000 | ------- | 23.1 | 54.4 | 11.8 | 52.5 |

This comparison would indicate that the metal in V4 was somewhat stronger and more ductile than in the 1R plate. The elliptical fracture of the tensile specimens found in V4 was also observed in the 1R tests and is illustrated in Figure 27. The long axis of the ellipse ran perpendicular to the plate surface. A practical measure of the anisotropic effect was taken as the ratio of the major and minor axes of the ellipse. From the data given in the table above, the ratio "major axis/minor axis" was 1.4 for 1R and 1.9 for V4 and therefore the latter is assumed to have had a greater amount of anisotropy.

A study of these directional properties was made to determine what would happen if the titanium were heated through the alpha-beta transformation. Heating to 1700°F (pure titanium transforms at 1615°F) was tried as shown in Table IV and Figures 27 and 28. The anisotropy was not removed and the metal suffered a loss in strength with little or no gain in ductility. The transformation range was than examined by the metallographic methods already described (Figure 22). It was found that the transformation in commercial titanium was only about 50% complete at 1700°F and that temperatures of 1750°F or higher were required for full transformation. A tensile blank from plate 1R was then heated to 1800°F and the resulting test showed the circular fracture in Figure 29(a). This indicated a substantially complete removal of directional properties. However there was a further reduction in tensile and yield strength without much change in ductility as shown below.

| Plate | Treatment | Tensile Strength (psi) | Yield Strength (psi) | Elongation in 4d (%) | Reduction of Area (%) |
|---|---|---|---|---|---|
| 1R (#19) | 1800°F - 10 mins., air cool. | 77,000 | 58,200 | 22.2 | 37.4 |

The decrease in strength associated with the removal of directional properties was obviously undesirable for better ballistic quality.

A theory was advanced by the Remington Arms Company that the anisotropic effect was related to preferred orientation developed in the crystal structure by cold working and annealing. Referring to the diagram of atomic arrangement in Figure 30, it is believed that the hexagonal close-packed crystal units tend to become oriented so that their basal planes are parallel to the surfaces of the plate.

The plates were too thin to permit tensile testing in the normal direction and further examination of the preferred orientation effect was based on Brinell hardness tests of a sample block which was positioned so that the axis of the indenter was respectively in the normal, longitudinal and transverse directions to the plane of rolling. Test results are summarized below from Table V.

| Plate | Treatment | Brinell Hardness Values (3000 kg. - 15 sec) Normal | Longitudinal | Transverse |
|---|---|---|---|---|
| 1R | None, as received. Oriented crystal structure. | 234 | 191 | 201 |
| 1R(#19) | Orientation removed by heating to 1800°F, air cool | 194 | 183 | 179 |

The plate material as received had a remarkable excess of hardness in the normal direction (across the thickness of the plate). This also corresponded to the direction of projectile penetration so that a favorable influence on penetration resistance could be expected. The excess hardness practically disappeared when the orientation was removed by heat treatment at 1800°F. A minor part of the differences in hardness was probably caused by the mechanical effects of elongated carbides in the matrix.

Standard Brinell hardness tests were taken to establish the average face and back hardness of plate 1R, both in the original condition and after experimental heat treatments, and the results are reported in Table VI. Some minor variations in hardness were observed which probably resulted from inhomogeneity in chemical composition. Micro-hardness surveys taken across sections of the plate also showed local differences in hardness as plotted in Figures 31 and 32. The high plateau at the right of the curve in Figure 32 was observed to be related to a segregation of titanium carbide particles in this area.

The results of tension-impact and Charpy V-notch impact tests are recorded in Tables VII and VIII and Figure 29(b).

f. Macrostructure

A center section extending halfway across the plate was etched by two different methods to show segregation and grain size, respectively.

The slight evidence of segregation shown in Figure 33 suggested partial mixing of an inhomogeneous melt. Carbon as titanium carbide was one of the segregating elements but the differences observed were probably not large enough to affect the physical properties seriously.

The macrostructure in Figure 34 revealed a fairly uniform size of grain from edge to center of the plate.

g. Discussion

The best penetration resistance in experimental armor plate fabricated from commercial titanium metal appears to be associated with the preferred orientation of an equi-axed grain structure developed by rolling and annealing below the alpha-beta transformation range. In 5/8" Remington titanium plates made by this practice, the oriented structure had about 10% greater hardness in a direction perpendicular to the plate surface with no reduction of ductility in directions parallel to the plate surface. It is not yet certain that the optimum orientation effect has been obtained. If the orientation was removed by heating through the transformation range, there was not much change in tensile elongation but the excess hardness disappeared so that lower ballistic properties could be expected.

When a final anneal was purposely omitted from the Remington practice, the 5/8" plates so produced had lowered resistance against HE shock and against Caliber .50 ammunition. Tests indicated that these work hardened plates (3R and 4R) could be improved by annealing at 1450°F.

The 5/8" plate No. 1D of duPont titanium was fabricated before the relative value of the E-alpha oriented structure was known and the plate probably had a structure tending toward the W-alpha type. Annealing at 1300°F did not improve the ballistic value of the plate.

## PART D

## CONCLUSIONS

8. a. Against Caliber .30 APM2 and Caliber .50 APM2 projectiles at 0° obliquity, the titanium plates tested, at an equiva-steel thickness from 0.350 to 0.370 inches, were superior in ballistic performances to homogeneous aircraft steel armor, equal to 24S-T4 aluminum alloy armor, and inferior to face hardened steel armor.

b. Against 20mm HE loaded and fuzed projectiles at 20° obliquity, the titanium plates tested, at an equivalent steel thickness from 0.350 to 0.360 inches, were inferior to homogeneous and face hardened steel armor. The overall shock properties were equal to those of 24S-T4 aluminum alloy armor in regard to protection afforded, but slightly inferior in regard to tendency to crack.

c. Titanium is suitable for use as an armor material insofar as ballistic properties are concerned but applications will depend upon reductions in the present high cost per pound of armor and upon the possibility of improving the present ballistic quality.

d. A metallurgical examination of one of the better titanium armor plates showed a characteristic equi-axed grain structure which also had a preferred crystal orientation developed in the process of rolling and annealing. The preferred orientation produces maximum hardness in a direction across the thickness of the plate and should help penetration resistance.

e. The oriented structure was less effective ballistically when the plate was finished in the maximum cold worked condition but subsequent experimental annealing restored some of the lost ballistic quality.

f. When the orientation was removed by transforming the structure at high temperature, the resultant structure was deficient in strength with indication of poorer ballistic quality.

Ballistic Test of 5/8" Titanium Armor Plates
and Metallurgical Examination of Plate 1R

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CONFIDENTIAL

NPG REPORT NO. 584

U. S. NAVAL PROVING GROUND
DAHLGREN, VIRGINIA

First Partial Report

on

Light Armor, Titanium

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Final Report

on

Ballistic Test of 5/8" Titanium Armor

Including Five Plates from the Remington

Arms Company and One Plate Forged by

the Naval Gun Factory from a duPont Ingot

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**Metallurgical Examination of Remington**

**Titanium Plate 1R**

Project No.: NPG-41-Re3a-128-1
Copy No: 15
No. of Pages: 20

Date: 17 JUL 1950

CONFIDENTIAL

NPG-39647 - [illegible] Remington Arms Co.,
after ballistic test.

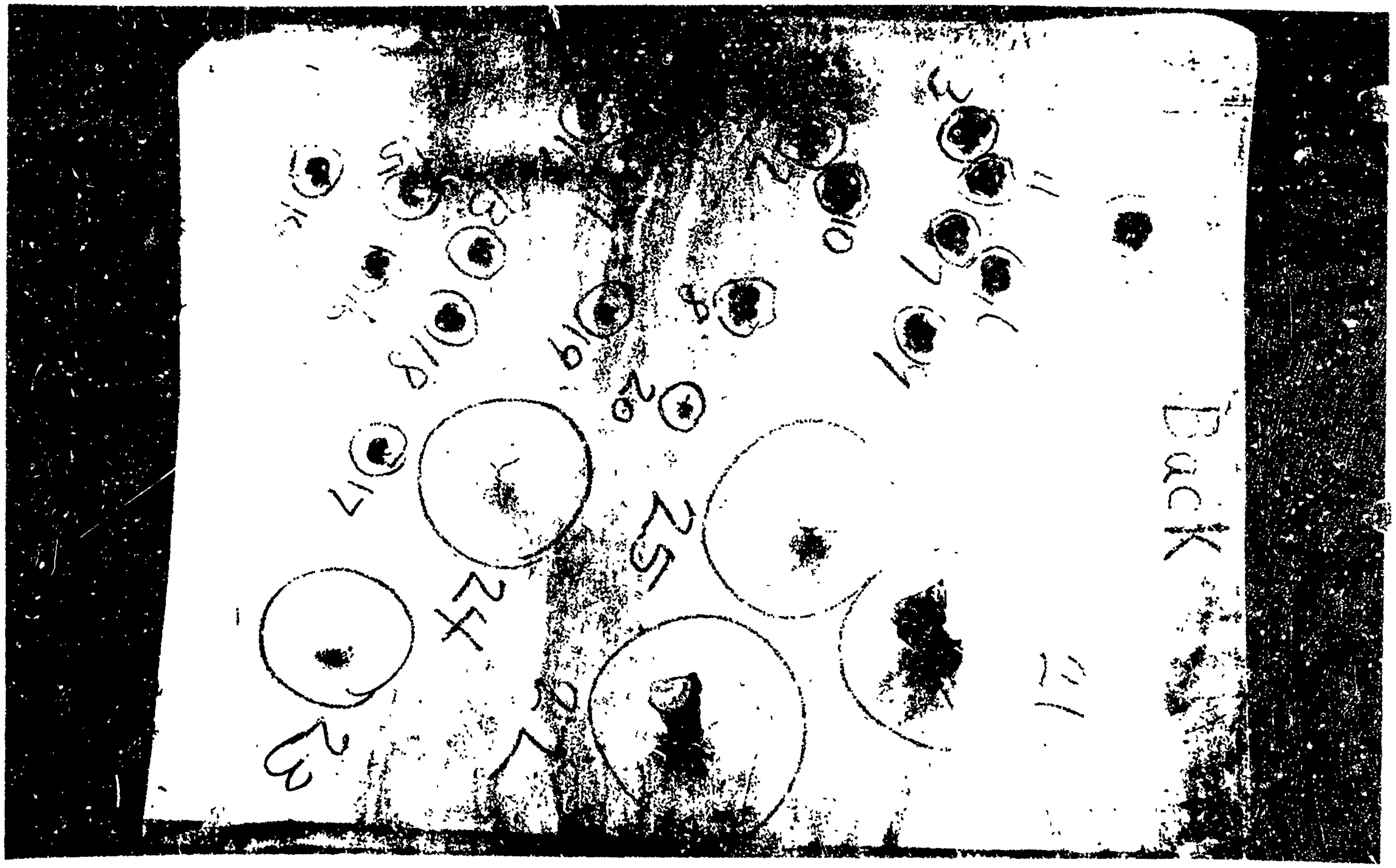
| Thickness | [illegible] | [illegible] | [illegible] | e'/t | [illegible] Limit | "V50" Limit | F(e'/d,θ) |
|---|---|---|---|---|---|---|---|
| 0.613 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1701 f/s | 66,000 |
| 0.613 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2212 f/s | [illegible] |
| 0.613 | [illegible] | [illegible] | [illegible] | --- | --- | 2394 f/s | --- |

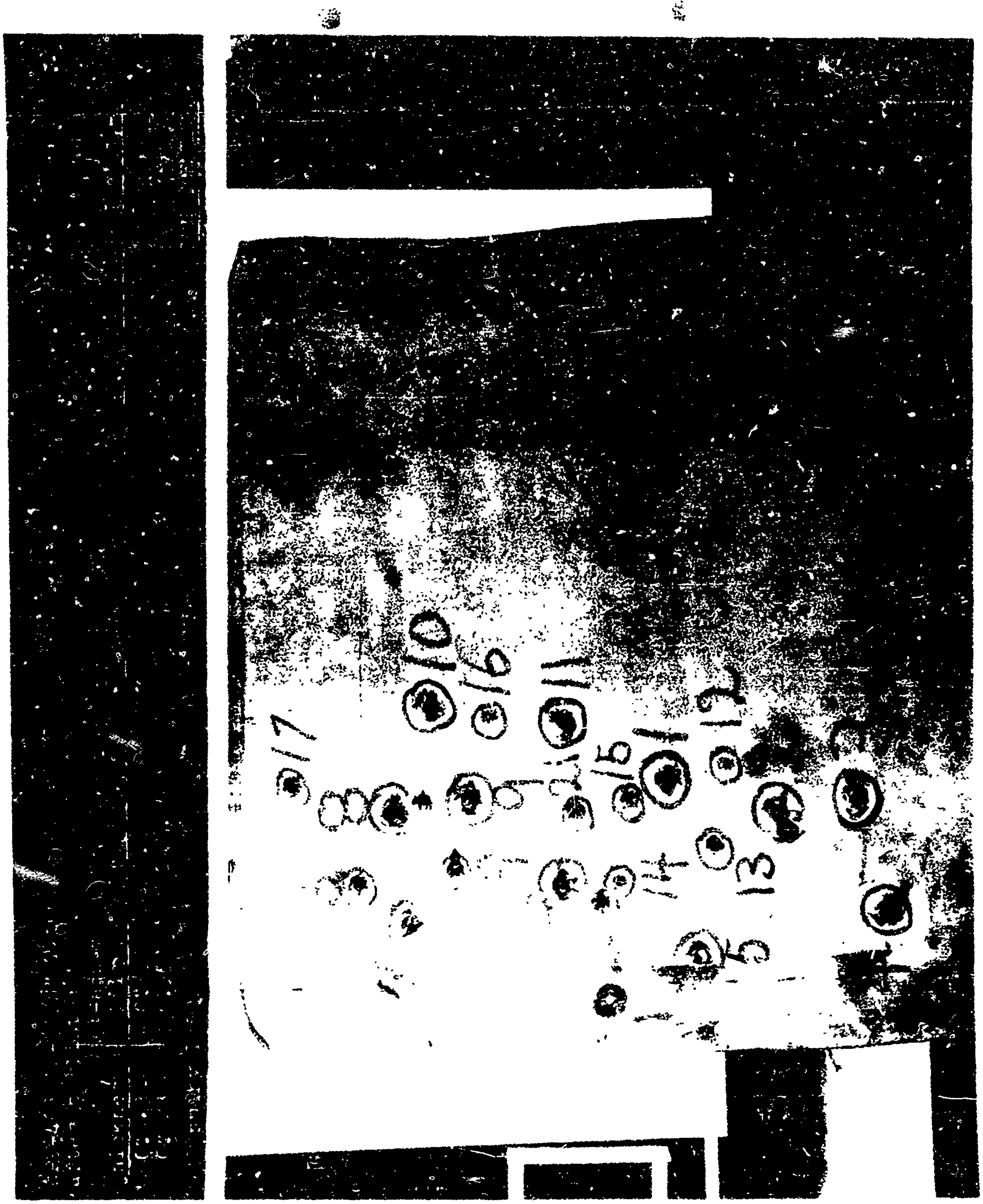
27 October 1949 Front View CONFIDENTIAL

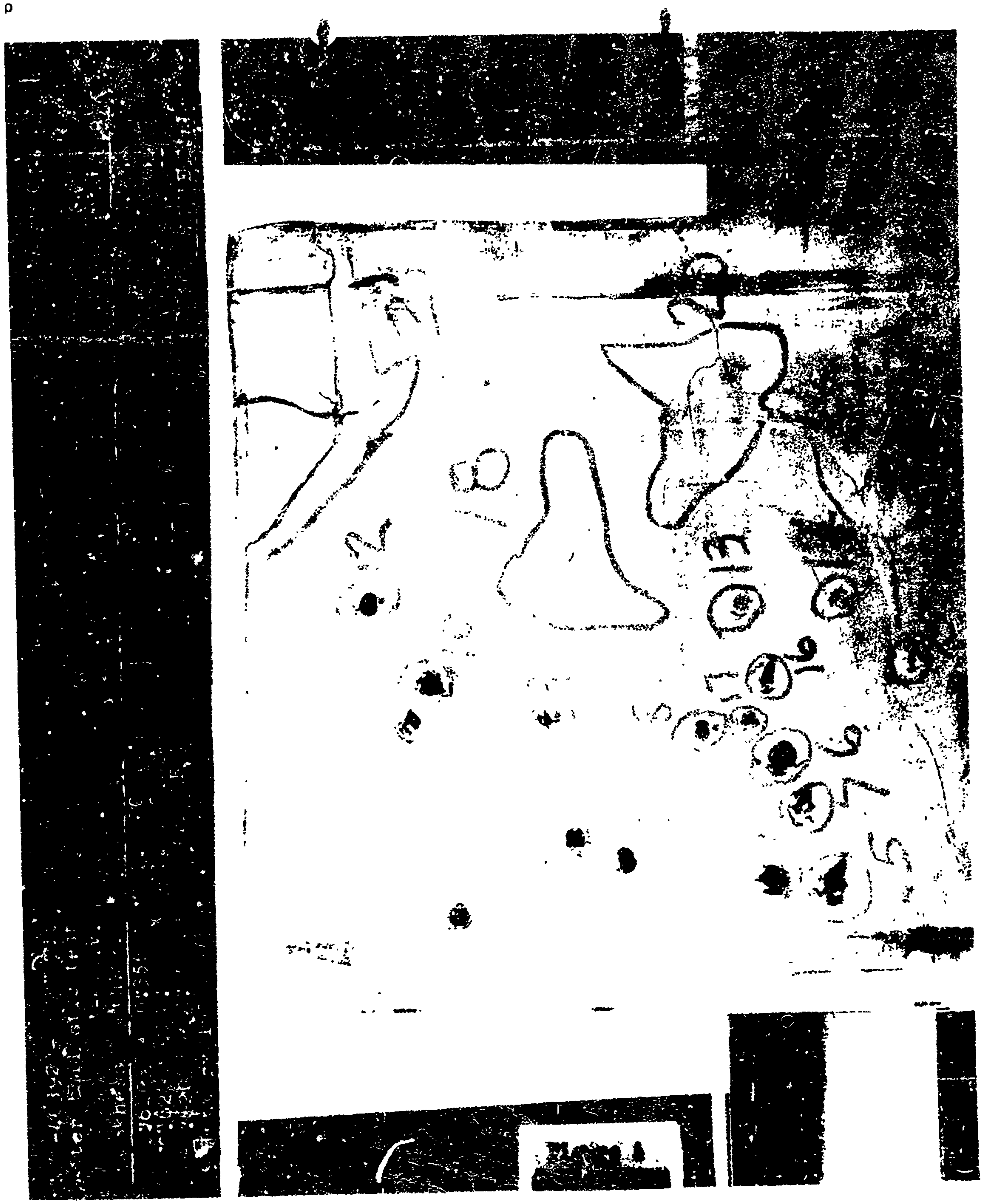
NPG-39648 - [illegible] (NPG [illegible]) [illegible] Remington Arms Co., after ballistic test.

| Thickness | e"-equiv. thick. | [illegible] | [illegible] | [illegible] | "VL" Limit | "Vp50" Limit | F(e"/d, θ) |
|---|---|---|---|---|---|---|---|
| C#013 | 0[illegible]52 | [illegible] | [illegible] | [illegible] | [illegible] f/s | 2701 f/s | [illegible]6,000 |
| C#013 | 0[illegible]52 | [illegible] | [illegible] | 1.[illegible] | [illegible] f/s | 2212 f/s | [illegible]6,600 |
| C#013 | 0[illegible]52 | [illegible] | [illegible] | [illegible] | -- | 2394 f/s | -- |

27 October 194[illegible] Back View CONFIDENTIAL







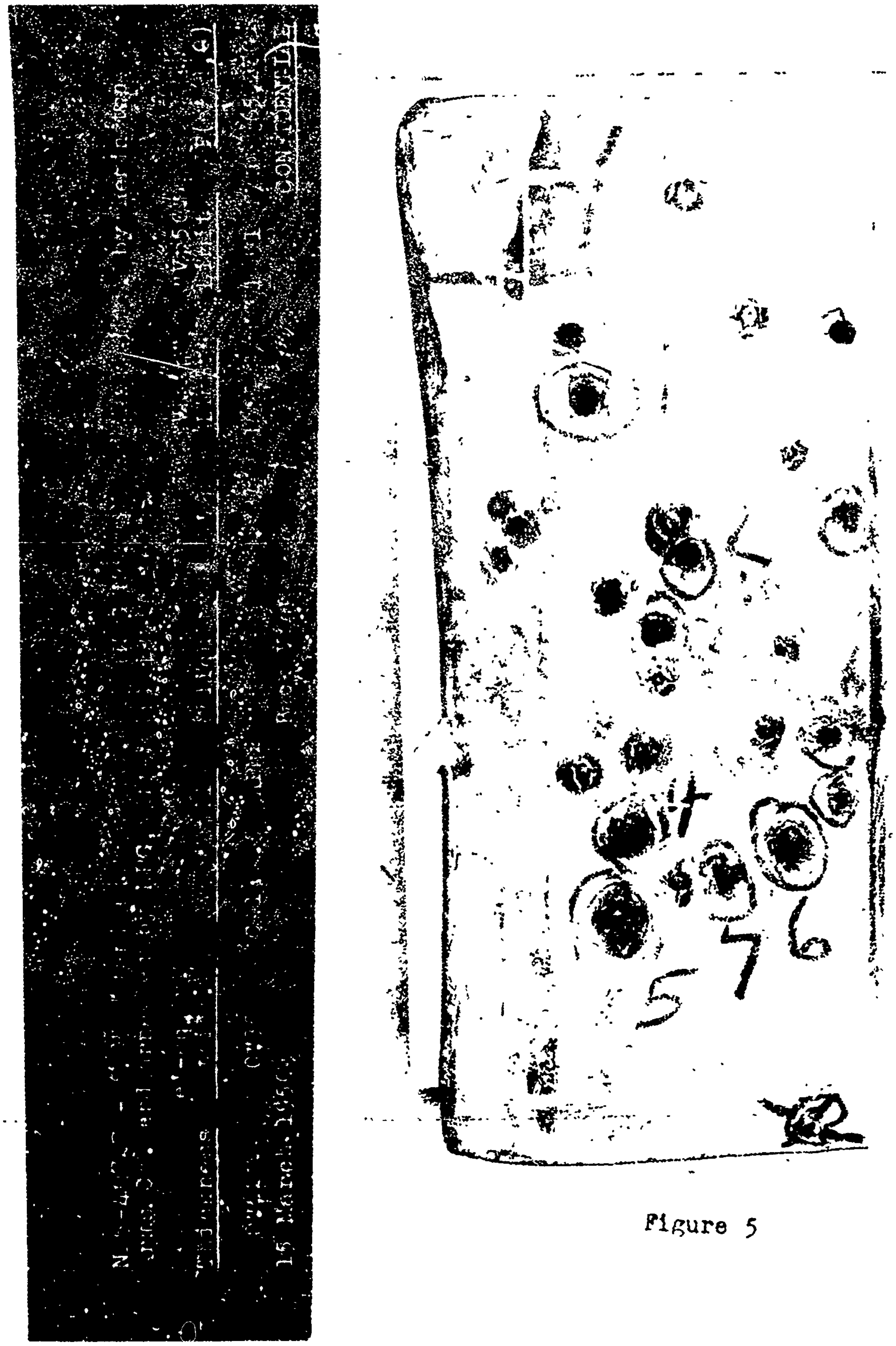
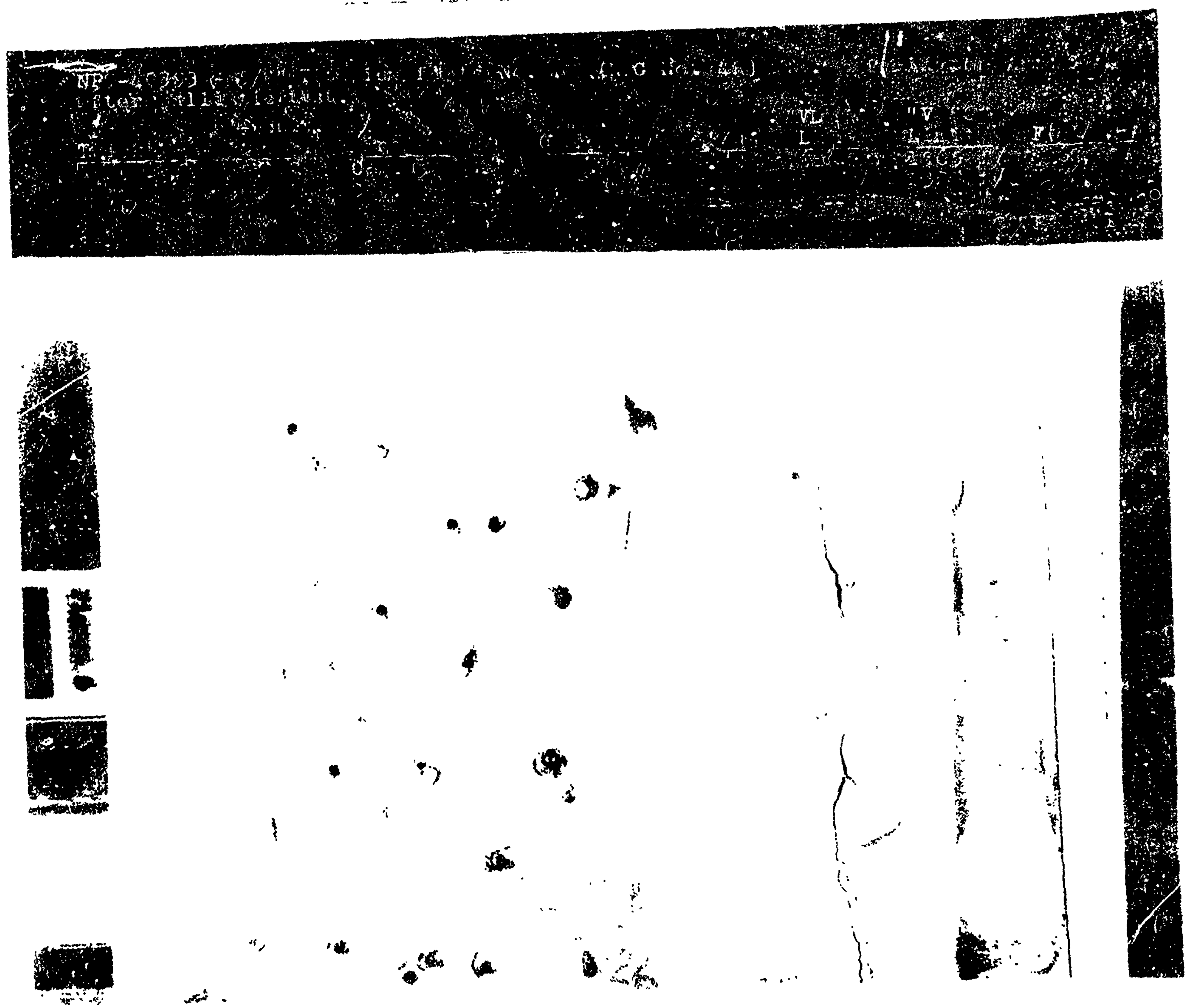


Figure 5



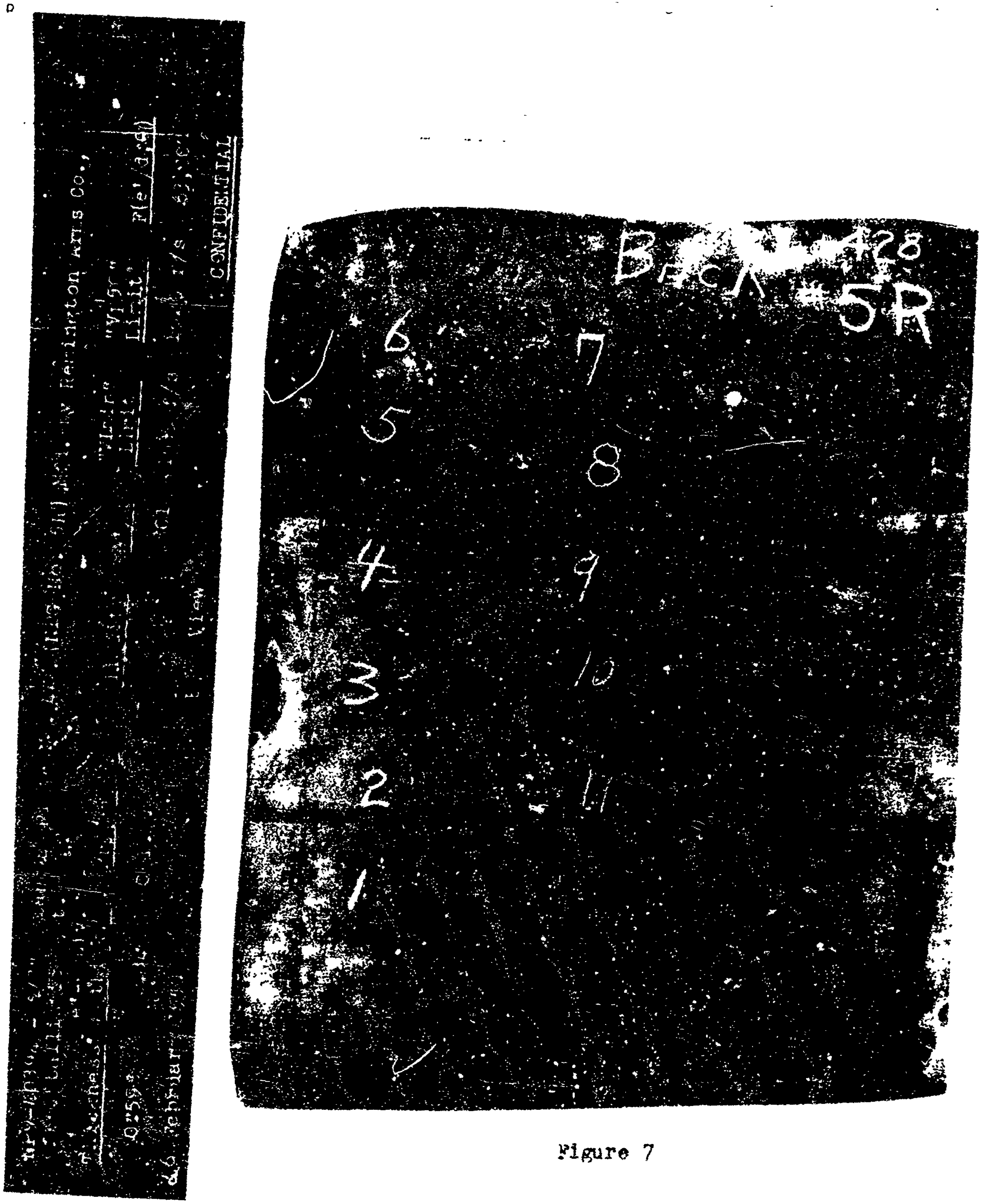



Figure 7

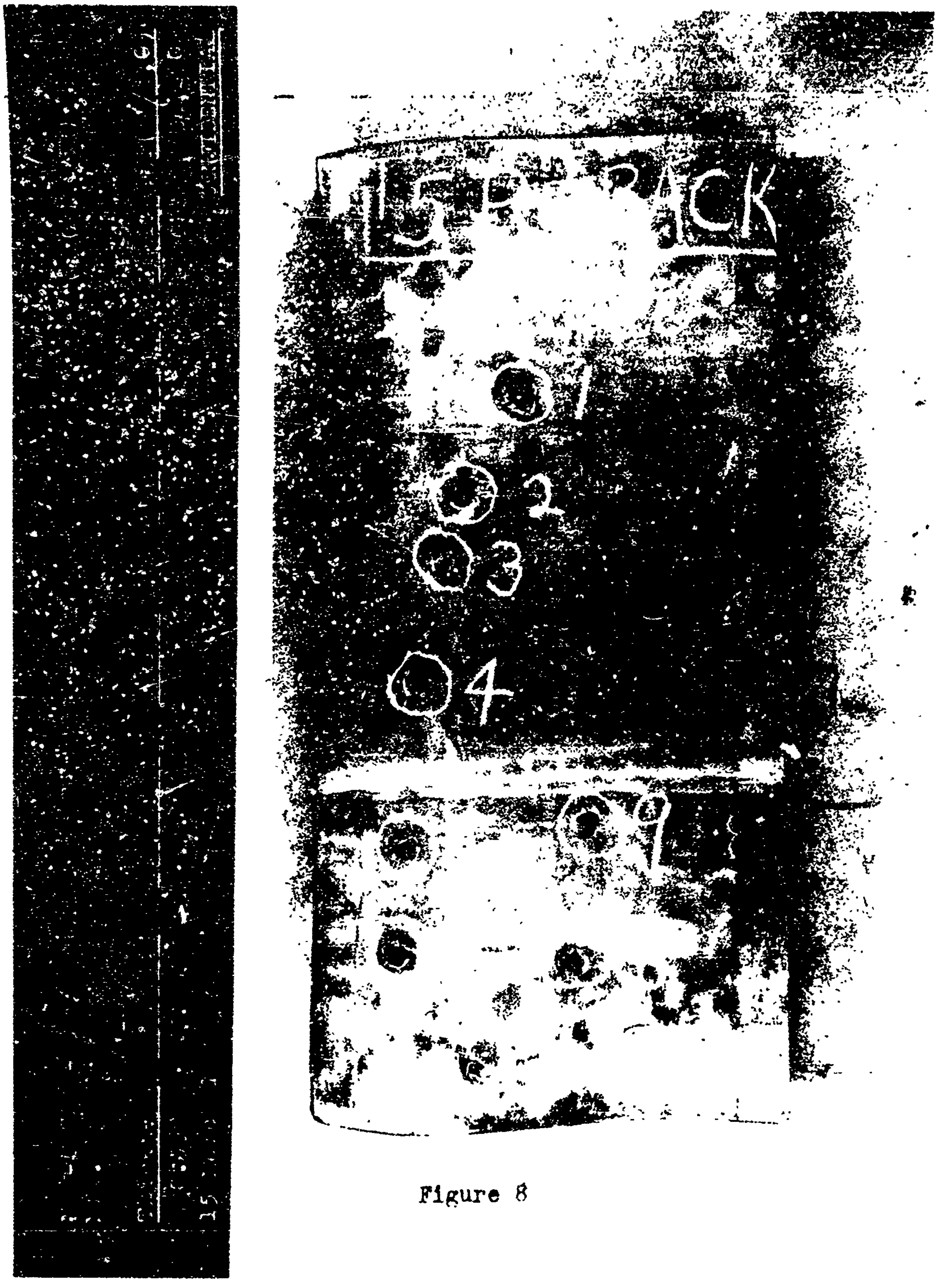


Figure 8

Figure 9

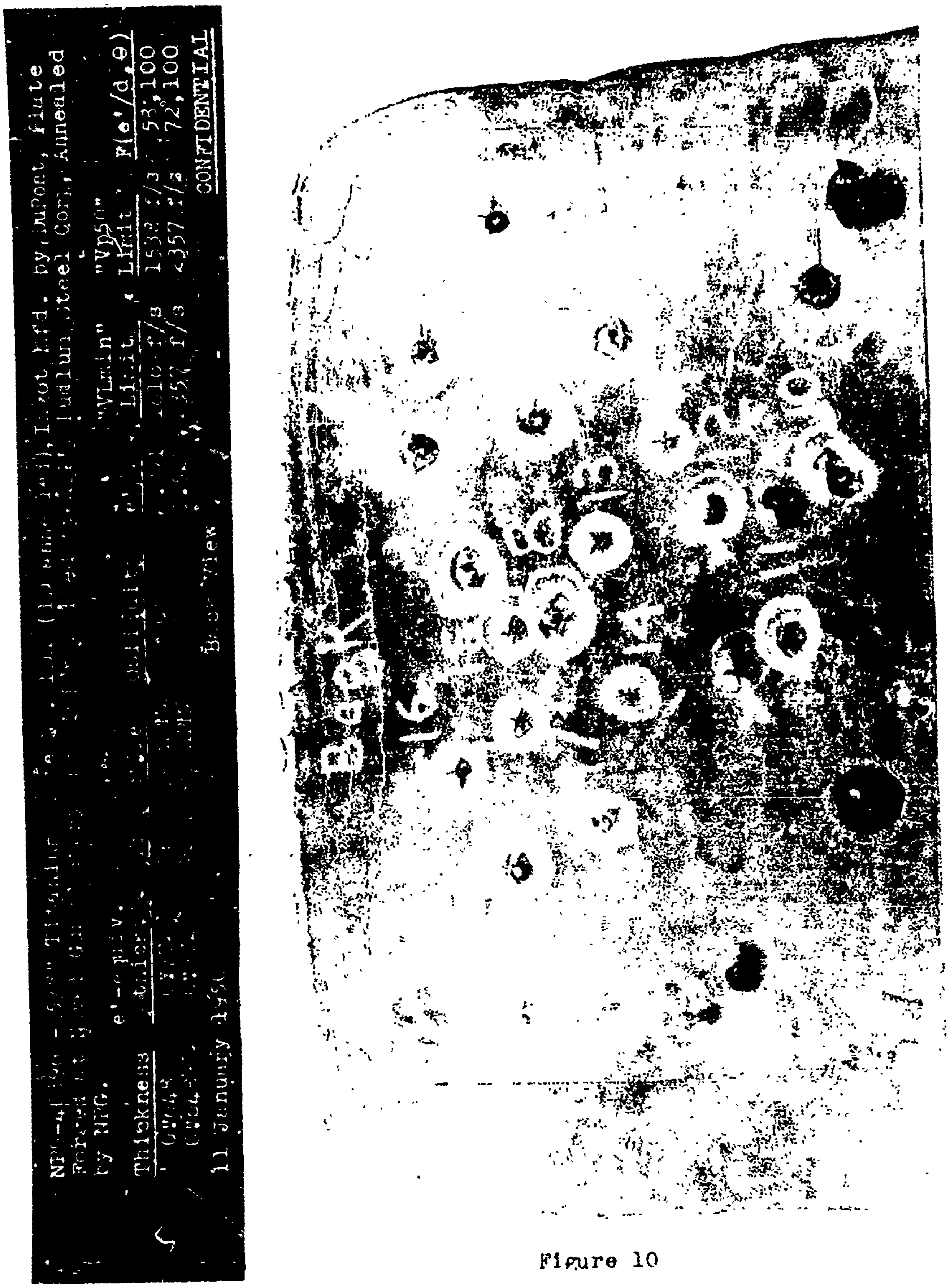

Ingot Mfd. by DuPont
Ludlum Steel Corp., Annealed
by NPG.
Thickness
Obliquity
"VLmin" Limit
1616 f/s
"Vp50" Limit
1532 f/s
<357 f/s
F(e'/d,θ)
53,100
72,100
CONFIDENTIAL
11 January
Back View
Back

Figure 10

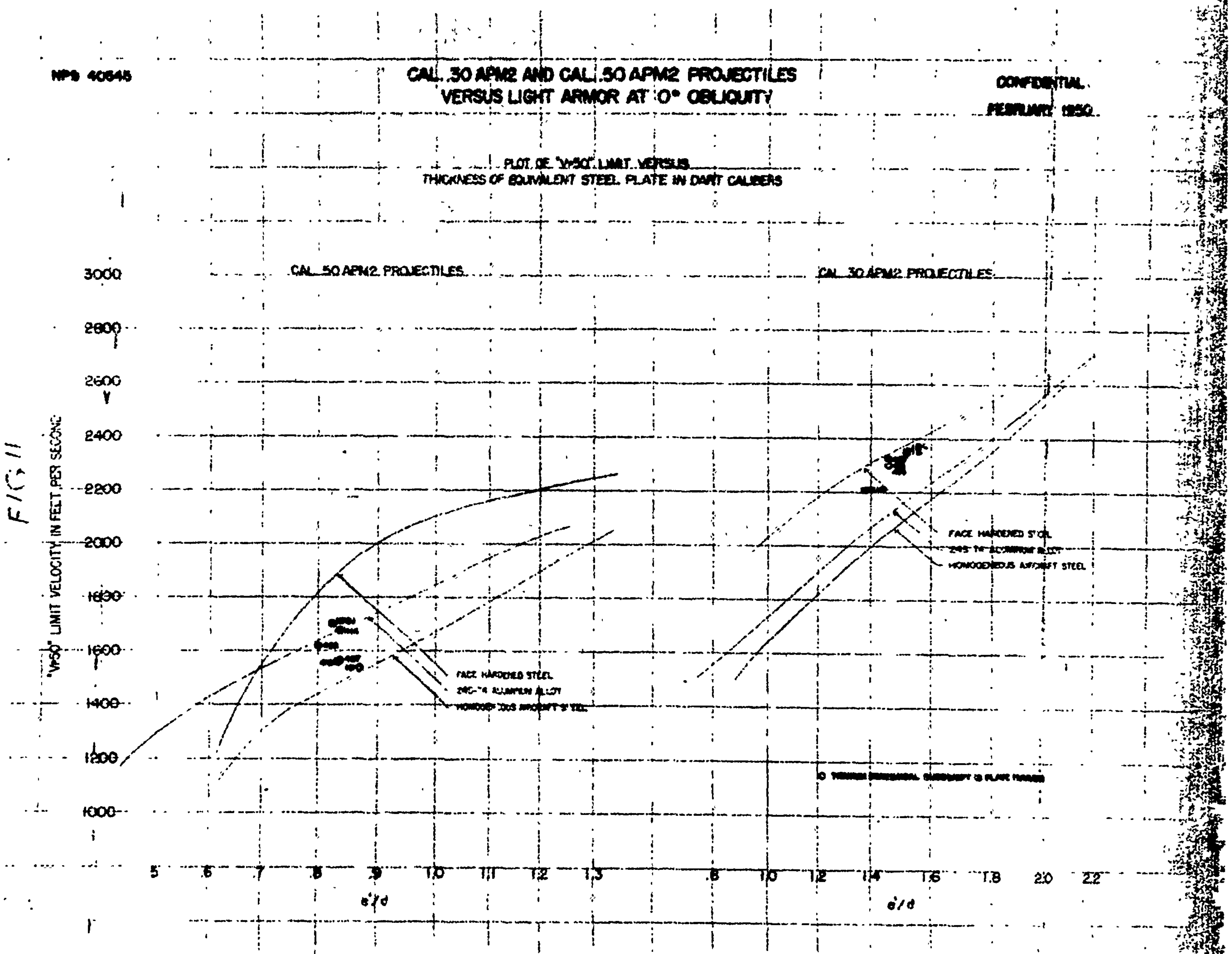
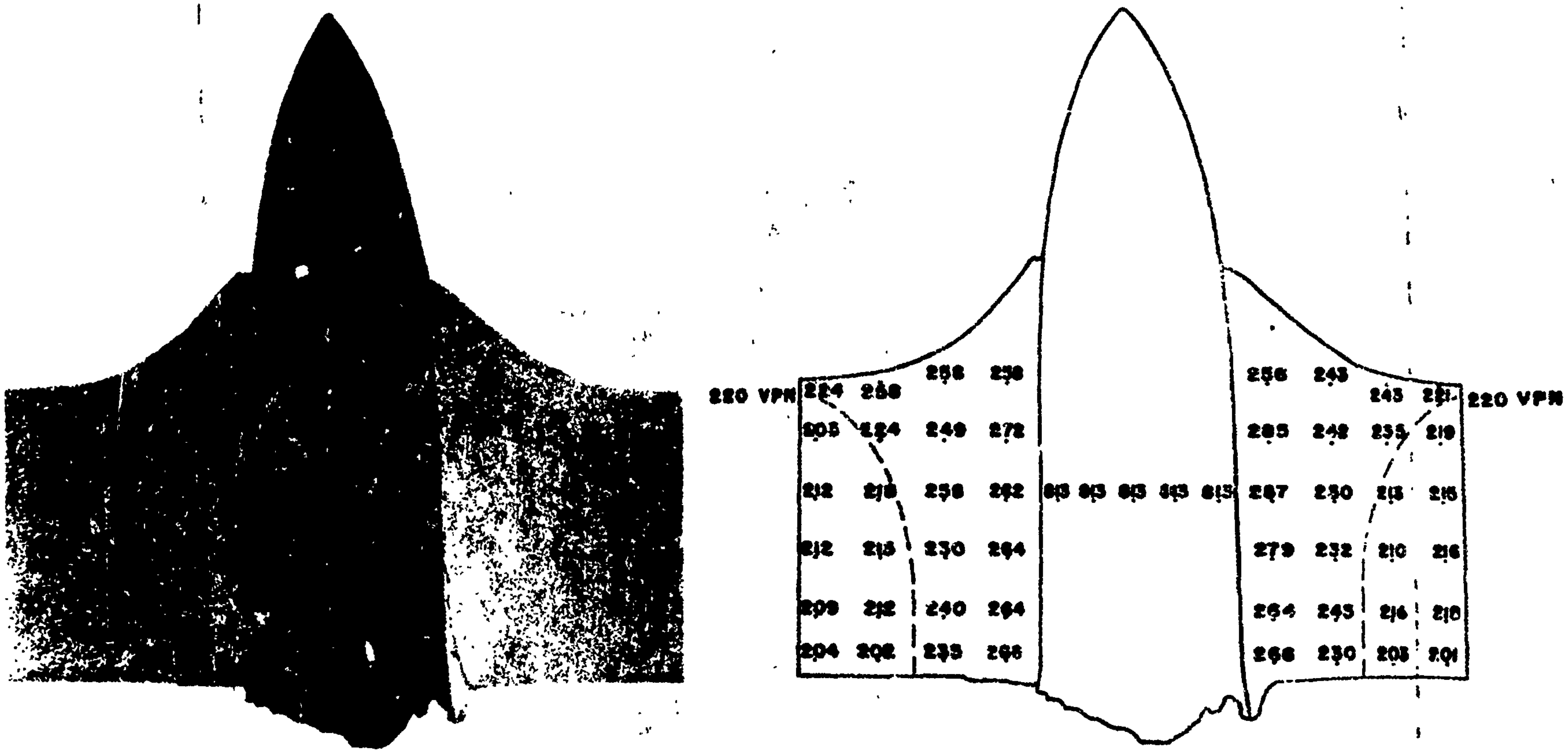

NPS 40645
CAL. .30 APM2 AND CAL. .50 APM2 PROJECTILES
VERSUS LIGHT ARMOR AT 0° OBLIQUITY
CONFIDENTIAL
FEBRUARY 1950
PLOT OF "V50" LIMIT VERSUS
THICKNESS OF EQUIVALENT STEEL PLATE IN DART CALIBERS
CAL. .50 APM2 PROJECTILES
CAL. .30 APM2 PROJECTILES
"V50" LIMIT VELOCITY IN FEET PER SECOND
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
FACE HARDENED STEEL
24S-T4 ALUMINUM ALLOY
HOMOGENEOUS AIRCRAFT STEEL
5
.6
.7
.8
.9
1.0
1.1
1.2
1.3
e'/d
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
e'/d
FIG 11

Fig. 11

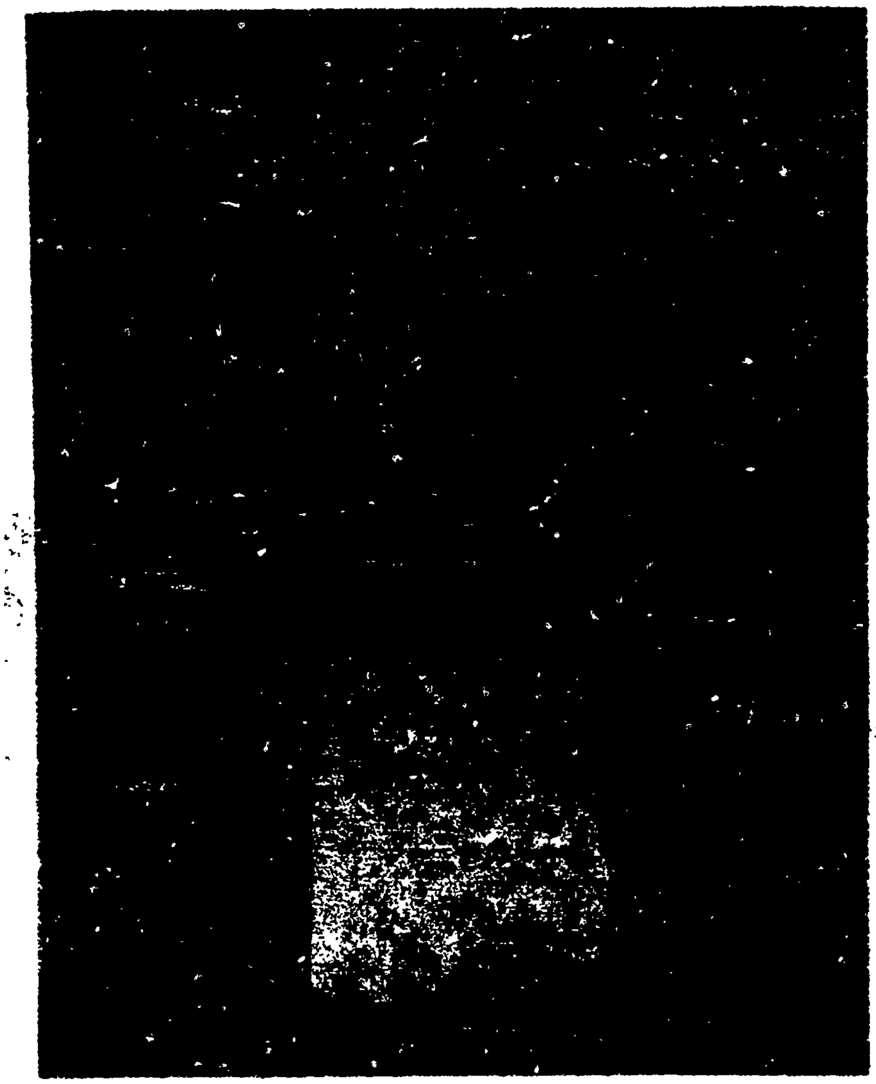



CROSS SECTION OF ROUND NO. 10, CAL. .50 APM2, STUCK IN PLATE, BASE OFF
HARDNESS PATTERN OF SURROUNDING ARMOR
REMINGTON NO. 1 TITANIUM ARMOR PLATE, 5/8" THICK
Hardness Values: Vickers Pyramid (10 kg)
Etch: HF, 1 Part; Glycerine, 1 Part
Magnification: 2X
Oblique Illumination

NPG 40082

CONFIDENTIAL

Figure 12



Etched Section Through Round No. 10, Cal. .50 APM2, Stuck in Plate, Base off

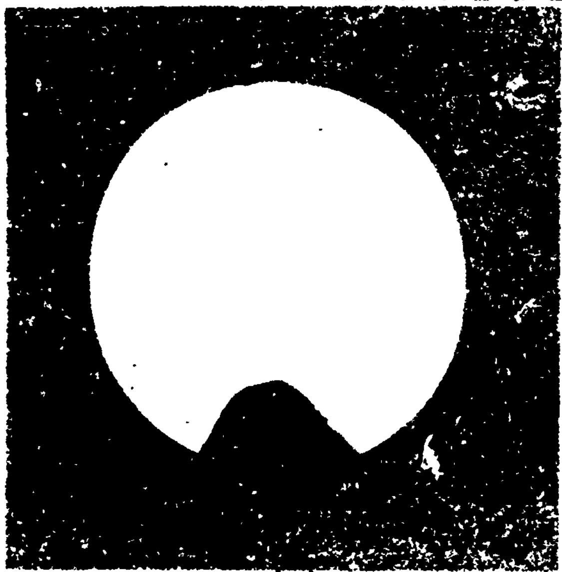
Remington No. 1 Titanium Armor Plate, 5/8" Thick.

Etch: - HF, 1 part; glycerine 1 part.
Magnification: 4X

The same field as in Figure 12 except taken with vertical illumination. The fine dark lines along the side of the projectile were paths of maximum shear stress which frequently were associated with the cracking shown by the heavier black lines.

NP9-40401

Ballistic Test of 5/8" Titanium Armor Plates
and Metallurgical Examination of Plate 1R



(a)

NP9-40601

Titanium Plate No. 1R

Section Through Base of Round No. 3, Cal. .50 APM2, Stuck in plate.

Etch: HF, 1 part; glycerine 1 part.
Magnification: 4X
Vertical illumination

The fine dark lines around the edge of the projectile are paths of maximum shear stress which follow an irregular pattern. Compare with a longitudinal view in Figure 13. The dark area in the core was bakelite filler used in mounting the specimen.

(b)

NP9-40602

Titanium Plate No. 1R

Section Through Hole Left by Round No. 14, Cal. .30 APM2, Complete Penetration

Magnification: 5X
Oblique illumination.

The hole is lined with a thin deposit of lead (gray areas) from the lead plug over the A.P. core.

Plastic
Titanium

(a)

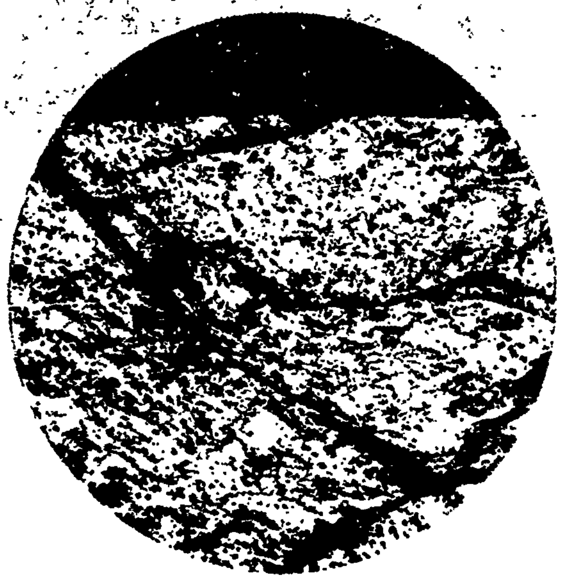
NP9-40617

Section of Edge of Round 5 Impact, Caliber .50 APM2, Showing Veining.

Magnification: 25X
Etch: 10%HF, 20%$HNO_3$ in water.

The irregular gray bands or veins in the titanium were paths of maximum shear stress formed during projectile penetration.

Plastic
Titanium



(b)

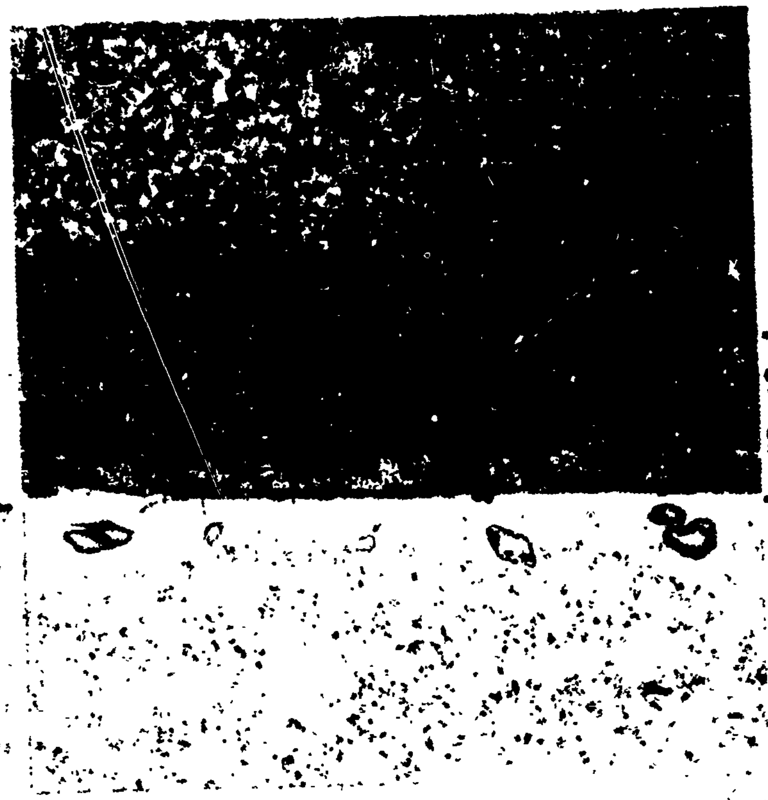
NP9-40618

Another Section at Edge of Round 5 Impact Showing Cracks and Veins.

Magnification: 25X
Etch: 10%HF, 20%$HNO_3$ in water.

Cracks developed in the veins where the shear stress exceeded the strength of the metal.

Photomicrographs Showing Typical Veining Which Developed in the Surrounding Titanium During Projectile Impact.
Titanium Plate 1R




Photomicrograph Showing Tempered Zone on Surface of Cal. .50 APM2 Dart Embedded in Remington No. 1 Titanium Armor Plate, 5/8" Thick. Dark Zone Indicates Tempering Resulting from Heat Generated During Entry of Dart into Plate. See Figure 17 for Hardness Tests in this Area.

Magnification: 1000X
Etch: Nital

NP9-40609

985 KHN

980 KHN

980 KHN

850 KHN

630 KHN

Cal. .50 APM2
Steel
Dart

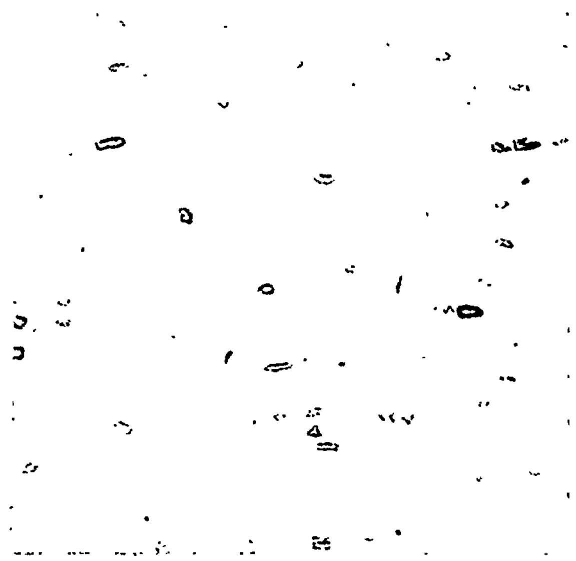
Titanium

Photomicrograph Showing Surface
Softening of Cal. .50 APM2 Dart
Embedded in Titanium Armor Plate.

Cross Section at Base of Round No. 3
Stuck in Remington No. 1 Titanium
Armor Plate, 5/8" Thick - Knoop
Hardness Indentations, 100 Gram Load.

Magnification: 500X
Etch: Nital

NP9-40610



(a)

NP9-40619

Center of Plate

Magnification: 100X

Unetched

Particles appear well dispersed and somewhat elongated in the direction of rolling.

(b)

NP9-40620

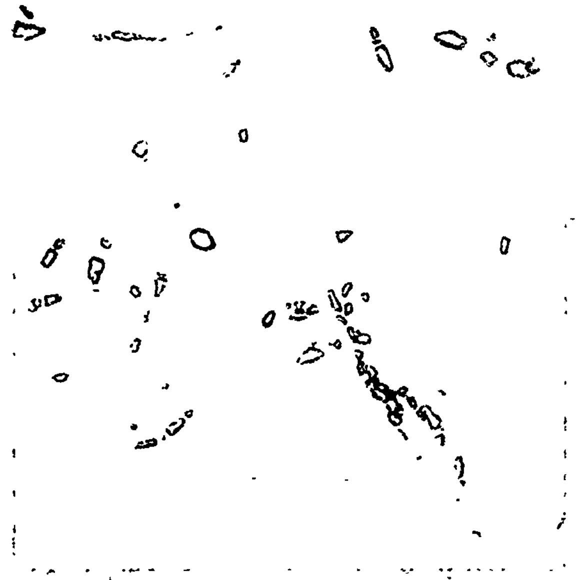
Corner of Plate

Magnification: 100X

Unetched.

Similar to (a) above.

Microstructures in Longitudinal Sections Showing
The Distribution of Titanium Carbide Particles.



(a)

NP9-40621

Center of Plate

Magnification: 100X

Unetched.

The carbide segregation parallel to the plate surface has not been broken up completely by rolling.

(b)

NP9-40622

Corner of Plate

Magnification: 100X

Unetched.

Similar to (a) above.

Microstructures of Sections Parallel to the Plate
Surface Showing the Distribution of Carbide Particles.
Titanium Plate 1R.

(a)

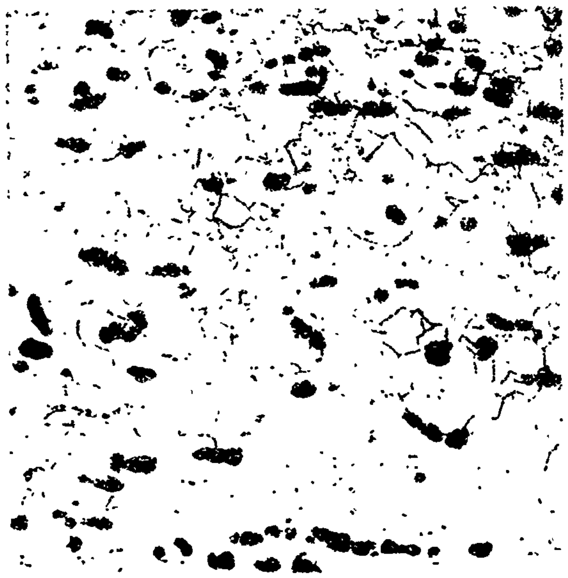
NP9-40623

Center of Plate

Magnification: 100X

Etch: 3% HF, 3% $HNO_3$, $H_2O$.

Equi-axed alpha titanium grains.
ASTM grain size #3.



(b)

NP9-40624

Corner of Plate

Magnification: 100X

Etch: 3% HF, 3% $HNO_3$, $H_2O$.

Equi-axed alpha titanium grains.
ASTM grain size: 30% #4, 70% #6.

Microstructures in Etched Longitudinal Sections
Showing Grain Structure.
Titanium Plate 1R

NP9-40626

Center of Plate

Magnification: 100X

Etch: 3% HF, 3% $HNO_3$, $H_2O$

Equi-axed alpha titanium grains.

(a)

NP9-40627

Corner of Plate

Magnification: 100X

Etch: 3% HF, 3% $HNO_3$, $H_2O$.

Equi-axed alpha titanium grains.

(b)

Grain Structure in Etched Sections Parallel to the Plate Surface.
Titanium Plate 1R

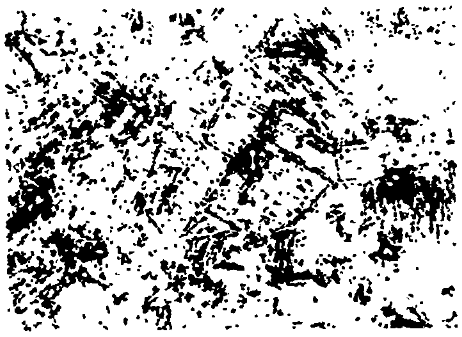
1600°F
[illegible] Transformed
D-4.52
$R_A$-57.4

1625°F
5% Transformed
D-4.52
$R_A$-58.4

1675°F
[illegible]% Transformed
D-4.52
$R_A$-60.9

1700°F
50% Transformed
D-4.52
$R_A$-37.3

1750°F
100% Transformed
D-4.52
$R_A$-57.7



1800°F
100% Transformed
D-4.52
$R_A$-58.1

ALPHA-BETA TRANSFORMATION IN TITANIUM PLATE IR

SAMPLES HELD 10 MINUTES AT INDICATED TEMPERATURES AND WATER QUENCHED

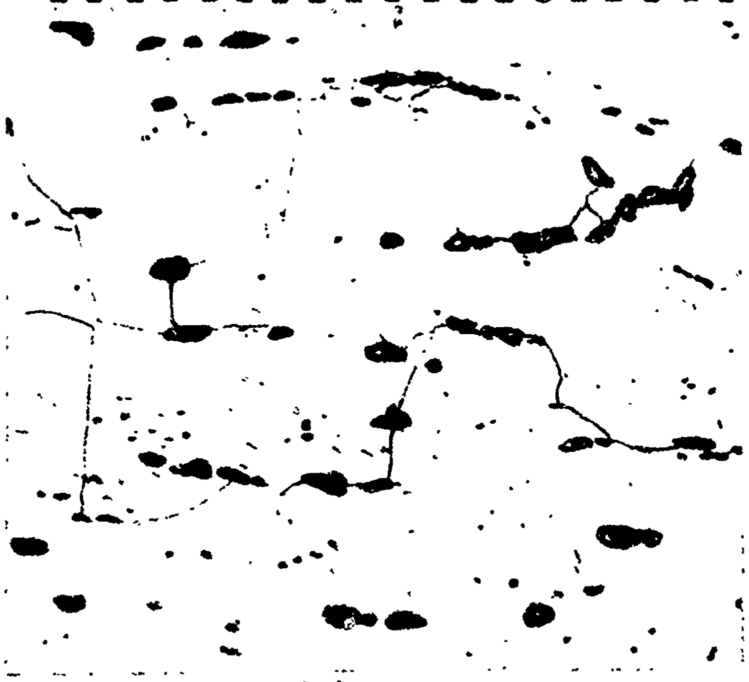
DENSITY AND ROCKWELL A HARDNESS SHOWN UNDER PHOTOMICROGRAPHS

MAGNIFICATION - 250X ETCH - "C" + "B"

NP9 40390

CONFIDENTIAL

FIGURE 22



(a)

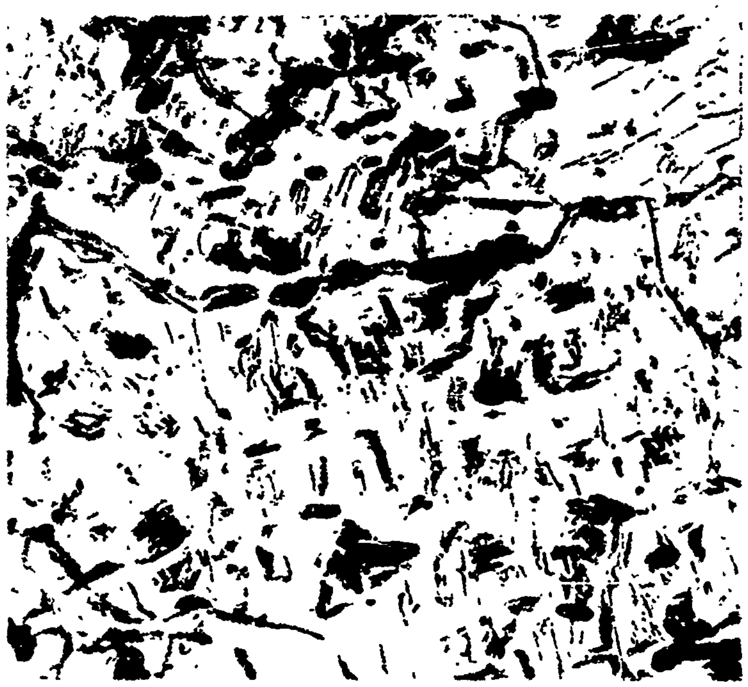
NP9-40629

Titanium Plate 1R
Material as received.

Magnification: 250X

Etch:

Equi-axed alpha grains.



(b)

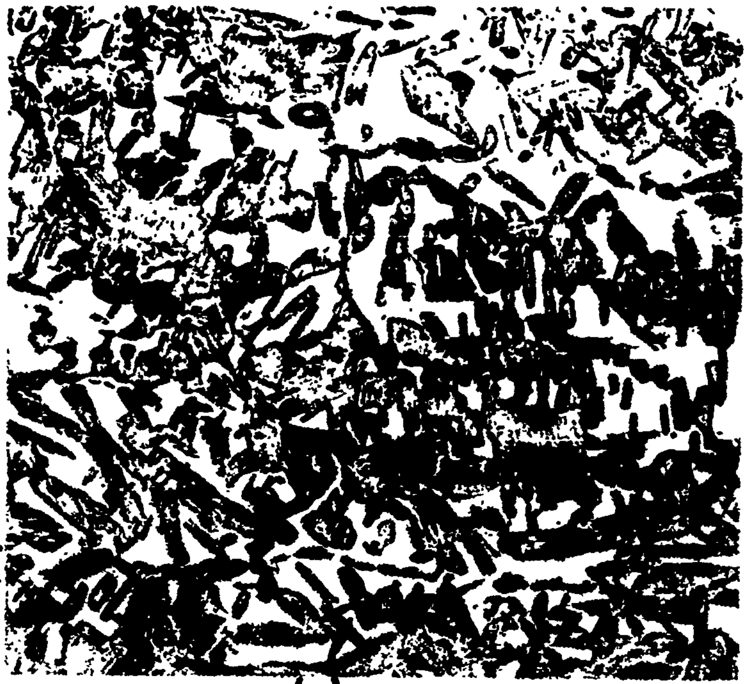
NP9-40630

Titanium Plate 1R
Sample heated to 1700°F for 12 minutes, air cooled.

Magnification: 250X

Etch: "B" solution.

The grain boundaries were from the original equi-axed alpha. The parallel structures within the grains were Widmanstätten alpha developed by heating in the transformation range.



(a)

NP9-40724

Titanium Plate 1R
Sample heated to 1700°F for 12 minutes and quenched in water.

Magnification: 250X

Etch: "B" solution.

The white areas were the original equi-axed alpha. The fine parallel structures were Widmanstätten alpha developed by rapid cooling from within the transformation range. See below.

(b)

NP9-40725

Same sample as in (a) above.

Magnification: 1000X

Etch: "C" and "B" solutions.

Details of the fine Widmanstätten structure were resolved at higher magnification.

(a)

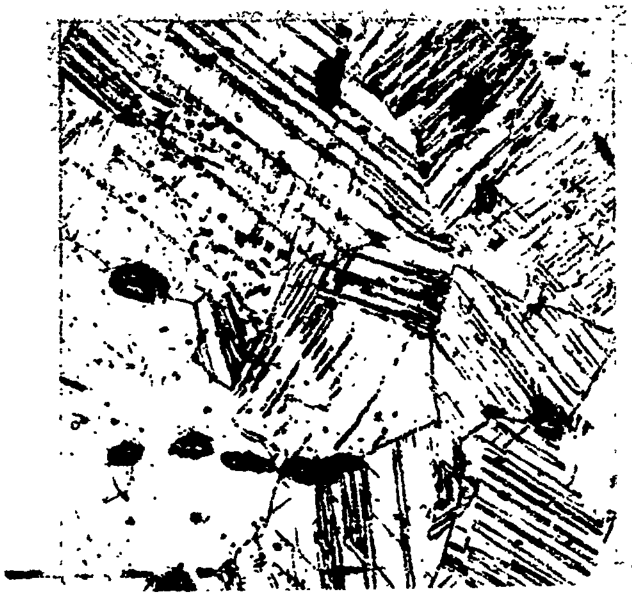
NP9-40726

Titanium Plate 1R
Sample heated to 1800°F for 10 minutes and cooled in air.

Magnification: 500X

Etch: "C" and "B" solutions.

A coarse Widmanstätten alpha structure developed by heating completely through the transformation range and air cooling. The original equi-axed grains disappeared entirely.



(b)

NP9-40760

Titanium Plate 1R

As received, sample near Round 5 Caliber .50 penetration.

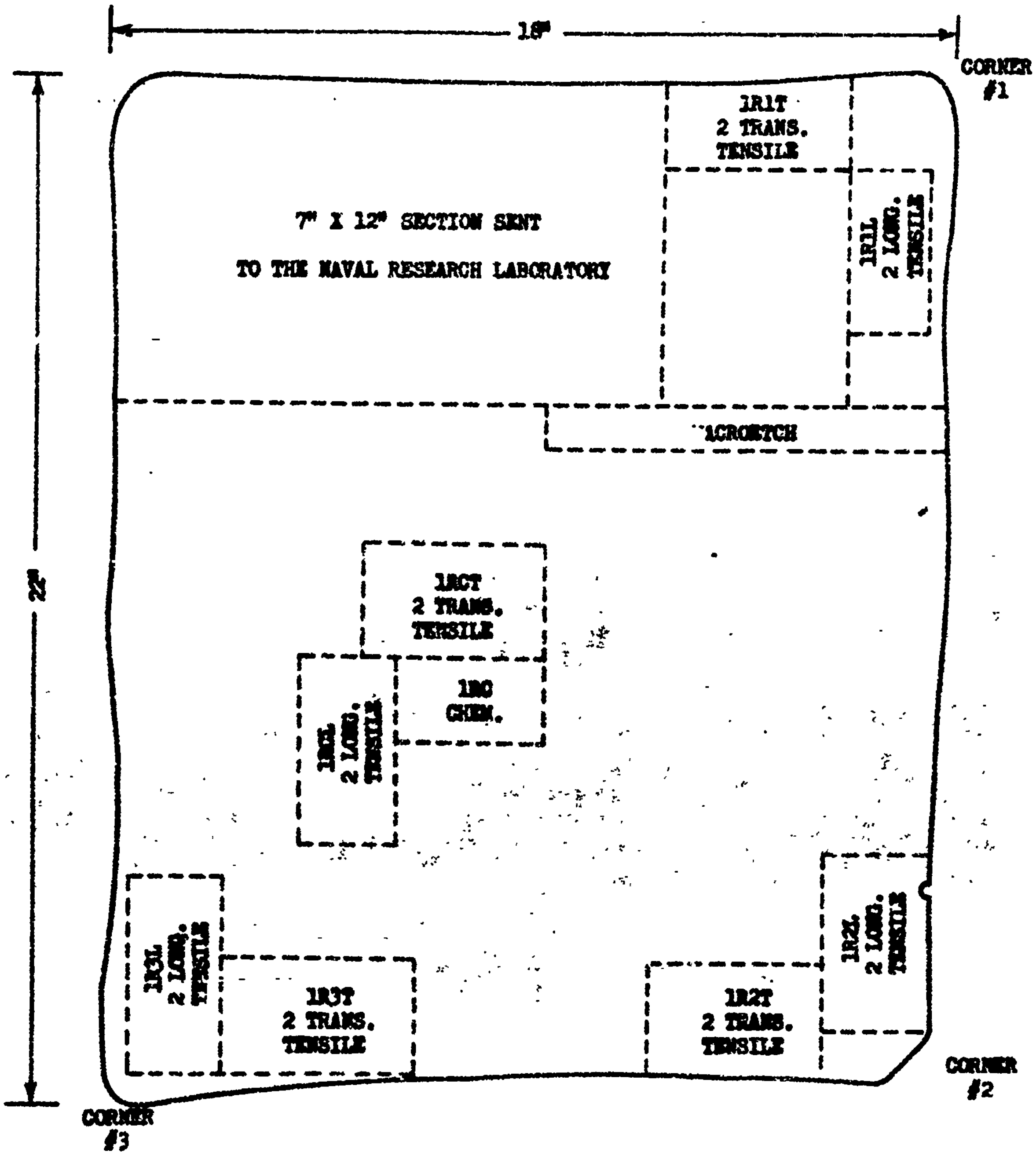
Magnification: 250X

Etch: "C" and "B" solutions.

Parallel lines represent twinning in equi-axed alpha grains caused by deformation of the metal during projectile penetration.



Figure 25




SKETCH OF REMINGTON TITANIUM PLATE NO. 1R, 5/8" THICK,

SHOWING LOCATION OF TEST SPECIMENS

*Other Samples Not Shown Were Taken in Clear Spaces Between Impacts or Along Edge.

Samples Cut the Long Way of the Plate were Marked "L"

Scale: 1" = 3"
Back View

NP9 40369

February 1950
CONFIDENTIAL

FIGURE 26

LONG. TRANS.

1 2 1 2

CORNER OF PLATE
(CODE 1R1)
MATERIAL AS RECEIVED

CENTER OF PLATE
(CODE 1RC)
MATERIAL AS RECEIVED

CORNER OF PLATE
(CODE 1R2)
HEAT TREATED AT NPG
1700°F FOR 12 MINS.
AIR COOL

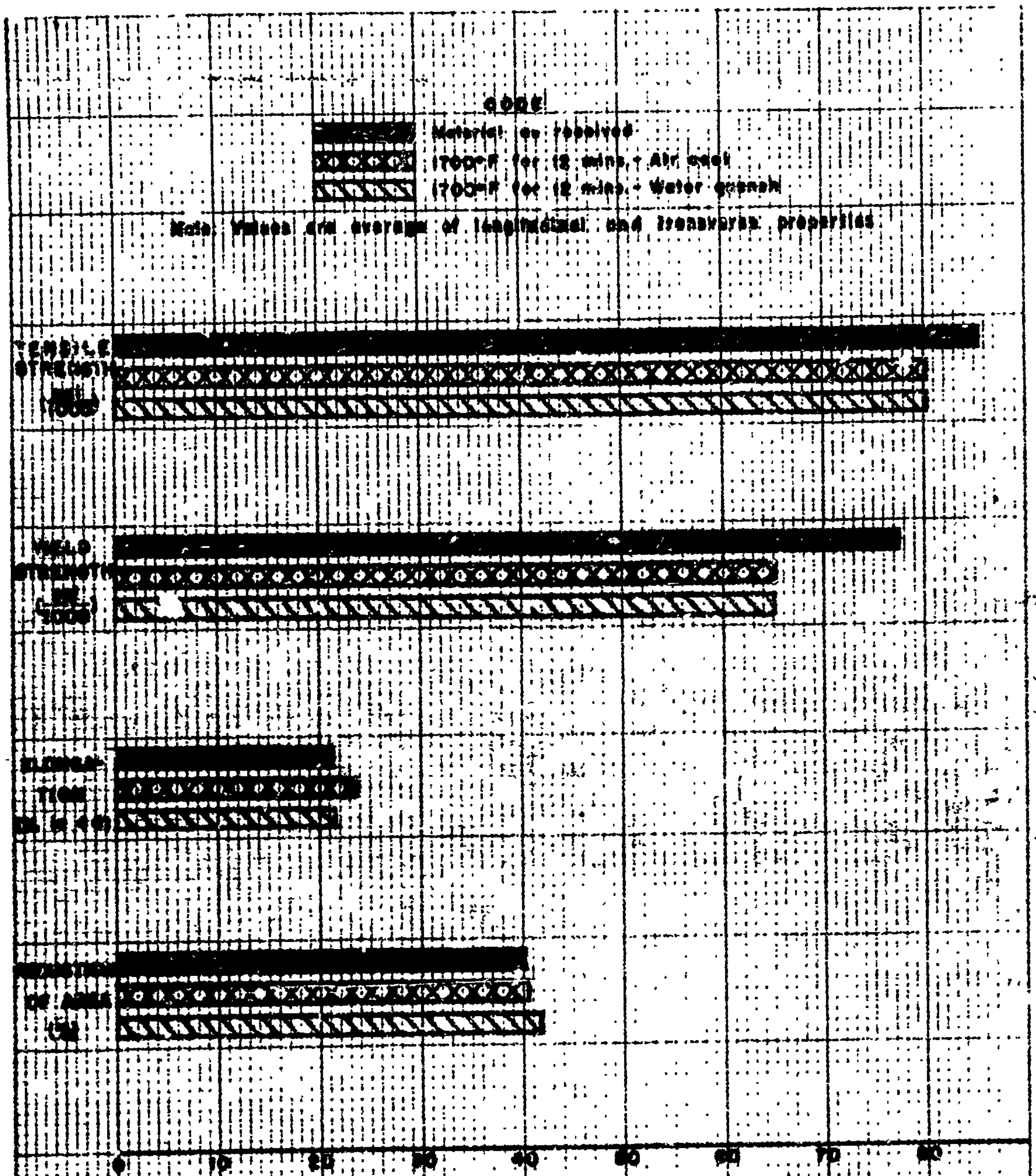
CORNER OF PLATE
(CODE 1R3)
HEAT TREATED AT NPG
1700°F FOR 12 MINS.
WATER QUENCH

BROKEN TENSILE TEST SPECIMENS SHOWING ELLIPTICAL
FRACTURE WITH MAJOR AXIS PERPENDICULAR TO SURFACE
OF PLATE
REMINGTON NO. 1 TITANIUM ARMOR PLATE, 5/8" THICK
SCALE: ACTUAL SIZE

NP9-40762

CONFIDENTIAL

Figure 27




EFFECT OF EXPERIMENTAL HEAT TREATMENT ON THE
TENSILE PROPERTIES OF TITANIUM ARMOR PLATE
No. 1R, 5/8" THICK

FIGURE 28

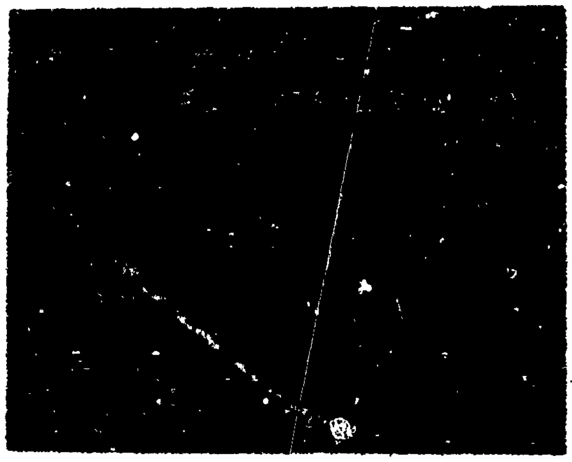
CONFIDENTIAL

NP9-40607

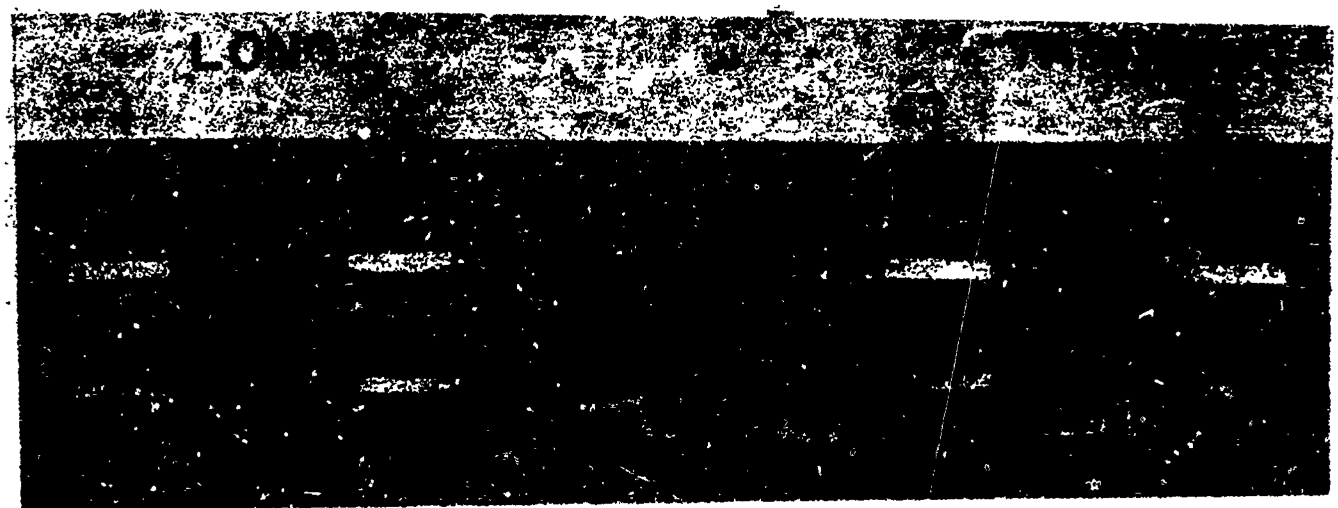
Titanium Plate No. 1R

Broken longitudinal tensile test specimen showing circular fracture after heating to 1800°F for 10 minutes and air cooling.

Scale: Actual size.



(a)

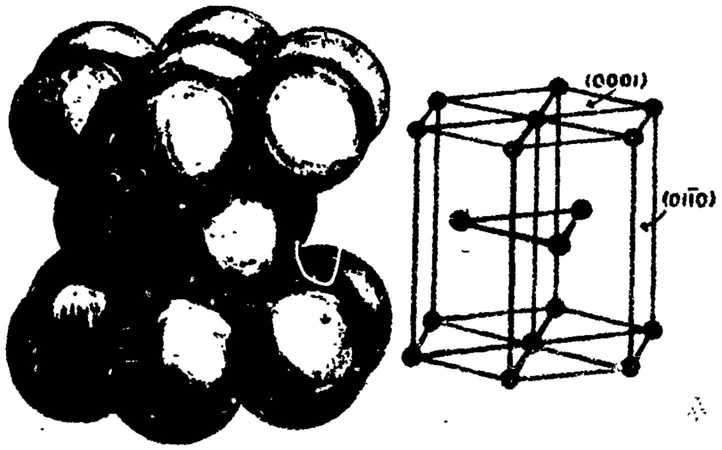


(b)
NP9-40608

Broken Charpy V-Notch Impact Test Specimens Showing Relatively Smooth Type of Fracture

Magnification: 1 1/2X

Remington No. 1 Titanium Armor Plate, 5/8" thick



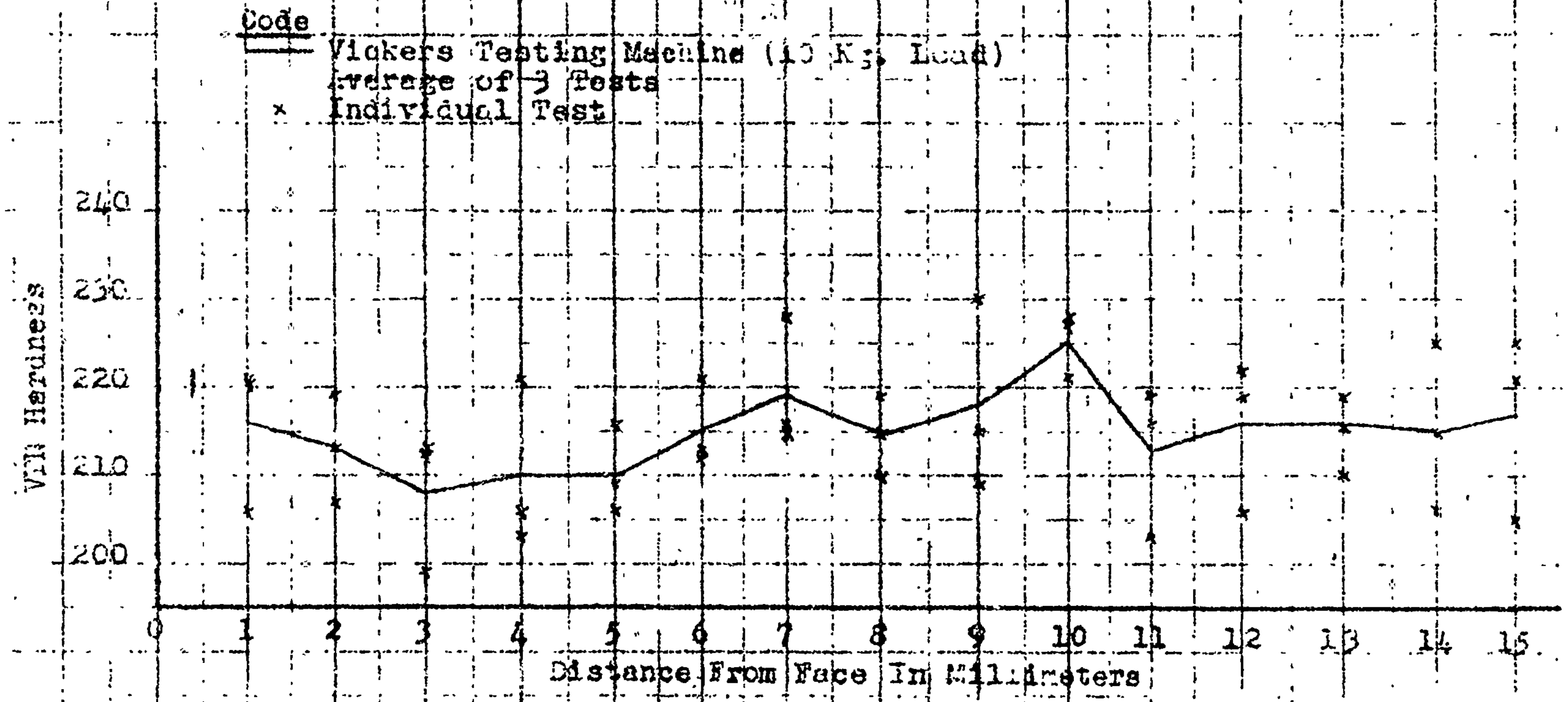

(from "The Structure of Metals
and Alloys" by Wm.Hume-Rothery)

Hexagonal Close-Packed Crystal Structure

Alpha titanium crystallizes in this type of structure.

The unit cell is represented by spheres(left) and a diagram (right).

NP9-40628



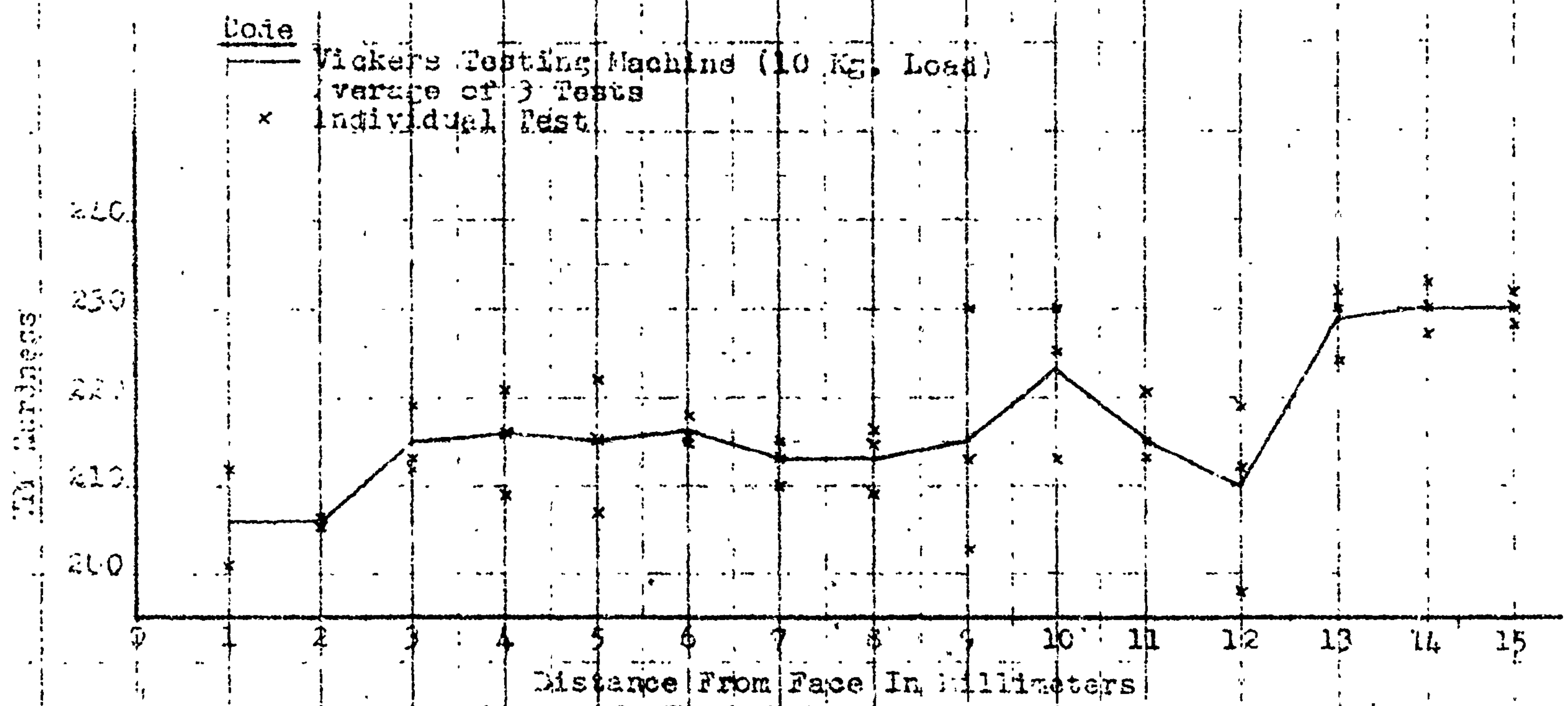

SERIES OF HARDNESS TESTS ACROSS LONGITUDINAL SECTION OF REMINGTON NO. 1 TITANIUM ARMOR PLATE, 5/8" THICK

Figure 11

NPG 40089

11 January 1950

CONFIDENTIAL

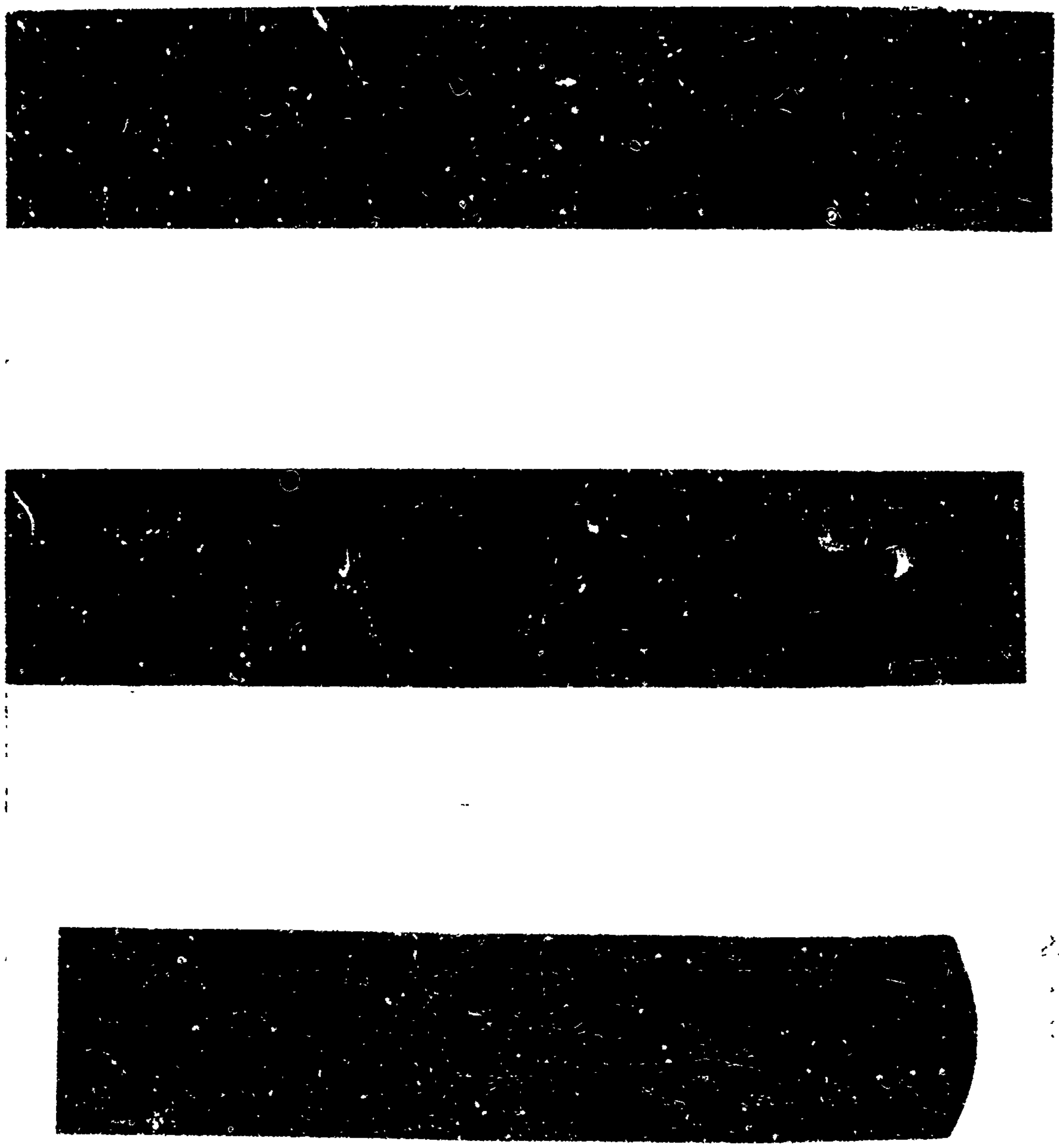



SERIES OF HARDNESS TESTS ACROSS TRANSVERSE SECTION
OF REMINGTON NO. 1 TITANIUM ARMOR PLATE, 5/8" THICK

11 January 1950

NF9 40090

Figure 32




Macroetched Sections Extending from Center to Edge.
Remington No. 1 Titanium Armor Plate, 5/8" Thick.
Etch: Boiling 50% HCL
Magnification: 2X
Streaks indicate slight segregation.

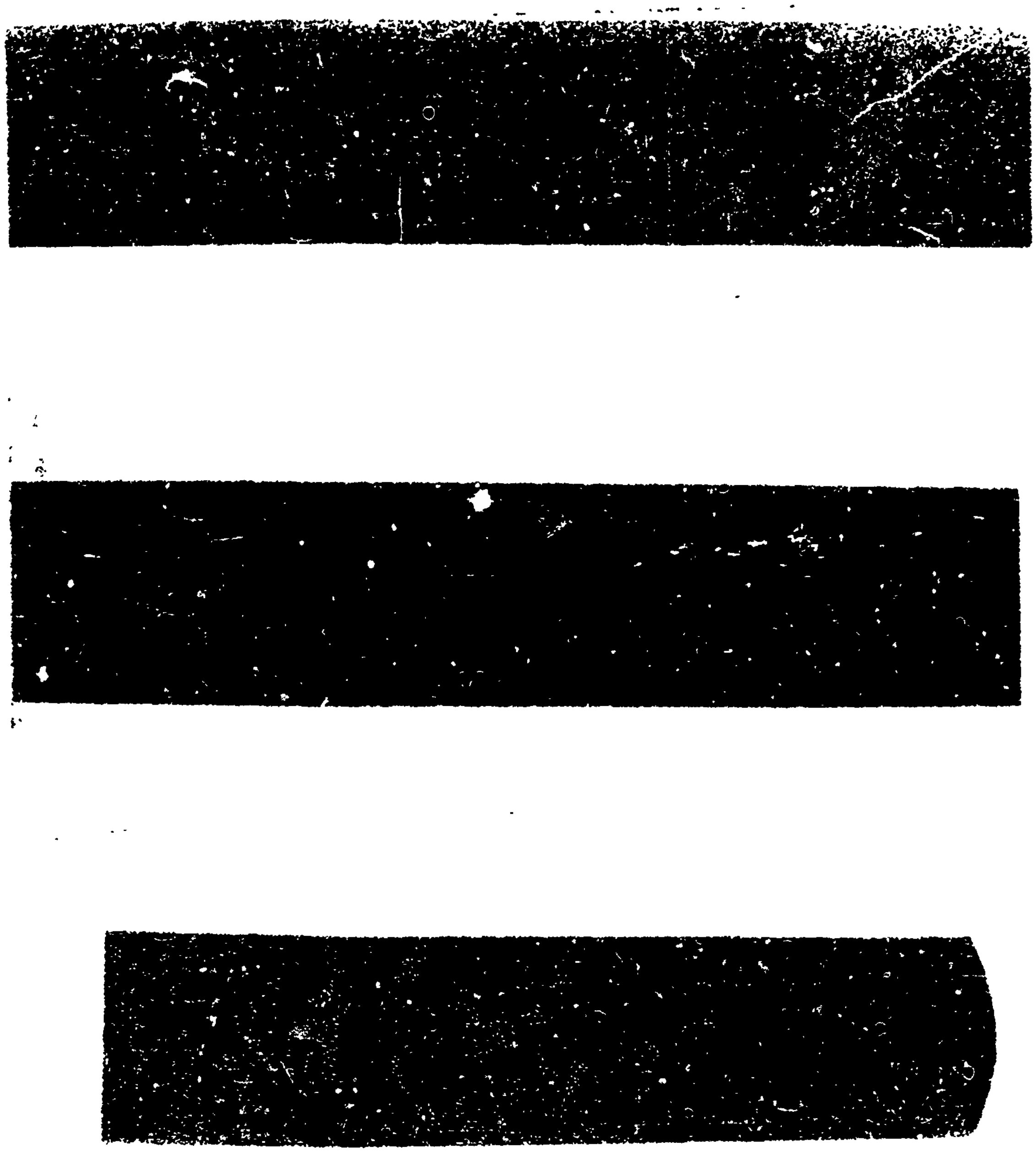
NP9-40615

Ballistic Test of 5/8" Titanium Armor Plates
and Metallurgical Examination of Plate 1R

Center I

II

II Edge



Macroetched Sections Extending from Center to Edge.

Remington No.-1 Titanium Armor Plate, 5/8" Thick.

Etch: 1.5% HF, 3% $HNO_3$, 95.5% $H_2O$.

Magnification: 2X

Same as Figure 21, etched to show grains.

NP9-40616

TABLE I

Summary of Ballistic Results

Cal. .50 APM2 - 0° Obliquity

| NPG No. | Mfrs. Plate No. | e | e' | e'/d | "Vpmin" limit ft/sec. | "Vp50" limit ft/sec. | F(e'/d,0)* | Remarks |
|---|---|---|---|---|---|---|---|---|
| 1R | 364 | .613 | .352 | .824 | 1709 | 1701 | 66,000 | Petals off some impacts. |
| 2R | 414 | .623 | .358 | .838 | 1685 | 1678 | 64,600 | Slight spall or petals out most impacts. |
| 3R | 415 | .620 | .356 | .834 | 1598 | 1561 | 60,200 | 1-1/4" back spall, 3 impacts. |
| 3R Annealed | 415 | .620 | .356 | .834 | 1655 | 1691 | 65,200 | Petals off some impacts. |
| 4R | 407 | .622 | .357 | .836 | 1646 | 1565 | 60,400 | 1" spall some impacts. |
| 4R Annealed | 407 | .622 | .357 | .836 | 1642 | 1630 | 62,800 | Slight spall, petals out. |
| 5R (a) | 428 | .598 | .344 | .801 | 1633 | 1620 | 63,800 | Petals out some impacts. |
| (b) | 428 | .598 | .344 | .801 | 1611 | 1650 | 64,200 | Duplicate test. |
| 1D | --- | .648 | .372 | .871 | 1641 | 1538 | 58,100 | 1-1/4" back spall 4 impacts. |
| 1D Annealed | --- | .648 | .372 | .871 | 1616 | 1538 | 58,100 | Large Spall some impacts. |

Cal. .30 APM2 - 0° Obliquity

| NPG No. | Mfrs. Plate No. | e | e' | e'/d | "Vpmin" limit ft/sec. | "Vp50" limit ft/sec. | F(e'/d,0)* | Remarks |
|---|---|---|---|---|---|---|---|---|
| 1R | 364 | .613 | .352 | 1.44 | 2212 | 2212 | 69,600 | Petals off some impacts. |
| 2R | 414 | .623 | .358 | 1.46 | 2294 | 2303 | 72,000 | Petals on, generally. |
| 3R | 415 | .620 | .356 | 1.46 | 2316 | 2316 | 72,300 | 3/4" spall most impacts. |
| 4R | 407 | .622 | .357 | 1.46 | 2328 | 2328 | 72,800 | 3/4" spall some impacts. |
| 4R Annealed | 407 | .622 | .357 | 1.46 | 2274 | 2279 | 71,200 | Slight spall. |
| 1D | --- | .648 | .372 | 1.52 | 2357 | 2349 | 71,900 | 5/8" spall most impacts. |
| 1D Annealed | --- | .648 | .372 | 1.52 | 2357 | 2357 | 72,100 | Spall most impacts. |

* Calculated from Vp50 limit.

TABLE I (Cont'd)

| NPG No. | Mfrs. Plate No. | e' | "Vpmin" Limit ft/sec. | Remarks |
|---|---|---|---|---|
| | | 20MM HE Mk3, Mk26-0 Fuze - 20° Obliquity | | |
| 1R | 364 | .352 | 2384 | |
| 2R | 414 | .358 | Not Tested | |
| 3R | 415 | .356 | 2295 | Thru cracks. |
| 4R | 407 | .357 | "2325" | Long thru directional cracks. |
| 1D | --- | .372 | Not Tested | |

## TABLE II

## CHEMICAL ANALYSIS OF TITANIUM PLATE NO. 1R

| Location of Sample | Carbon % | Nitrogen % | Iron % | Density g/cc. |
|---|---|---|---|---|
| Center of plate, face side. | 0.48 | 0.02 | 0.12 | 4.51 |
| Center of plate, back side. | 0.64 | 0.02 | 0.13 | 4.51 |
| Corner #1 of plate, face side. | 0.47 | ---- | 0.14 | ---- |
| Corner #1 of plate, back side. | 0.42 | ---- | 0.13 | ---- |

Spectrographic tests showed that small amounts of aluminum, calcium, copper, magnesium, manganese and silicon also were present.

## TABLE III

### TENSILE PROPERTIES OF TITANIUM ARMOR PLATE NO. 1R, 5/8" THICK

### REMINGTON ARMS CO. - MATERIAL AS RECEIVED

| Identification | Test Direction | Specimen Number | Tensile Strength (psi) | Yield Strength (psi at .2%) | Elongation in 4D (%) | Reduction of Area (%) | Reduction of Diameter (%) Major Axis | Reduction of Diameter (%) Minor Axis |
|---|---|---|---|---|---|---|---|---|
| CORNER OF PLATE (CODE 1R1) | Long. | 1 | 77,400 | 68,000 | 20.0 | 43.2 | 9.5 | 37.3 |
| | | 2 | 77,600 | 67,300 | 23.6 | 42.5 | 10.1 | 36.2 |
| | | Ave. | 77,500 | 67,600 | 21.8 | 42.9 | 9.8 | 36.7 |
| | Trans. | 1 | 84,500 | 75,400 | 23.6 | 43.9 | 11.5 | 36.7 |
| | | 2 | 87,000 | 80,700 | 21.4 | 45.1 | 11.8 | 37.8 |
| | | Ave. | 85,800 | 78,000 | 22.5 | 44.5 | 11.6 | 37.2 |
| | Long. & Trans. | Ave. | 81,650 | 72,800 | 22.1 | 43.7 | 10.7 | 37.0 |
| CENTER OF PLATE (CODE 1RC) | Long. | 1 | 84,100 | 76,300 | 20.0 | 36.7 | 7.5 | 31.6 |
| | | 2 | 85,000 | 76,900 | 21.4 | 38.5 | 7.8 | 33.3 |
| | | Ave. | 84,600 | 76,600 | 20.7 | 37.6 | 7.6 | 32.4 |
| | Trans. | 1 | 86,500 | 79,300 | 22.9 | 45.2 | 10.0 | 39.1 |
| | | 2 | 86,100 | 78,200 | 21.4 | 40.4 | 9.5 | 34.2 |
| | | Ave. | 86,300 | 78,800 | 22.1 | 42.8 | 9.8 | 36.6 |
| | Long. & Trans. | Ave. | 85,450 | 77,700 | 21.4 | 40.2 | 8.7 | 34.5 |

## TABLE IV

### TENSILE PROPERTIES OF TITANIUM ARMOR PLATE NO. 1R, 5/8" THICK

### REMINGTON ARMS CO. - MATERIAL GIVEN

### EXPERIMENTAL HEAT TREATMENTS AT NPG

| Identification | Direction | Specimen Number | Tensile Strength (psi) | Yield Strength (psi at .2%) | Elongation in 4D (%) | Reduction of Area (%) | Reduction in Diameter (%) Major Axis | Reduction in Diameter (%) Minor Axis |
|---|---|---|---|---|---|---|---|---|
| | Long. | 1 | 80,400 | 64,800 | 22.9 | 39.7 | 9.2 | 33.6 |
| | | 2 | 79,900 | 62,400 | 22.2 | 40.2 | 10.0 | 33.5 |
| CORNER OF PLATE (CODE 1R2) | | Ave. | 80,200 | 63,600 | 22.5 | 40.0 | 9.5 | 33.5 |
| 1700°F for 12 Min. Air Cool | Trans. | 1 | 81,200 | 67,900 | 24.4 | 40.4 | 7.6 | 35.6 |
| | | 2 | 79,500 | 65,400 | 25.8 | 42.4 | 9.2 | 36.6 |
| | | Ave. | 80,400 | 66,700 | 25.1 | 41.4 | 8.4 | 36.1 |
| | Long. & Trans. | Ave. | 80,300 | 65,150 | 23.8 | 40.7 | 9.0 | 34.8 |
| | Long. | 1 | 80,500 | 65,100 | 20.7 | 42.7 | 10.6 | 37.2 |
| | | 2 | 81,000 | 65,500 | 19.3 | 44.0 | 10.1 | 37.8 |
| | | Ave. | 80,800 | 65,300 | 20.0 | 43.3 | 10.3 | 37.5 |
| CORNER OF PLATE (CODE 1R3) | | 1 | 81,000 | 66,400 | 22.9 | 39.2 | 7.3 | 34.5 |
| 1700°F for 12 Min. Water Quench | Trans. | 2 | 78,700 | 63,100 | 23.6 | 41.6 | 9.2 | 35.8 |
| | | Ave. | 79,900 | 64,800 | 23.2 | 40.4 | 8.3 | 35.[illegible] |
| | Long. & Trans. | Ave. | 80,350 | 65,050 | 21.6 | 41.9 | 9.3 | 36.3 |
| CENTER OF PLATE (CODE 1R - Heat Treatment #19) 1800°F for 10 Min. Air Cool | Long. | 1 | 77,000 | 58,200 | 22.2 | 37.4 (Circular Fracture) | | |

TABLE V

Directional Hardness Properties in
Titanium Armor Plate No. 1R, 5/8" Thick

| Sample Location | Treatment | Brinell Hardness Values (300kg. - 15 sec.) Face and Back-Av.(1) | Longitudinal Section (2) | Transverse Section (3) |
|---|---|---|---|---|
| Center of plate | None, as received | 234 | 191 | 201 |
| Center of plate | 1800°F for 10 mins., Air cool. | 194 | 183 | 179 |

(1) Axis of indenter perpe... lar to plate surface.

(2) Axis of indenter in plane of plate and perpendicular to the direction of rolling.

(3) Axis of indenter in plane of plate and parallel to the direction of rolling.

Note: Approximately 1/32" machined off face and back surfaces before testing.

## TABLE VI

Hardness Tests on Titanium Armor Plate
No. 1R, 5/8" Thick, Taken With The Indenter
Normal to the Plate Surface

A. Material as Received

| Identification | Brinell Hardness Values (300kg., -15 sec.) Face | Back | Average |
|---|---|---|---|
| Center of plate | 229 | 234 | 232 |
| Corner #2 of plate | 223 | 235 | 229 |
| Corner #3 of plate | 232 | 228 | 230 |
| | | Grand Average | 230 BHN |

B. Experimental Heat Treatments at NFG

| | | | |
|---|---|---|---|
| 1700°F for 12 Mins., Air cool | 226 | 228 | 227 |
| 1700°F for 12 mins., Water quench. | 228 | 235 | 232 |
| 1800°F for 10 mins., Air cool | 197 | 191 | 194 |

Note: Approximately 1/32" machined off surfaces before testing.

## TABLE VII

### TENSION-IMPACT PROPERTIES OF TITANIUM ARMOR PLATE NO. 1R, 5/8" THICK

| Identification | Test Direction | Specimen Number | Tension-Impact Strength (ft.lb.) | Reduction of Area (%) | Reduction of Diameter (%) Major Axis | Reduction of Diameter (%) Minor Axis |
|---|---|---|---|---|---|---|
| CENTER OF PLATE | Long. | 1 | 44 | 20.4 | 6.0 | 15.9 |
| (CODE 1RC) | | 2 | 48 | 23.6 | 7.2 | 17.7 |
| MATERIAL AS RECEIVED | | Ave. | 46 | 22.0 | 6.6 | 16.8 |
| | Trans. | 1 | 50 | 28.7 | 7.6 | 23.5 |
| | | 2 | 48 | 34.2 | 9.6 | 27.9 |
| | | Ave. | 49 | 31.4 | 8.6 | 25.7 |

## TABLE VIII

### CHARPY V-NOTCH IMPACT STRENGTH OF TITANIUM ARMOR PLATE NO. 1R, 5/8" THICK

| Identification | Test Direction | Specimen Number | Impact Strength (ft.lb.) | Average Hardness (Rockwell "B") |
|---|---|---|---|---|
| CENTER OF PLATE | Long. | 1 | 15 | 99.2 |
| (CODE 1RC) | | 2 | 15 | 100.0 |
| MATERIAL AS RECEIVED | | Ave. | 15 | 99.6 |
| | Trans. | 1 | 9 | 99.9 |
| | | 2 | 10 | 100.9 |
| | | Ave. | 9.5 | 100.4 |

Note: Notch cut perpendicular to the plate surface.

## Metallographic Technique for Titanium
## U. S. Naval Proving Ground

The examination of complex structures in titanium necessitates special care in the polishing and etching of metallographic specimens as outlined below.

Mounting. A small specimen size of less than 1/4" square facilitates polishing. The cut-off wheel should be relatively soft; American Instrument Company wheel No. 5-2212 has proved satisfactory. Bakelite is used for mounting because it does not crack on cooling.

Polishing. The mounted specimen is first ground on a clean 120 grit motor-driven wet belt. After the wet belt, the specimen is polished on emery paper ranging from #2 down through #00. Paper is preferred over lead laps because the latter causes dragging and piling up of the removed metal.

Following the #00 emery paper, the specimen is polished on a silk cloth using No. 600 carborundum grit. After the specimen is free from scratches made in the early stages of polishing, the polishing is continued for approximately one minute to remove worked metal that might be present before proceeding to the next wheel. Here again silk is used with a No. 900 grit (Precisionite #3), following the same procedure as on the 600 grit wheel.

The intermediate polishing is done in two steps, with the first on a Gamal cloth using NBS #14 diamond abrasive to give a flat surface by eliminating carbide relief. NBS #6 diamond abrasive on Gamal cloth is used in the second step. The final polishing is carried out with Shamva abrasive on Gamal cloth. The specimen should be polished and very lightly etched from one to three times until all worked metal is removed.

Etching. A good etch for removing worked metal consists of 1.5% HF and 3% $HNO_3$ in water. This etch is also used for revealing the grain boundaries in equi-axed alpha titanium. All etching solutions are applied with a cotton swab because a satisfactory etch can be obtained only by a vigorous rubbing action.

Ballistic Test of 5/8" Titanium Armor Plates
and Metallurgical Examination of Plate 1R

---

A combination of two etching solutions gives the best results with Widmanstätten structures in alpha titanium. The "B" etch[1] consists of 1 part HF and 1 part glycerine. The "C" etch[2] contains 1 ml. HF, 3 ml. $HNO_3$, 3 grams $Pb(NO_3)_2$ and 95.5 ml. water. The procedure in using these etches is to first etch with "C" for 5 to 10 seconds by swabbing, wash in warm water rubbing with cotton, flush with alcohol and dry. The "B" etch is then applied for 3 to 7 seconds by swabbing, followed by a water wash, flushing with alcohol and drying.

Metallography References:

(1) Optical Metallography of Titanium, W. T. Finlay, J. Resketo, and M. B. Vordahl, Industrial and Engineering Chemistry, Vol. 42, No. 2, p. 218, (February 1950).

(2) Metallography of Zirconium and Zirconium Alloys, A. H. Roberson, Metal Progress, Vol. 56, No. 5, p. 667 (November, 1949).

PRNC-NPG-59 SHEET NO.

| X X X X X | TEMPERATURE | TIME | | | | |
|---|---|---|---|---|---|---|
| ANNEAL | | | | YP | | |
| NORM | | | | TS | | |
| HARDEN | | | | EL | PLATE | |
| QUENCH | | | | RA | SIZE | 18 x 21.5 |
| DRAW | — | — | — | — | WEIGHT | [illegible] |
| GAUGE | [illegible] | [illegible] | [illegible] | C | DATE | 27 Oct. 1949 |
| PROJ. | Cal. .50 AP M2 | Cal. .30 AP M2 | [illegible] | Mn | MFR. | Remington Arms Co. |
| GUN | 273 | 129-773 | [illegible] | S | CONTR. | NORD 10583 (Exp.) |
| RANGE | 1 | 1 | 3 | P | TYPE | [illegible] |
| OBL. | 0 | 0 | 20 | Si | SPECS. | |
| RC | Vpmin | Vpmin | Vpmin | Ni | PLATE | NPG-1 |
| LC | 1637 | 2216 | 2451 | Cr | GROUP | |
| HI | — V50 | 2207 V50 | 2554 | Mo | HEAT | |
| LIMIT | 1635 1701 | 2217 2212 | [illegible] | | BHN | 235 |
| RESULT | Vpmin 1709 | 2212 | | | STEEL | T-30-4-1 |

| RD. | BULLET | CHARGE | STR. VEL | OBL. | YAW | PENET | BULLET | CONDITION OF PLATE |
|---|---|---|---|---|---|---|---|---|
| 1 | Cal. .50 M2 | 9.9 | 1743 | 0 | 0 | X Disregard | Hit plate frame RJ | 5/16" Hole 1/3 P.O. |
| 2 | " | 9.7 | 1764 | 0 | 0 | C | NR | 3/8" Hole 5/8" B. Spall |
| 3 | " | 9.4 | 1638 | 0 | 0 | I | CIP | 5/8" Nose B. Spall |
| 4 | " | 9.4 | 1637 | 0 | 0 | X | CIP | 5/8" Nose 1/2 PO |
| 5 | " | 9.5 | 1733 | 0 | 0 | C | NR | 3/8" Hole 1/2 PO |
| 6 | " | 9.45 | 1673 | 0 | 0 | I | CIP | 5/8" Nose G Pet |
| 7 | " | 9.46 | 1707 | 0 | 0 | I | CIP | 1 1/4" Nose G. Pet |
| 8 | " | 9.46 | 1646 | 0 | 0 | I | CIP | 3/8" Nose G. Pet |
| 9 | " | 9.5 | 1710 | 0 | 0 | C | NR | 3/8" Hole 1/3 PO |
| 10 | " | 9.45 | 1702 | 0 | 0 | I | CIP | 7/8" Nose G. Pet |
| | | | | | | | | |
| 11 | Cal. .30 M2 | 2.55 | 2044 | 0 | 0 | I | RJ | HB |
| 12 | " | 2.65 | 2142 | 0 | 0 | I | CIP | 1/4" Nose |
| 13 | " | 2.70 | 2216 | 0 | 0 | C | FCIP | 1/4" Hole G Pet |
| 14 | " | 2.70 | 2237 | 0 | 0 | C | FCIP | 1/4" Hole G. Pet |
| 15 | " | 2.65 | 2183 | 0 | 0 | I | CIP | 3/16" Nose G. Pet |
| 16 | | 2.72 | 2242 | 0 | 0 | C | NR | 1/4" Hole 2/3 PO |
| 17 | " | 2.67 | 2207 | 0 | 0 | I | CIP | 7/16" Nose G. Pet |
| 18 | " | 2.67 | 2205 | 0 | 0 | I | CIP | 1/2" Nose G. Pet |



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PRNC-3-10-49-6800

Encl. (        )

PLATE

1 - Titanium

T-3014-1

| RD. | BULLET | CHARGE | STRIKING VELOCITY | OBL. | YAW | PENET. | BULLET | CONDITION OF PLATE |
|---|---|---|---|---|---|---|---|---|
| 19 | Cal. 20 mm | 2.68 | 2226 | 0 | 0 | C | NR | 1/4" Hole 2/3 PO |
| 20 | " | 2.68 | 2202 | 0 | 0 | I | CIP | 1/8" Nose B. Pet |
| | | | | | | | | |
| 21 | 20mm HE | 460 | 2544 | 20 | - | C | HO | 3/4" opening. 1" B. Spall 4 (1½" cracks) |
| 22 | " | 430 | 2434 | 20 | - | C | HO | 3/4" Hole. B. Spall 1" 2 (1" cracks) 2 (1½" cracks) |
| 23 | " | 370 | 2144 | 20 | - | I | HO | SB |
| 24 | " | 400 | 2297 | 20 | - | I | HO | MB Radial cracks 1", 2", and 1½" |
| 25 | " | 415 | 2354 | 20 | - | I | HO | MB Radial cracks 1½", 1½", 2" |

Slight spall on some Caliber .50 impacts.

Petals off on some Caliber .30 impacts.

CONFIDENTIAL



PBSD-2-10-48-0000

LIGHT ARMOR FIRING RECORD

FRAC-UPG-59

SHEET NO.

| X X X X X | TEMPERATURE | TIME | | | | |
|---|---|---|---|---|---|---|
| ANNEAL | | | YP | | | |
| NORM | | | TS | | | |
| HARDEN | | | EL | | PLATE | |
| QUENCH | | | RA | | SIZE | |
| DRAW | | | | | WEIGHT | |
| | | | | | | |
| GAUGE | | | C | | DATE | |
| PROJ. | | | Mn | | MFR. | |
| GUN | | | S | | CONTR. | |
| RANGE | | | P | | TYPE | TITANIUM |
| OBL. | | | Si | | SPECS. | |
| RC | | | Ni | | PLATE | |
| LC | | | Cr | | GROUP | |
| HI | | | Mo | | HEAT | |
| LIMIT | | | | | BHN | |
| RESULT | | | | | STEEL | |

| RD. | BULLET | CHARGE | STR. VEL. | OBL. | YAW | PENET | BULLET | CONDITION OF PLATE |
|---|---|---|---|---|---|---|---|---|
| [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | NR | [illegible] Hole [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | CIP | [illegible] 2/3 PO |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] Nose 2/3 PO |
| [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | CIP | [illegible] Nose 1/3 PO |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | CIP | [illegible] PO |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] Nose PO |
| 7 | [illegible] | 92 | 162[illegible] | 0 | [illegible] | [illegible] | RO | 1/4" Hole G Pat. |
| 8 | " | 92 | 165[illegible] | 0 | [illegible] | I | CIP | 3/8" Nose 2/3 PO |
| 9 | " | 92 | 169[illegible] | 0 | [illegible] | I | CIP | 3/4 Nose 2/3 PO |
| 10 | " | 91 | 1665 | 0 | 0 | I | CIP | 1/2" Nose 1/3 PO |
| 11 | " | 94 | 17[illegible] | 0 | 0 | C | NR | 7/16" Hole 2/3 PO |
| | | | | | | | | |
| 12 | [illegible] | 270 | 228[illegible] | 0 | 0 | I | CIP | 1/64" Nose |
| 13 | " | 275 | 2297 | 0 | 0 | C | NR | 1/16" Hole 1/4 PO |
| 14 | " | 270 | 22[illegible] | 0 | 0 | I | CIP | 1/32" Nose |
| 15 | " | 270 | 2247 | 0 | 0 | I | CIP | 1/4" Nose G Pat |
| 16 | " | 270 | [illegible] | 0 | 0 | I | RO | 1/16" Hole G Pat. |
| 17 | " | 275 | [illegible] | 0 | 0 | C | NR | 1/16" Hole 1/4 PO |
| 18 | [illegible] | [illegible] | [illegible] | 0 | 0 | I | CIP | [illegible] |

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FRAC-S-10-60-4000

FIRING RECORD

SHEET NO.

Encl. (     )

PLATE

417

14 Jan 1950

T-3614-1

| RD. | BULLET | CHARGE | STRIKING VELOCITY | OBL. | YAW | PENET. | BULLET | CONDITION OF PLATE |
|---|---|---|---|---|---|---|---|---|
| 19 | Cal .30 AP | 275 | 2303 | 0 | 0 | I | CIP | 5/8" Nose G Pet. |
| 20 | " | 275 | 2303 | 0 | 0 | I | CIP | 7/16" Nose G Pet |
| 21 | " | 275 | 2275 | 0 | 0 | I | CIP | 3/8" Nose G Pet. |

Slight spall on petals pulled out on Cal 50 impacts.
Petals generally intact on Cal 50 impacts.

CONFIDENTIAL



PRBC-3-10-48-8000

| X X X X X | TEMPERATURE | TIME | | | | |
|---|---|---|---|---|---|---|
| ANNEAL | | | | YP | | |
| NORM | | | | TS | | |
| HARDEN | | | | EL | PLATE | |
| QUENCH | | | | RA | SIZE | 18"x.8" |
| DRAW | | | | | WEIGHT | 35.5 |
| GAUGE | 0".622 | 0".622 | 0".622 | C | DATE | 9, 19 Jan. 1950 |
| PROJ. | Cal. .50 A.P. M2 | Cal. .30 AP M2 | 20MM HE | Mn | MFR. | Remington Rand Co. |
| SUM | 297 | 11957/3 | 104733 | S | CONTR. | 6.42 |
| RANGE | 1 | 1 | 2 | P | TYPE | Titanium |
| OBL. | 0 | 0 | 2-13 | Si | SPECS. | |
| RC | Yaw n | Yaw n | | Ni | PLATE | 407 |
| LC | 1542 | 2348 | | Cr | GROUP | |
| HI | 1587 1650 | 2307 1650 | 2311 | Mo | HEAT | |
| LIMIT | 1595 1565 | 2328 2328 | "2325" | | BHN | 255 |
| RESULT | $V_{min}$ 1646 | 2328 | | | STEEL | |

T-3014-1

| RD. | BULLET | CHARGE | STR. VEL. | OBL. | YAW | PENET | BULLET | CONDITION OF PLATE |
|---|---|---|---|---|---|---|---|---|
| 1 | Cal. .50 M2 | 8.6 | 1555 | 0 | 0 | I | CIP | 5/16" Nose 1/3 PO |
| 2 | " | 8.7 | 1542 | 0 | 0 | X | FCIP | 5/16" Nose 2/3 PO |
| 3 | " | 8.7 | 1555 | 0 | 0 | I | RJ | 1/8" Hole 1/4 PO |
| 4 | " | 8.7 | 1587 | 0 | 0 | I | RJ | 1/8" Hole G. Pet |
| 5 | " | 8.8 | 1604 | 0 | 0 | I | CIP | 5/16" Nose 2/3 PO |
| 6 | " | 8.9 | 1641 | 0 | 0 | X | FCIP | 5/16" Nose 2/3 PO |
| 7 | " | 8.8 | 1600 | 0 | 0 | X | CIP | 1/2" Nose PO |
| 8 | " | 8.9 | 1650 | 0 | 0 | C | NR | 1/2" Hole 2/3 PO |
| 9 | " | 8.8 | 1563 | 0 | 0 | X | CIP | 5/16" Nose 1/3 PO |
| 10 | " | 8.7 | 1520 | 0 | 0 | X | CIP | 3/8" Nose. Hit 1 3/4" from edge of plate causing 5" flaw and of defect. |
| 11 | " | 8.8 | 1588 | 0 | 0 | X | CIP | 1" Nose PO |
| | Note: | Round No. 10 apparently hit plate on internal defect causing cracking. Disregarded in limit calculation. | | | | | | |
| 12 | Cal. .30 M2 | 2.80 | 2348 | 0 | 0 | C | NR | 1/4" Hole 1/2" E. Spall |
| 13 | " | 2.75 | 2279 | 0 | 0 | I | CIP | 1/8" Nose G Pet |
| 14 | " | 2.75 | 2258 | 0 | 0 | I | CIP | 1/32" Nose G. Pet |
| 15 | " | 2.75 | 2282 | 0 | 0 | I | CIP | 1/16" Nose G. Pet |

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LIGHT ARMOR FIRING RECORD
PGBC-878-890

SHEET NO.
Encl. ( )

PLATE
407

Remington Arms [illegible]

T-3014-1
and 19,
10 Jan. 1950

| RD. | BULLET | CHARGE | STRIKING VELOCITY | OBL. | YAW | PENET. | BULLET | CONDITION OF PLATE |
|---|---|---|---|---|---|---|---|---|
| 16 | Cal. .30 AP | 280 | [illegible] | 0 | 0 | I | FCIP | 3/16" Nose 1/2 PO |
| 17 | " | 280 | 2358 | 0 | 0 | C | NR | 1/4" Hole PO |
| 18 | " | 280 | 2362 | 0 | 0 | C | NR | 1/4" Hole PO |
| 19 | " | 275 | 2297 | 0 | 0 | I | CIP | 3/16" Nose G Pet |
| 20 | " | 275 | 2307 | 0 | 0 | I | CIP | 3/16" Nose G. Pet |
| 21 | " | 280 | 2368 | 0 | 0 | C | NR | 1/2" Hole G. Pet |
| 22 | " | 280 | 2358 | 0 | 0 | C | NR | 1/4" Hole 1/3 PO |
| 23 | " | 275 | 2274 | [illegible] | 0 | I | CIP | 1/4" Nose G. Pet |
| 24 | " | 275 | 2282 | [illegible] | 0 | I | CIP | 1/2" Nose G. Pet |
| 25 | " | 285 | 2362 | 0 | 0 | C | NR | 1/4" Hole 1/3 PO |
| 26 | " | 275 | 2305 | 0 | 0 | I | CIP | 1/8" Nose |
| | | | | | | | | |
| | | 1" Spall on same caliber 50 impacts | | | | | | |
| | | 3/4" Spall on same caliber 30 impacts | | | | | | |
| | 19 Jan 1950 | | | | | | | |
| 27 | 90MM HE | 400 | 2272 | 20 | — | I | HO | ~~9" Thru Crack~~ HB 2", 1" Cracks |
| 28 | " | 410 | 2311 | 20 | — | I | HO | 18" open ~~7" Thru Crack~~ joining Crack ~~from round 27 and~~ almost breaking plate ~~in two.~~ 2" and 1" Thru Cracks. ~~Crack from round~~ 10 extended to Cal. 50 impact. |

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PGBC-9-19-48-8200

LIGHT ARMOR FIRING RECORD

PRSC-APG-69 SHEET NO.

| XXXXX | TEMPERATURE | TIME | | |
|---|---|---|---|---|
| ANNEAL | | | YP | |
| NORM | | | TS | |
| HARDEN | | | EL | PLATE |
| QUENCH | | | RA | SIZE |
| DRAW | | | | WEIGHT [illegible] |

| | | | | | |
|---|---|---|---|---|---|
| GAUGE | [illegible] | [illegible] | [illegible] | C | DATE 1, 17 Jan 1950 |
| PROJ. | Cal .50 M2 | [illegible] | [illegible] | Mn | MFR. [illegible]ington Arms Co. |
| GUN | [illegible] | [illegible] | [illegible] | S | CONTR. |
| RANGE | 1 | 1 | 2 | P | TYPE [illegible] |
| OBL. | 0 | 0 | 20 | SI | SPECS. |
| RC | VP min | VP min | | Ni | PLATE 415 |
| LC | 1565 | 229 | 2331 | Cr | GROUP |
| HI | 1576 V050 | 2313 V050 | 2285 | Mo | HEAT |
| LIMIT | 1555 1561 | 2316 2316 | 2295 | | BHN [illegible] |
| RESULT | V1 min 1598 | 2316 | | | STEEL T-3014-1 |

| RD. | BULLET | CHARGE | STR. VEL. | OBL. | YAW | PENET | BULLET | CONDITION OF PLATE |
|---|---|---|---|---|---|---|---|---|
| 1 | Cal.50 M2 | 9.4 | 1745 | 0 | 0 | C | NR | 7/16" Hole 1 1/4" B Spall |
| 2 | " | 9.2 | 1673 | 0 | 0 | C | NR | 7/16" Hole 2/3 PO |
| 3 | " | 9.1 | 1654 | 0 | 0 | C | NR | 7/16" Hole 2/3 PO |
| 4 | " | 9.0 | 1639 | 0 | 0 | C | NR | 1/2" Hole PO |
| 5 | " | 8.9 | 1594 | 0 | 0 | I | CIP | 3/4" Nose 1/8" B Spall |
| 6 | " | 8.8 | 1602 | 0 | 0 | C | NR | 1/2" Hole 1 1/4" B Spall |
| 7 | " | 8.7 | 1581 | 0 | 0 | X | FCIP | 7/16" Hole PO |
| 8 | " | 8.6 | 1536 | 0 | 0 | I | FCIP | 1/4" Nose 1/3 PO |
| 9 | " | 8.6 | 1546 | 0 | 0 | I | RJ | 3/16" Hole G Pet. |
| 10 | " | 8.7 | 1624 | 0 | 0 | C | NR | 7/16" Hole PO |
| 11 | " | 8.65 | 1563 | 0 | 0 | X | CIP | 1/2" Nose 2/3 PO |
| 12 | " | 8.7 | 1573 | 0 | 0 | X | CIP | 5/8" Nose PO |
| | | | | | | | | |
| 13 | Cal 30 M2 | 275 | 2319 | 0 | 0 | C | NR | 1/4" Hole PO |
| 14 | " | 275 | 2313 | 0 | 0 | I | CIP | 5/16" Nose G Pet |
| 15 | " | 275 | 2273 | 0 | 0 | I | CIP | 1/4" Nose G Pet. |
| 16 | " | 275 | 2307 | 0 | 0 | I | CIP | 5/8" Nose 1/2 PO |
| 17 | " | 275 | 2270 | 0 | 0 | I | CIP | 1/4" Nose 1/4 PO |

1 1/4" Each spall on 3 Cal .50 Rounds 3/4" Spall on most Cal 30 rounds



PRSC-9-10-49-C-[illegible]

CONFIDENTIAL

LIGHT ARMOR FIRING RECORD
PRNC-NPG-89A

SHEET NO.
Encl. (    )

PLATE
415
TITANIUM ARMOR
MFR Remington Arms
20MM HE MK 3 - MK 26-0 FUZE

19, JAN 1950
T-30:4-1

| RD. | BULLET | CHARGE | STRIKING VELOCITY | OBL. | YAW | PENET. | BULLET | CONDITION OF PLATE |
|---|---|---|---|---|---|---|---|---|
| 18 | 20MM HE MK3 | 380 | 2131 | 20 | — | I | HD | HB 3", 2, 1½" Cracks |
| 19 | " | 390 | 2246 | 20 | — | I | HO | HB 3", 2", 2", 1½" Cracks |
| 20 | " | 400 | 2268 | 20 | — | I | HO | HB Back Cracks and Thin Cracks 6", 3" rotated on front 2", 2", |
| 21 | " | 410 | 2321 | 20 | — | C | HO | 3" x 3" Section out 2" Thin Crack H... 3" From edge of Plate |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
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CONFIDENTIAL



PNGF-3-18-48-6000

LIGHT ARMOR FIRING RECORD

PRDC-WPG-69

SHEET NO.

| X X X X X | TEMPERATURE | TIME | | | | |
|---|---|---|---|---|---|---|
| ANNEAL | | | YP | | | |
| NORM | | | TS | | | |
| HARDEN | | | EL | | PLATE | |
| QUENCH | | | RA | | SIZE | |
| DRAW | | | | | WEIGHT | |

| | | | | | | |
|---|---|---|---|---|---|---|
| GAUGE | 0.5?? | 0.548 | C | | DATE | 9 Jan 1950 |
| PROJ. | Cal .50 M2 | Cal .30 M2 | Mn | | MFR. | DUPONT-NGF-AL |
| GUN | 299 | 1195775 | S | | CONTR. | |
| RANGE | 1 | 1 | P | | TYPE | TITANIUM |
| OBL. | 0 | 0 | Si | | SPECS. | |
| RC | VPMIN | VPMIN | Ni | | PLATE | 13 |
| LC | 1497 | 2376 | Cr | | GROUP | |
| HI | 1485 V1532 | 2311 V150 | Mo | | HEAT | |
| LIMIT | 1471 1532 | 2019 2359 | | | BHN | 230 |
| RESULT | V50 MIN = 1644 | 2357 | | | STEEL | T-3014-1 |

| RD. | BULLET | CHARGE | STR. VEL. | OBL. | YAW | PENET | BULLET | CONDITION OF PLATE |
|---|---|---|---|---|---|---|---|---|
| 1 | Cal .50 M2 | 8.9 | 1634 | 0 | 0 | X | CIP | 1" Nose PO |
| 2 | " | 8.8 | 1557 | 0 | 0 | X | CIP | 5/16" Nose 2/3 PO |
| 3 | " | 8.7 | 1621 | 0 | 0 | X | CIP | 7/16" Nose 1/2 PO |
| 4 | " | 8.6 | 1582 | 0 | 0 | X | CIP | 5/16" Nose 1/2 PO |
| 5 | " | 8.6 | 1600 | 0 | 0 | X | CIP | 9/16" Nose 1/2 PO |
| 6 | " | 8.5 | 1516 | 0 | 0 | I | CIP | 1/4" Nose 1 1/4" Back Spall Stuck |
| 7 | " | 8.6 | 1565 | 0 | 0 | X | CIP | 7/8" Nose 2/3 PO |
| 8 | " | 8.5 | 1520 | 0 | 0 | I | RJ | 3/8" Hole 1/4 PO |
| 9 | " | 8.5 | 1541 | 0 | 0 | I | CIP | 1/4" Nose 1/2" B Spall |
| 10 | " | 8.5 | 1497 | 0 | 0 | X | CIP | 1/4" Nose 2/3 PO |
| 11 | " | 8.4 | 1527 | 0 | 0 | X | CIP | 1/4" Nose 3/4 PO |
| 12 | " | 8.3 | 1525 | 0 | 0 | I | CIP | 1/4" Nose PO |
| 13 | " | 8.2 | 1485 | 0 | 0 | I | RJ | 1/8" Hole 1/4 PO |
| 14 | Cal .50 API M8 | 8.9 | 1647 | 0 | 0 | C | NR | 7/16" Hole 1/4" B Spall |
| 15 | " | 8.8 | 1625 | 0 | 0 | C | NR | 1/2" Hole 1 1/4" B Spall |
| 16 | " | 8.7 | 1525 | 0 | 0 | I | RJ | 1/4" Hole 1/3 PO |
| | | | | | | | | |
| 17 | Cal .30 M2 | 27.0 | 2281 | 0 | 0 | I | CIP | 1/8" Nose 1/2 PO |
| 18 | " | 26.5 | 2256 | 0 | 0 | I | CIP | PPB |

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PRDC-8-10-48-6000

**LIGHT ARMOR FIRING RECORD**

SHEET NO.
Encl. ( )

PLATE

1D - TITANIUM

9 Jan. 1950

T-3014-1

| RD. | BULLET | CHARGE | STRIKING VELOCITY | OBL. | YAW | PENET. | BULLET | CONDITION OF PLATE |
|---|---|---|---|---|---|---|---|---|
| 19 | Cal 30 M2 | 270 | 2247 | 0 | 0 | I | RJ | 1/16" Hole G Pet. |
| 20 | " | 275 | 2311 | 0 | 0 | I | FCIP | PPB |
| 21 | " | 275 | 2326 | 0 | 0 | X | CIP | 3/8" Nose 2/3 PO |
| 22 | " | 275 | 2258 | 0 | 0 | I | CIP | 1/32" Nose 1/4 PO |
| 23 | " | 280 | 2350 | 0 | 0 | I | CIP | 1/4" Nose 2/3 PO |
| 24 | " | 275 | 2279 | 0 | 0 | I | CIP | PPB |
| 25 | " | 280 | 2364 | 0 | 0 | C | NR | 1/4" Hole 2/3 PO |
| 26 | " | 280 | 2378 | 0 | 0 | C | NR | 1/4" Hole 2/3 PO |
| 27 | " | 275 | 2217 | 0 | 0 | I | RJ | HB |
| 28 | " | 280 | 2328 | 0 | 0 | I | CIP | 1/8" Nose 1/2 PO |
| 29 | " | 280 | 2328 | 0 | 0 | I | CIP | 1/16" Nose 1/2 PO |

1 1/4" Back Spall on 4 Cal. 30 impacts
5/8" Spalls on most Cal. 30 impacts

CONFIDENTIAL

**LIGHT ARMOR FIRING RECORD**

SHEET NO.

| X X X X X | TEMPERATURE | TIME | | | | | |
|---|---|---|---|---|---|---|---|
| ANNEAL | | | YP | | | | |
| NORM | | | TS | | | | |
| HARDEN | | | EL | | PLATE | | |
| QUENCH | | | RA | | SIZE | | |
| DRAW | | | | | WEIGHT | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| GAUGE | 0".648 | 0".648 | C | | DATE | 11 Jan. 1950 |
| PROJ. | Cal .50 APM2 | Cal .30 [illegible] | Mn | | MFR. | |
| GUN | [illegible] | [illegible] | S | | CONTR. | |
| RANGE | [illegible] | | P | | TYPE | TITANIUM |
| OBL. | 0 | 0 | Si | | SPECS. | |
| RC | [illegible] | | Ni | | PLATE | [illegible] ANNEALED BY NPI |
| LC | [illegible] | 2318 | Cr | | GROUP | |
| HI | [illegible] VP50 | 2336 VP50 | Mo | | HEAT | |
| LIMIT | 1506 1538 | 2357 2357 | | | BHN | |
| RESULT | VP50 1516 | 2357 | | | STEEL | T-3014-1 |

| RD. | BULLET | CHARGE | STR. VEL. | OBL. | YAW | PENET | BULLET | CONDITION OF PLATE |
|---|---|---|---|---|---|---|---|---|
| 1 | Cal 50 M2 | 8.8 | 1599 | 0 | 0 | X | CIP | 5/16" Nose 3/4" B Spall |
| 2 | " | 8.9 | 1632 | 0 | 0 | C | NR | 7/16" Hole 1 1/2" x 1 [illegible] B Spall |
| 3 | " | 8.7 | 1562 | 0 | 0 | I | RJ | 1/8" Hole 1/2 PO |
| 4 | " | 8.7 | 1574 | 0 | 0 | X | CIP | 5/16" Nose 1/2 PO |
| 5 | " | 8.5 | 1557 | 0 | 0 | X | RJ | 1/4" Hole 1/3 PO |
| 6 | " | 8.5 | 1515 | 0 | 0 | X | CIP | 1/4" Nose 3/4" B Spall |
| 7 | " | 8.4 | 1496 | 0 | 0 | I | RJ | 3/16" Hole 5/8" x 3/4" B Spall |
| 8 | " | 8.3 | 1518 | 0 | 0 | I | RJ | 3/16" Hole 1/2 PO |
| | | | | | | | | |
| 9 | Cal 30 M2 | 275 | 2272 | 0 | 0 | I | RJ | 1/32" Nose |
| 10 | " | 275 | 2258 | 0 | 0 | I | CIP | 1/8" Nose 1/2 PO |
| 11 | " | 280 | 2378 | 0 | 0 | C | NR | 1/4" Hole PO |
| 12 | " | 280 | 2394 | 0 | 0 | C | NR | 1/4" Hole PO |
| 13 | " | 275 | 2295 | 0 | 0 | I | PCIP | 1/64" Nose G Pet. |
| 14 | " | 275 | 2237 | 0 | 0 | I | RJ | PPB |
| 15 | " | 280 | 2336 | 0 | 0 | I | CIP | 1/8" Nose 1/4 PO |
| 16 | " | 277 | 2324 | 0 | 0 | I | CIP | 3/16" Nose 1/4 PO |
| 17 | " | 280 | 2323 | 0 | 0 | I | CIP | 1/8" Nose 1/4 PO |
| 18 | " | 280 | 2394 | 0 | 0 | X | CIP | 7/16" Nose 2/3 PO |

CONFIDENTIAL

**LIGHT ARMOR FIRING RECORD**
PRNC-EPG-69A

SHEET NO.
Encl. (        )

PLATE
1" D ANNEALED
TITANIUM

11 Jan 1950

T-3014-1

| RD. | BULLET | CHARGE | STRIKING VELOCITY | OBL. | YAW | PENET. | BULLET | CONDITION OF PLATE |
|---|---|---|---|---|---|---|---|---|
| 19 | Cal.30 W2 | 280 | 2328 | 0 | 0 | I | CIP | 1/8" Nose 1/4 FO |

Large Back Spalls on some Cal 50 impacts
Slight Back Spall on most Cal. 30 impacts

# LIGHT ARMOR FIRING RECORD

PRRC-HPQ-59

SHEET NO.

| X X X X X | TEMPERATURE | TIME | | |
|---|---|---|---|---|
| ANNEAL | | | YP | |
| NORM | | | TS | |
| HARDEN | | | EL | PLATE |
| QUENCH | | | RA | SIZE |
| DRAW | | | | WEIGHT |

| | | | |
|---|---|---|---|
| GAUGE | 0.5[illegible] | C | DATE 6 February 1950 |
| PROJ. | Cal .50 APM2 | Mn | MFR. Remington Arms Co |
| GUN | 249 | S | CONTR. [illegible] (Exp.) |
| RANGE | | P | TYPE Titanium |
| OBL. | 0 | Si | SPECS. |
| RC | | Ni | PLATE #28 As Received |
| LC | 1586 | Cr | GROUP |
| HI | 1585 1650 | Mo | HEAT |
| LIMIT | 1586 1620 | | BHN |
| RESULT | $V_L$ max 1633 | | STEEL |

T-[illegible]-1

| RD. | BULLET | CHARGE | STR. VEL. | OBL. | YAW | PENET | BULLET | CONDITION OF PLATE |
|---|---|---|---|---|---|---|---|---|
| 1 | Cal.50 ML | 8.5 | 1561 | 0 | 0 | I | CIP | 3/8" Nose G Pet. |
| 2 | " | 8.6 | 1508 | 0 | 0 | I | Rd | 3/16" Hole G Pet. |
| 3 | " | 8.8 | 1585 | 0 | 0 | I | CIP | 7/16" Nose G Pet. |
| 4 | " | 8.9 | 1616 | 0 | 0 | I | CIP | 1/2" Nose 1/3 PO |
| 5 | " | 8.9 | 1569 | 0 | 0 | I | CIP | 7/8" Nose 1/2 PO |
| 6 | " | 8.9 | 1602 | 0 | 0 | I | CIP | 9/16" Nose G Pet. |
| 7 | " | 9.0 | 1553 | 0 | 0 | I | CIP | 3/8" Nose G Pet. |
| 8 | " | 9.1 | 1624 | 0 | 0 | I | CIP | 5/8" Nose 1/3 PO |
| 9 | " | 9.2 | 1662 | 0 | 0 | C | NR | 7/16" Hole PO |
| 10 | " | 9.1 | 1642 | 0 | 0 | C | NR | 7/16" Hole PO |
| 11 | " | 9.0 | 1586 | 0 | 0 | X | CIP | 3/4" Nose PO |





PRRC-2-10-49-0063

LIGHT ARMOR FIRING RECORD

PRNC-RPN-69

SHEET NO.

| XXXXX | TEMPERATURE | TIME | | | | |
|---|---|---|---|---|---|---|
| ANNEAL | | | YP | | | |
| NORM | | | TS | | | |
| HARDEN | | | EL | | PLATE | |
| QUENCH | | | RA | | SIZE | |
| DRAW | | — | | | WEIGHT | |

| | | | | | |
|---|---|---|---|---|---|
| GAUGE | 0.598 | C | | DATE | 15 March 1950 |
| PROJ. | Cal .50 M2 | Mn | | MFR. | Remington Arms Co. |
| GUN | 279 | S | | CONTR. | |
| RANGE | 1 | P | | TYPE | TITANIUM |
| OBL. | 0 | Si | | SPECS. | |
| RC | | Ni | | PLATE | 428 – |
| LC | 1611 | Cr | | GROUP | AS Received |
| HI | 1610 VF50 | Mo | | HEAT | 2ND Test. |
| LIMIT | 1611 1630 | | | BHN | |
| RESULT | V min 1611 | | | STEEL | T-3014-1 |

| RD. | BULLET | CHARGE | STR. VEL. | OBL. | YAW | PENET | BULLET | CONDITION OF PLATE |
|---|---|---|---|---|---|---|---|---|
| 1 | Cal. .50 M2 | 9.0 | 1610 | 0 | 0 | I | CIP | 7/8" Nose 1/2 PO |
| 2 | " | 8.8 | 1595 | 0 | 0 | I | CIP | 5/8" Nose G Pet |
| 3 | " | 8.9 | 1615 | 0 | 0 | I | CIP | 3/4" Nose G Pet. |
| 4 | " | 9.0 | 1624 | 0 | 0 | I | CIP | 1 1/4" Nose 1/3 PO |
| 5 | " | 9.0 | 1642 | 0 | 0 | C | NR | 7/16" Hole G Pet. |
| 6 | " | 9.0 | 1660 | 0 | 0 | C | NR | 7/16" Hole G Pet. |
| 7 | " | 8.9 | 1571 | 0 | 0 | I | CIP | 5/16" Nose G Pet. |
| 8 | " | 9.0 | 1621 | 0 | 0 | I | CIP | 3/4" Nose G Pet. |
| 9 | " | 9.0 | 1611 | 0 | 0 | C | NR | 7/16" Hole PO |

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PRNC-S-18-49-6669

LIGHT ARMOR FIRING RECORD

PRRC-UPC-69

SHEET NO.

| X X X X X | TEMPERATURE | TIME | | | | |
|---|---|---|---|---|---|---|
| ANNEAL | | | YP | | | |
| NORM | | | TS | | | |
| HARDEN | | | EL | | PLATE | |
| QUENCH | | | RA | | SIZE | |
| DRAW | | | | | WEIGHT | |
| GAUGE | 0".220 | | C | | DATE | 15 March 1950 |
| PROJ. | Cal .50 AP M2 | | Mn | | MFR. | Remington Arms Co. |
| GUN | 229 | | S | | CONTR. | |
| RANGE | 1 | | P | | TYPE | Titanium |
| OBL. | 0 | | Si | | SPECS. | |
| RC | | | Ni | | PLATE | 415 - ANNEALED |
| LC | 1675 | | Cr | | GROUP | |
| HI | 1635 1250 | | Mo | | HEAT | |
| LIMIT | 1655 1071 | | | | SHN | |
| RESULT | V50 BN 1655 | | | | STEEL | T-3014-1 |

| RD. | BULLET | CHARGE | STR. VEL. | OBL. | YAW | PENET | BULLET | CONDITION OF PLATE |
|---|---|---|---|---|---|---|---|---|
| 1 | Cal .50 M2 | 8.8 | 1613 | 0 | 0 | I | CIP | 5/16" Nose G Pet. |
| 2 | " | 8.9 | 1599 | 0 | 0 | I | RJ | 3/16" Hole G Pet. |
| 3 | " | 9.1 | 1628 | 0 | 0 | I | CIP | 3/8" Nose G Pet. |
| 4 | " | 9.2 | 1677 | 0 | 0 | I | CIP | 5/8" Nose G Pet |
| 5 | " | 9.2 | 1683 | 0 | 0 | I | CIP | 1 1/8" Nose 1/4 PO |
| 6 | " | 9.2 | 1675 | 0 | 0 | C | NR | 7/16" Hole 1/4 PO |
| 7 | " | 9.2 | 1734 | 0 | 0 | C | NR | 7/16" Hole 2/3 PO |
| 8 | " | 9.1 | 1700 | 0 | 0 | C | NR | 1/2" Hole 1"x1" B Spall |
| 9 | " | 9.0 | 1595 | 0 | 0 | I | CIP | 3/8" Nose 1/2 PO |
| 10 | " | 9.1 | 1597 | 0 | 0 | I | CIP | 3/8" Nose 1/2 PO |
| 11 | " | 9.1 | 1616 | 0 | 0 | I | CIP | 1/2" Nose G Pet. |
| 12 | " | 9.2 | 1628 | 0 | 0 | I | CIP | 7/16" Nose G Pet. |
| 13 | " | 9.2 | 1635 | 0 | 0 | I | RJ | 5/16" Hole G Pet |
| 14 | " | 9.2 | 1693 | 0 | 0 | I | CIP | 1" Nose 1/4 PO |

CONFIDENTIAL

LIGHT ARMOR FIRING RECORD

SHEET NO.

| X X X X X | TEMPERATURE | TIME | | | | |
|---|---|---|---|---|---|---|
| ANNEAL | | | YP | | | |
| NORM | | | TS | | | |
| HARDEN | | | EL | | PLATE | |
| QUENCH | | | RA | | SIZE | |
| DRAW | | | | | WEIGHT | |

| | | | | | | |
|---|---|---|---|---|---|---|
| GAUGE | 0".622 | 0".622 | C | | DATE | 30, MARCH. 1950 |
| PROJ. | Cal.50 APM2 | Cal.30 M2 | MN | | MFR. | Remington Arms Co. |
| GUN | 299 | 1224913 | S | | CONTR. | EXP. |
| RANGE | 1 | 1 | P | | TYPE | TITANIUM |
| OBL. | 0 | 0 | SI | | SPECS. | |
| RC | | | NI | | PLATE | 407 - ANNEALED |
| LC | 1624 | 2277 | Cr | | GROUP | |
| HI | 1598 V50 | 2270 V50 | Mo | | HEAT | |
| LIMIT | 1647 1650 | 2274 2279 | | | BHN | |
| RESULT | V50 1642 | 2274 | | | STEEL | |

T-3014-1

| RD. | BULLET | CHARGE | STR. VEL. | OBL. | YAW | PENET | BULLET | CONDITION OF PLATE |
|---|---|---|---|---|---|---|---|---|
| 1 | Cal.50APM2 | 8.8 | 1576 | 0 | 0 | I | RJ | 1/4" Hole |
| 2 | " | 9.0 | 1668 | 0 | 0 | C | NR | 7/16"x1/2" Hole P.O |
| 3 | " | 8.9 | 1636 | 0 | 0 | I | CIP | 7/16" Nose 2/3 PO |
| 4 | " | 8.9 | 1647 | 0 | 0 | C | NR | 7/16" Hole PO |
| 5 | " | 8.8 | 1624 | 0 | 0 | X | CIP | 3/4" Nose PO |
| 6 | " | 8.7 | 1537 | 0 | 0 | I | RJ | 1/8" Hole. |
| 7 | " | 8.8 | 1598 | 0 | 0 | I | RJ | 3/16" Hole G Pet. |
| 8 | " | 8.8 | 1551 | 0 | 0 | I | RJ | 1/4" Hole 3/4" Back Spall |
| 9 | " | 8.8 | 1597 | 0 | 0 | I | RJ | 1/8" Hole G Pet. |
| | | | | | | | | |
| 10 | Cal.30 M2 | 275 | 2338 | 0 | 0 | C | NR | 1/4" Hole G Pet. |
| 11 | " | 270 | 2275 | 0 | 0 | Disregard | | hit old rd. |
| 12 | " | 270 | 2270 | 0 | 0 | I | CIP | 9/16" Nose 3/4 PO |
| 13 | " | 265 | 2277 | 0 | 0 | C | NR | 1/4" Hole G Pet |
| 14 | " | 265 | 2228 | 0 | 0 | I | RJ | 1/8" Hole. |
| 15 | " | 265 | 2253 | 0 | 0 | I | CIP | 3/16" Nose G Pet. |
| 16 | " | 265 | 2155 | 0 | 0 | I | RJ | 1/16" Hole. |
| 17 | " | 270 | 2280 | 0 | 0 | I | CIP | 1/2" Nose G Pet. |
| 18 | " | 270 | 2319 | 0 | 0 | C | NR | 1/4" Hole 1/2 PO |

CONFIDENTIAL

## DESCRIPTION OF THE BALLISTIC TESTING PROCEDURE

1. In the penetration tests with armor piercing projectiles performed herein, the velocity of each impact was measured and the two following ballistic limits evaluated.

a. Minimum Limit Velocity "Vlmin".

This limit is the average of the velocities of, (a) the lowest velocity impact causing a complete penetration and (b) the impact with the next lower velocity.

b. Mean Protection Limit Velocity "Vp50".

This limit is determined by a statistical analysis of all impacts and is an estimate of the striking velocity at which 50% of the projectiles will defeat the plate. A defeat, in this case, was a protection failure.

2. A complete penetration was considered to have occurred when the projectile passed completely through the plate.

3. A protection failure was considered to have occurred when any piece of the plate or projectile penetrated a 0.020 piece of 24S-T4 aluminum alloy placed parallel to the armor and 6" behind.

4. The following formula is used to determine the mean protection limit velocity "Vp50":

$$\text{"Vp50"} = \frac{\Sigma V + (Ni - No)25}{Ni + No}$$

Where:

"Vp50" = mean protection limit velocity.

$\Sigma$ V = the sum of the velocities of the impacts considered.

Ni = number of impacts considered not causing protection failure. *

No = number of impacts considered causing protection failure. *

* An impact was considered in determination of the mean protection limit velocity when its velocity was within the velocity bracket between the lowest velocity impact causing protection failure and the highest velocity impact not causing protection failure.

5. In order to compare plates of slightly different thicknesses, the mean protection limit velocities obtained in the penetration tests are expressed in terms of F(e'/d,θ) values where F(e'/d,θ) is defined as follows:

$$F(e'/d,\theta) = \frac{41.57\ M^{1/2}\ Vp50\ \cos\theta}{e'^{1/2}\ d}$$

Where:

M is the projectile mass in pounds, Vp50, the mean protection limit velocity in feet per second, θ, the obliquity, is the angle between normal to the plate and the line of flight, e', the equivalent thickness of the plate, that is, the actual plate thickness in inches, divided by 1.74 to account for the lower density of titanium in comparison with steel and d, the diameter of the projectile in inches.

Ballistic Test of 5/8" Titanium Armor Plates
and Metallurgical Examination of Plate 1R

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6. The characteristics of the armor piercing projectiles used in the penetration tests are summarized in the following table:

| Projectile Cal. Type | Average Diameter | Weight in lbs. without Jacket or Windshield | $M/d^3$ in lbs./cu.ft. |
|---|---|---|---|
| Cal. .30 APM2 | 0"2444 | .01204 | 1425 |
| Cal. .50 APM2 | 0"4272 | .05600 | 1241 |

Ballistic Test of 5/8" Titanium Armor Plates
and Metallurgical Examination of Plate 1R

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| Local: | |
| TO | 1 |
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Naval Proving Ground, Dahlgren, Va

(UNCLASSIFIED Title) BALLISTIC TEST OF 5/8" TITANIUM ARMOR PLATES AND METALLURGICAL EXAMINATION OF PLATE IR - FIRST PARTIAL REPORT ON LIGHT ARMOR,TITANIUM.

First Partial Rpt. 17 July 50, 20p. (NPG Rpt No. 584)

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SUBJECT HEADINGS

DIV: Ordnance (22)

SECT: Armor (2)

Armor plate - Physical properties

Titanium - Physical properties

(Copies obtainable from ASTIA-DSC)

NTIS, Auth: USNSWC ltr, 24 Feb 75 [redacted]