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U. S. NAVAL PROVING GROUND

DAHLGREN, VIRGINIA

REPORT NO. 584

LIGHT ARMOR, TITANIUM

11955

1st Partial Report

- -

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

- -

METALLURGICAL EXAMINATION OF
REMINGTON TITANIUM PLATE IR

C-59115

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 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.

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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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 and Metallurgical Examination of Plate 1R

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.

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]he 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 Nitrogen 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.

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.

- -

c. 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

- -

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

- -

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.

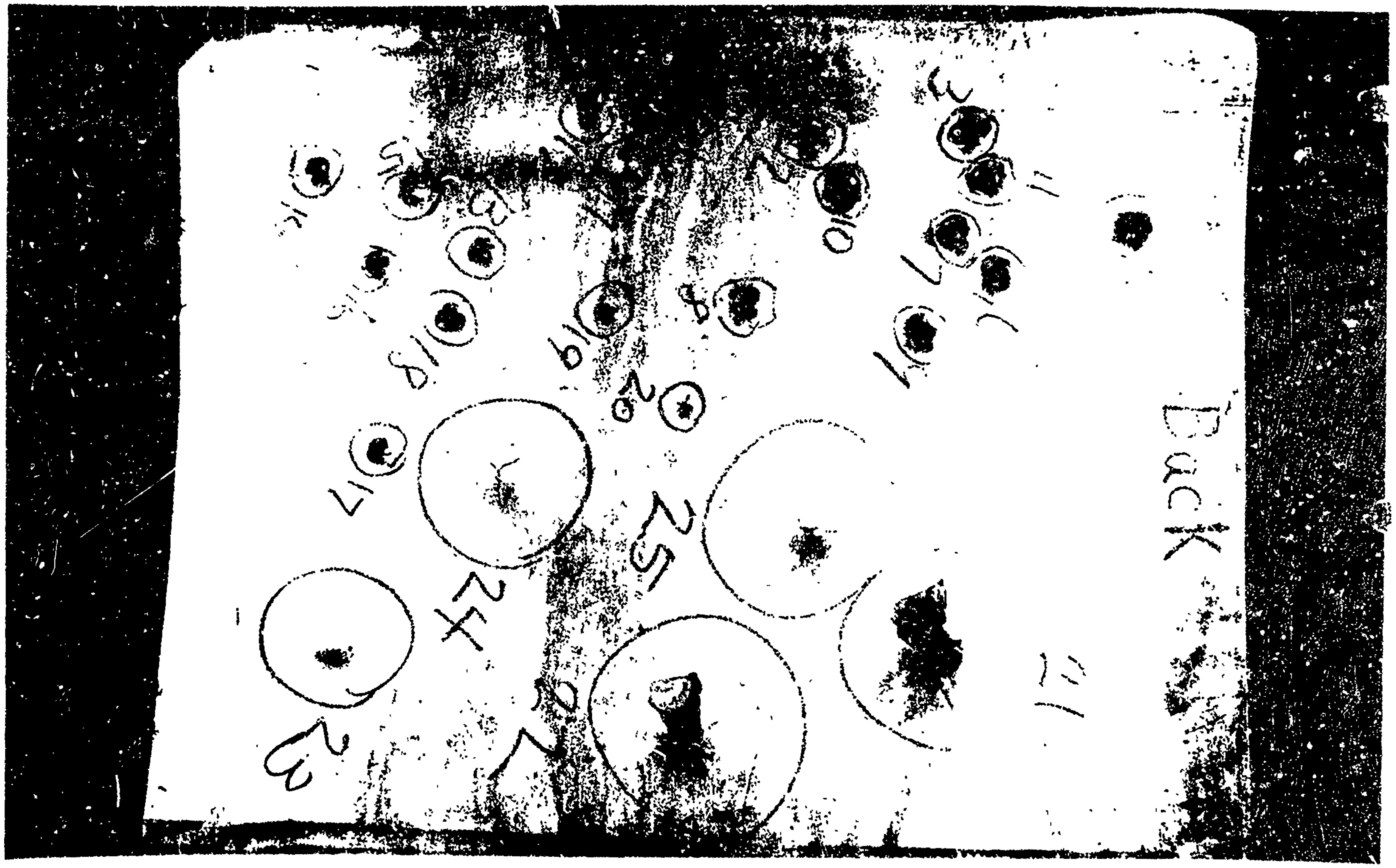
Thickness	[illegible]	Projectile	[illegible]	e'/d	Limit	"Vp50" Limit	F(e'/d,θ)
0.613	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1701 f/s	66,000
0.613	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2212 f/s	[illegible]
0.613	[illegible]	[illegible]	[illegible]	---	---	2394 f/s	---

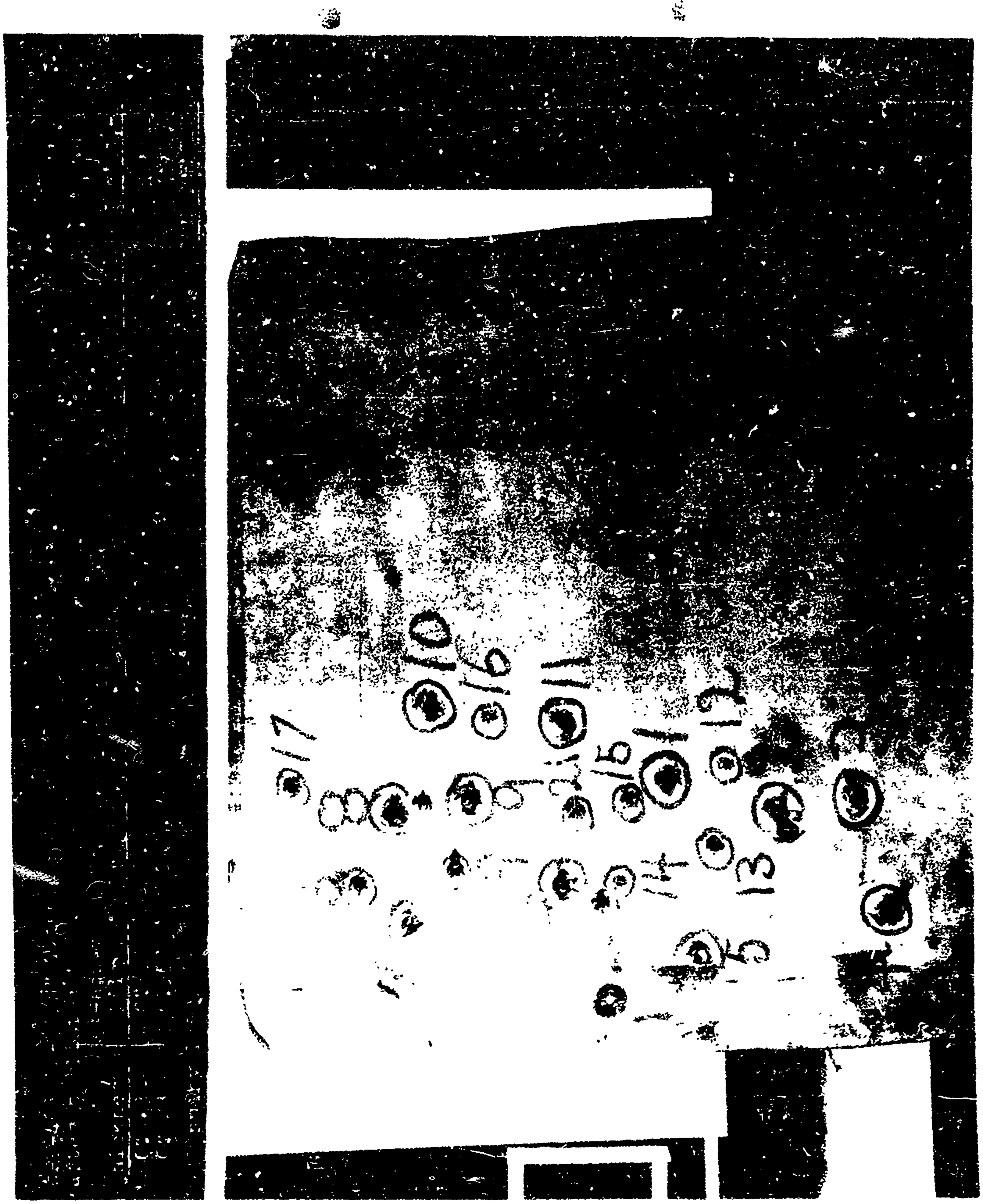
27 October 1949 Front View CONFIDENTIAL

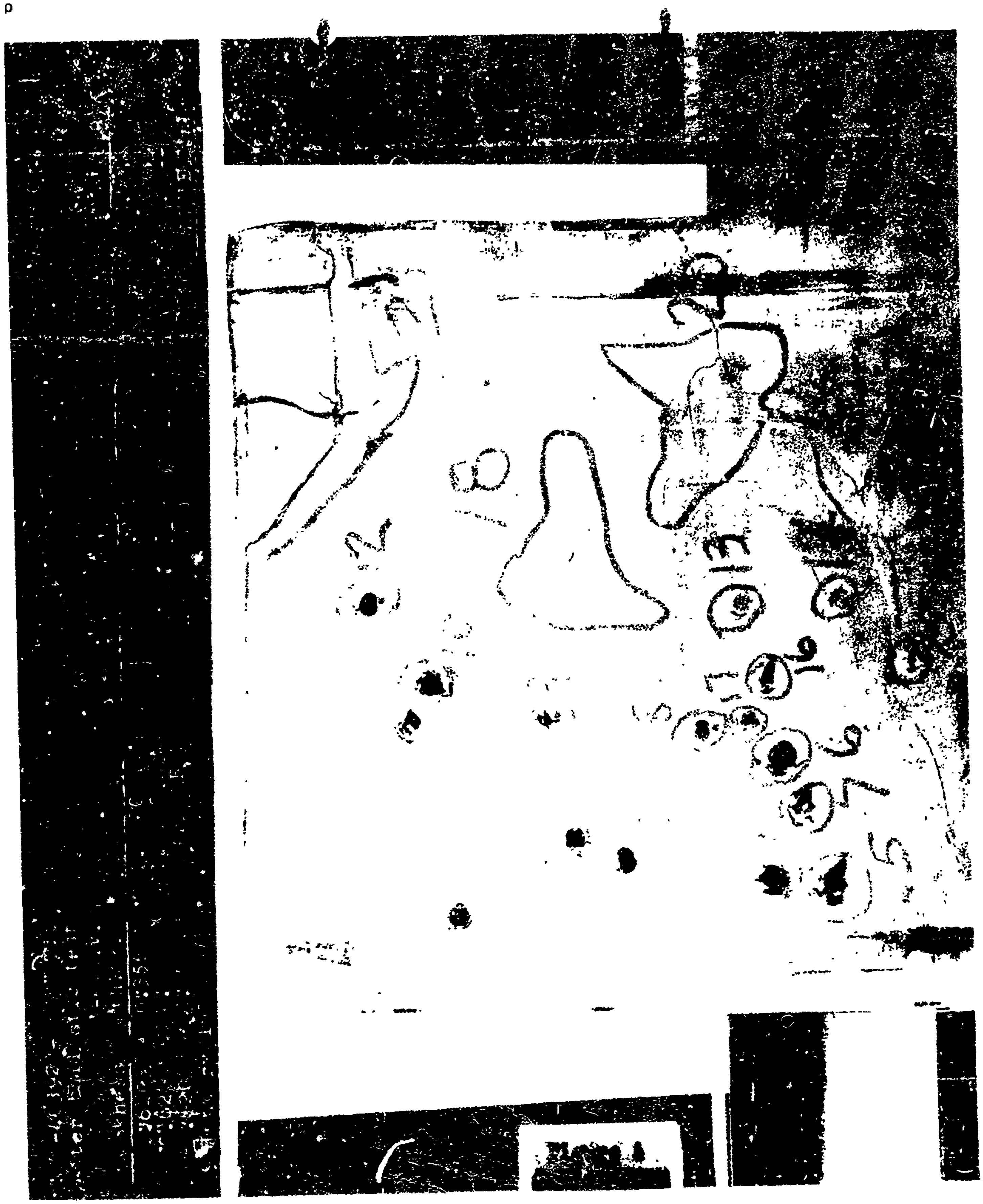
NPG-39648 - [illegible] Titanium Plate [illegible] (NPG [illegible]) [illegible] Remington Arms Co., after ballistic test.

Thickness	[illegible] thick.	[illegible]	[illegible]	[illegible]	"VL Min" Limit	"Vp50" Limit	F(e"/d,θ)
C-513	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] f/s	2701 f/s	[illegible]6,000
C-513	[illegible]	[illegible]	[illegible]	1.44	[illegible] f/s	2212 f/s	[illegible]6,500
C-513	[illegible]	[illegible]	[illegible]	[illegible]	--	2394 f/s	--

27 October 194[illegible] Back View CONFIDENTIAL







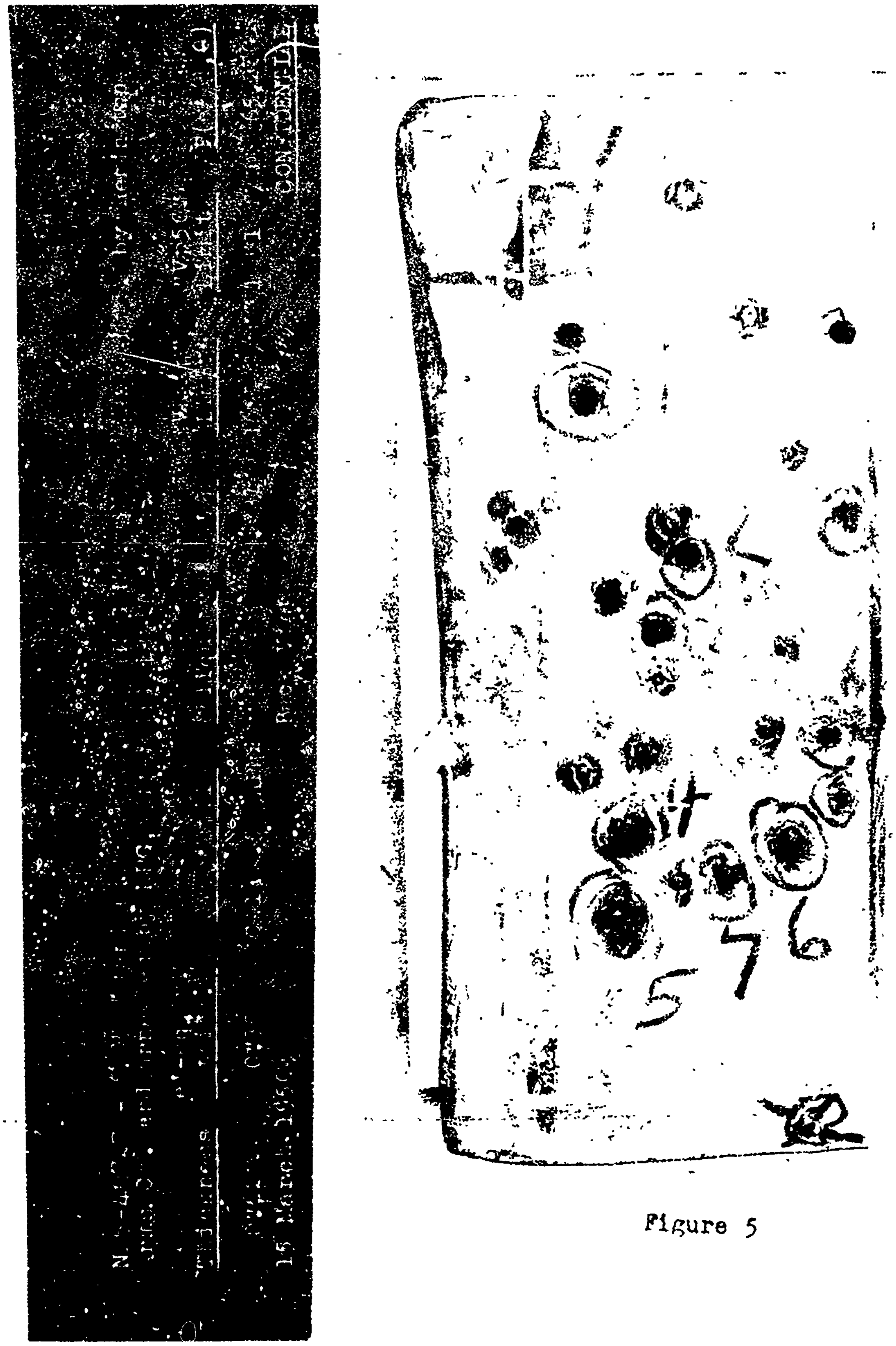
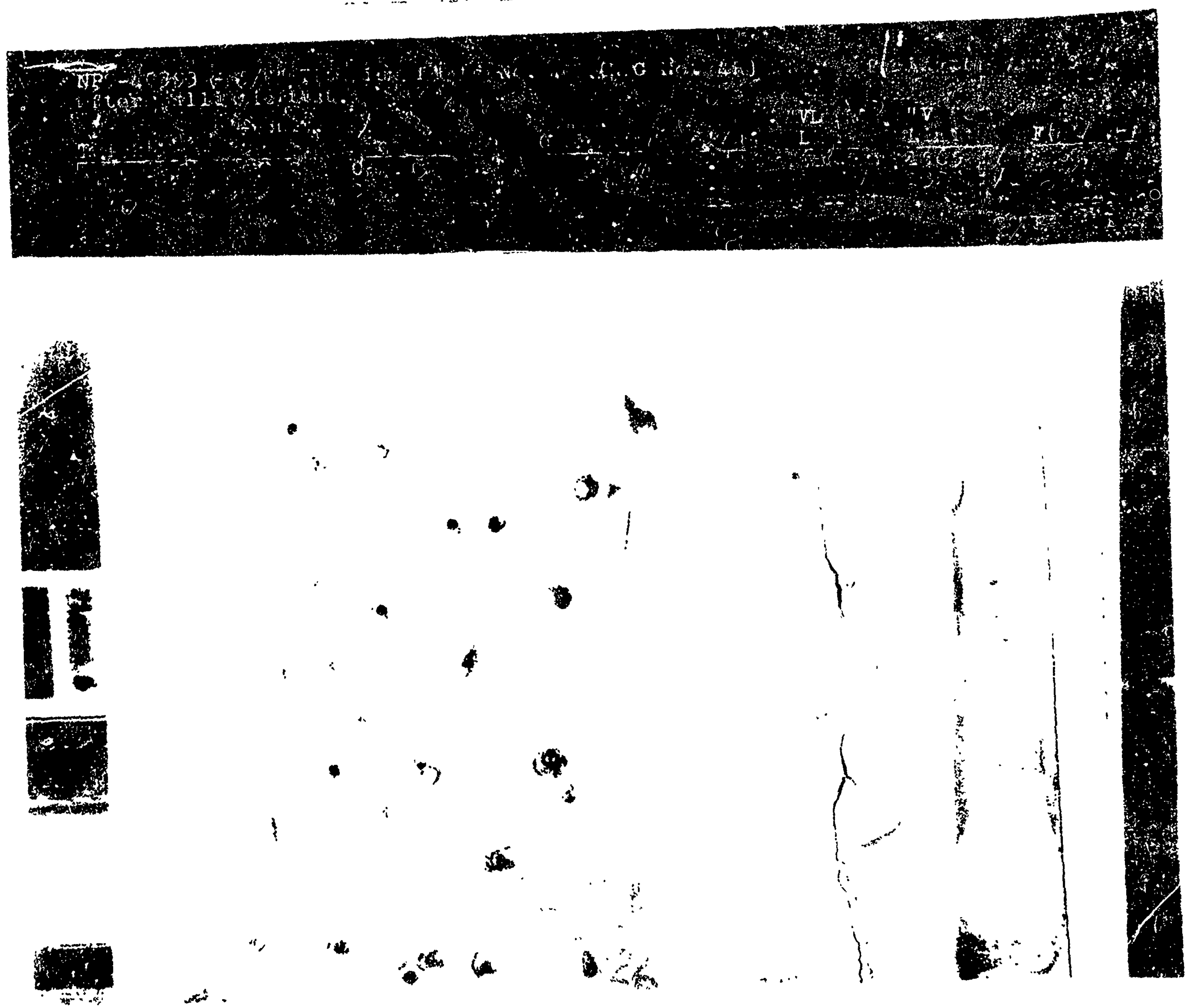


Figure 5



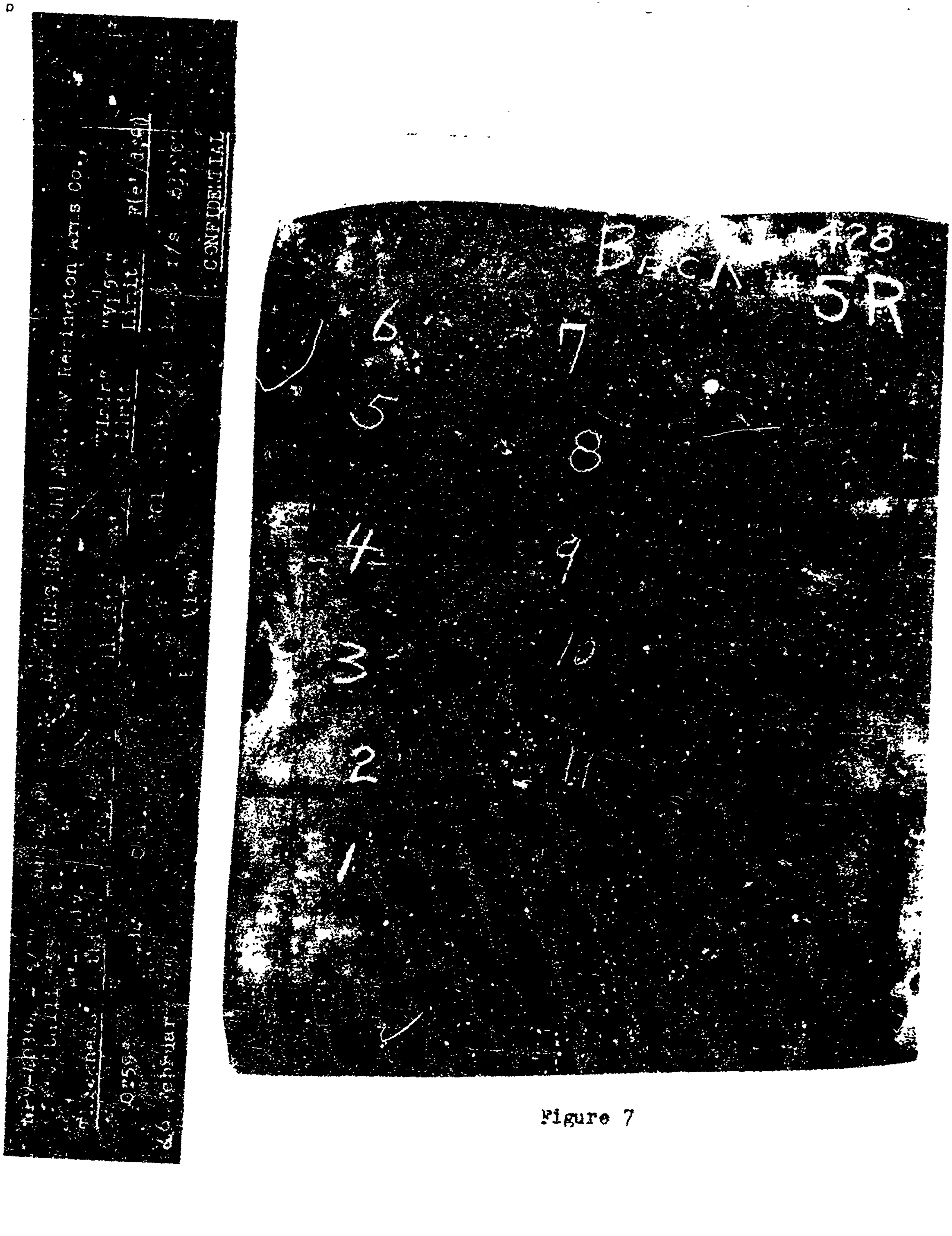


Figure 7

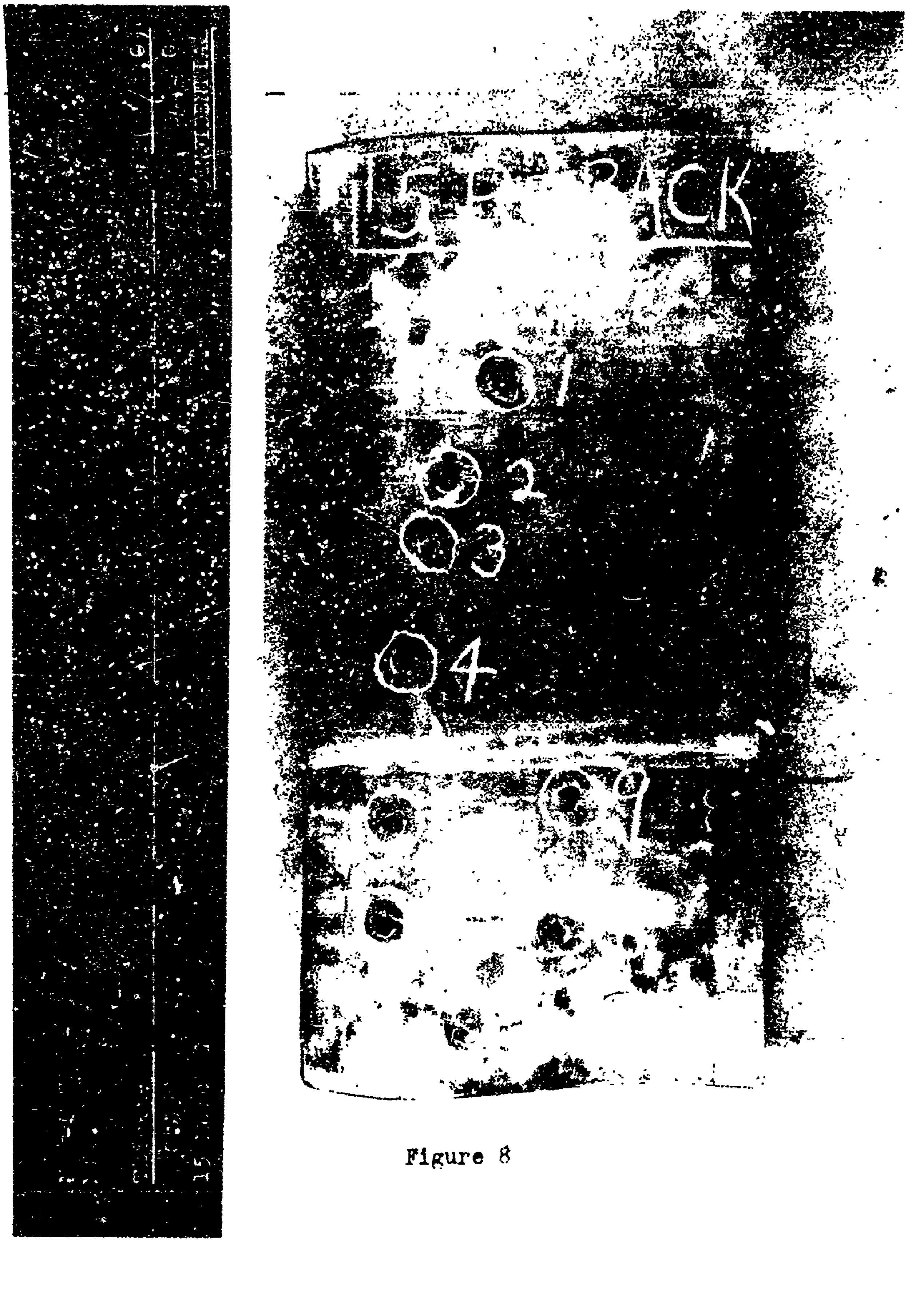


Figure 8

Figure 9

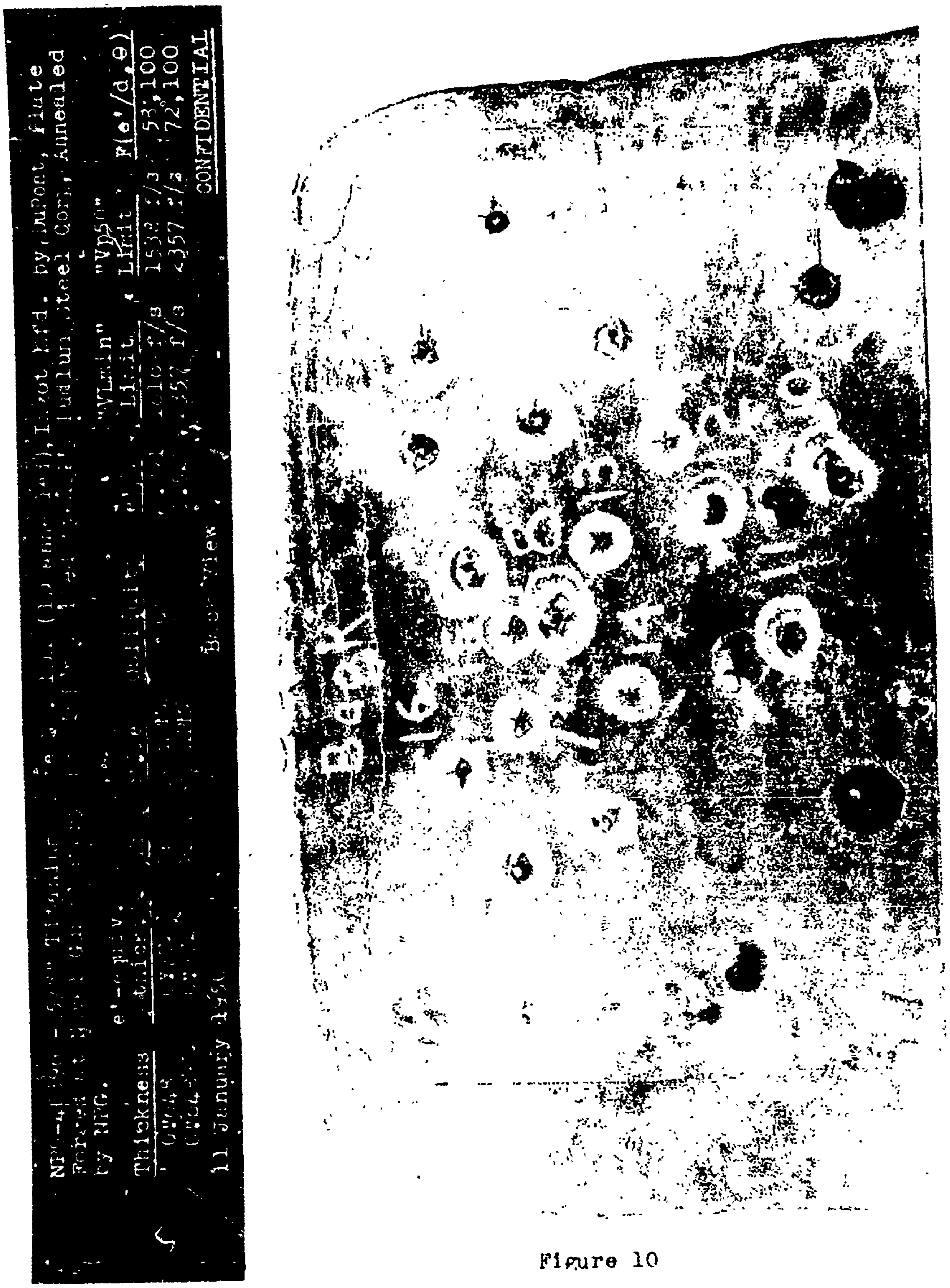


Figure 10

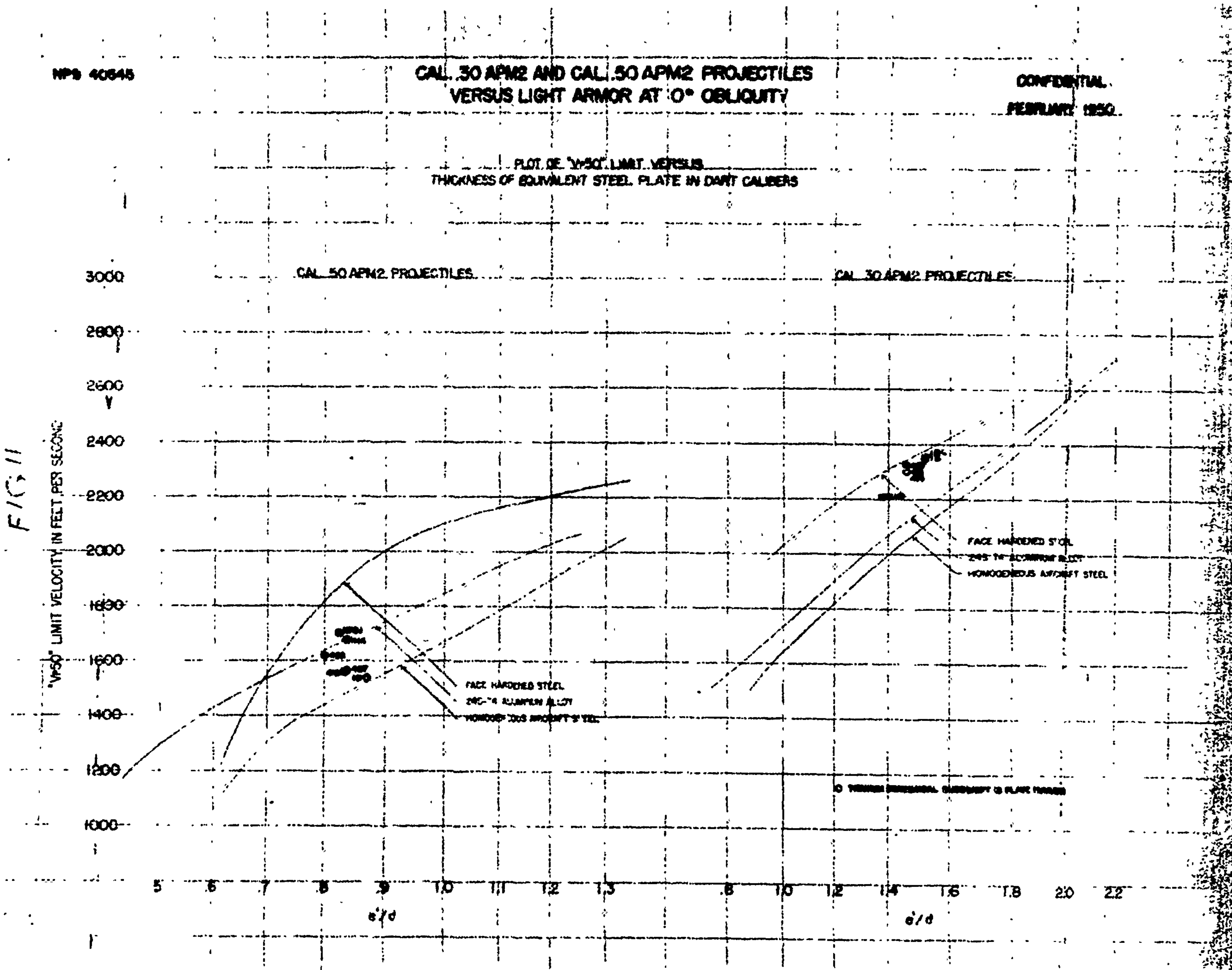
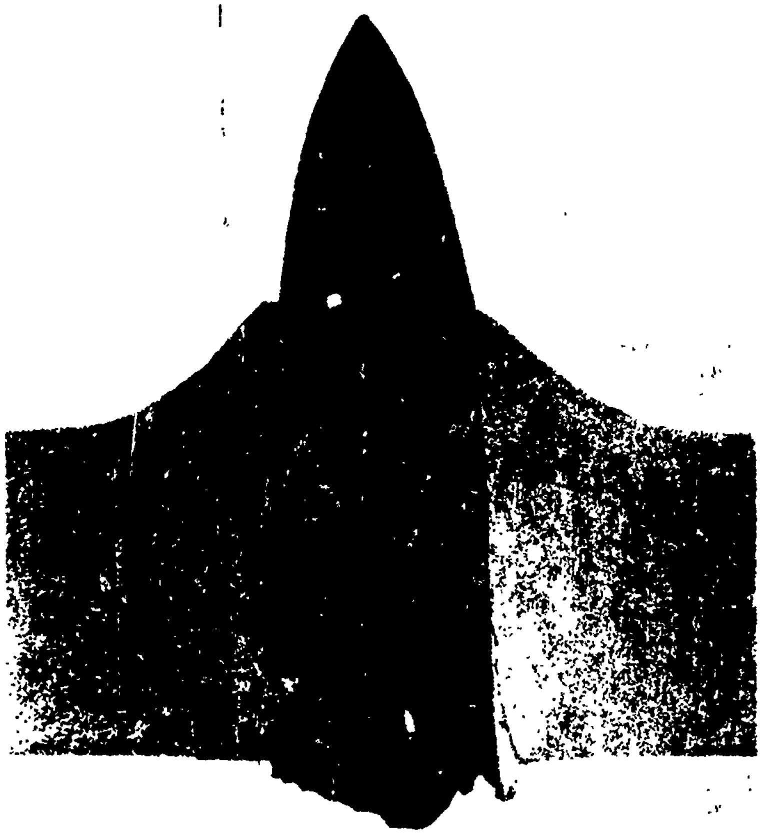
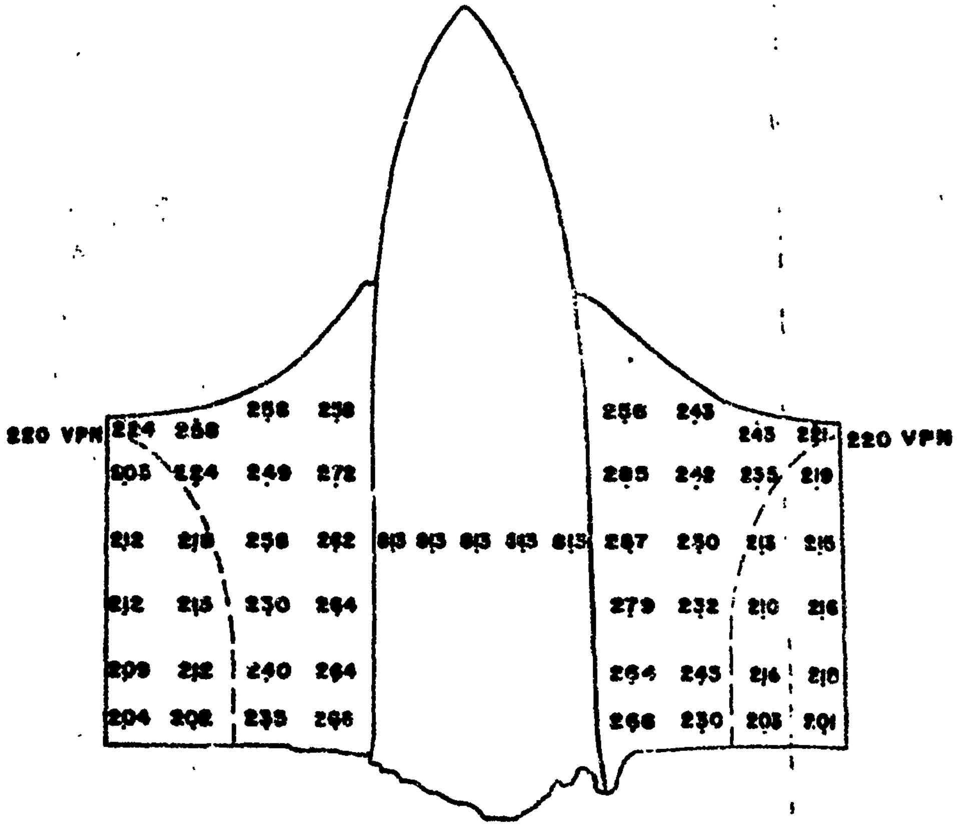

NPS 40645
CAL. .30 APM2 AND CAL. .50 APM2 PROJECTILES
VERSUS LIGHT ARMOR AT 0° OBLIQUITY
CONFIDENTIAL
FEBRUARY 1950
PLOT OF "V50" LIMIT VERSUS
THICKNESS OF EQUIVALENT STEEL PLATE IN DART CALIBERS
CAL. .50 APM2 PROJECTILES
CAL. .30 APM2 PROJECTILES
"V50" LIMIT VELOCITY IN FEET PER SECOND
3000
2800
2600
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
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
e'/d
e'/d
FIG 11

Fig. 11



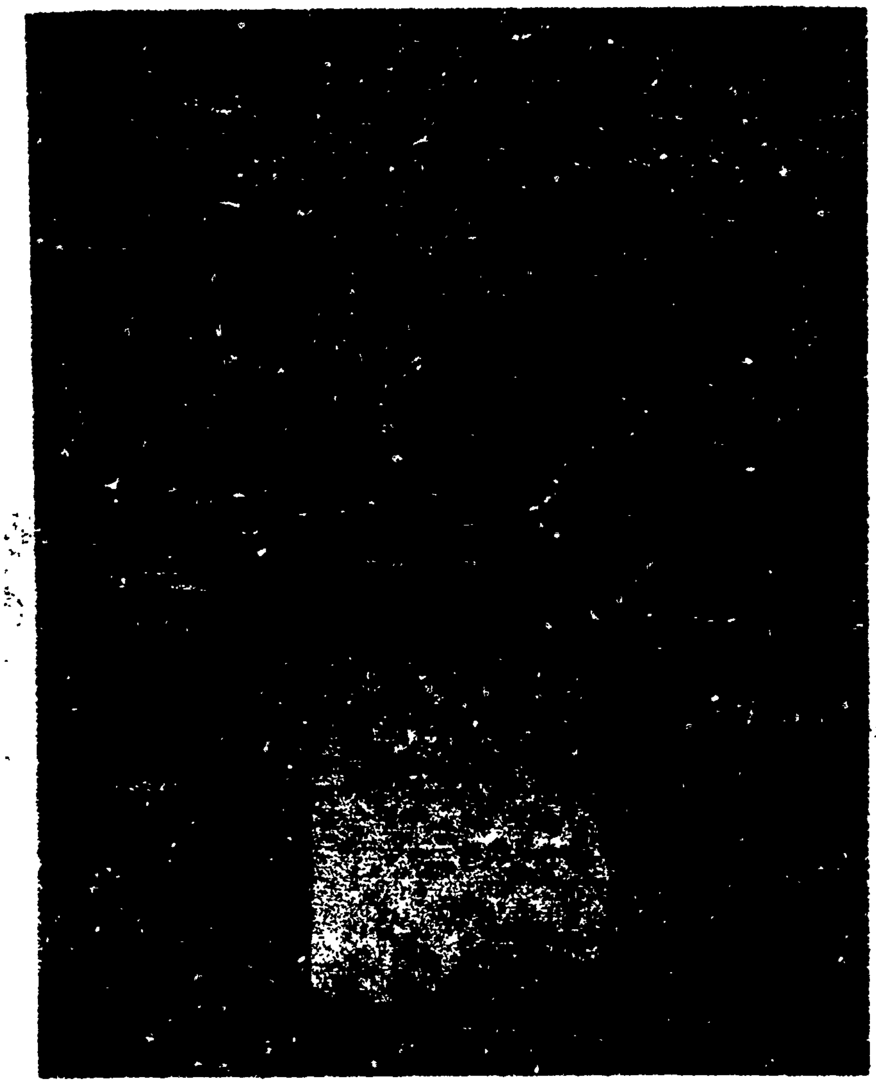


CROSS SECTION OF ROUND NO. 10, CAL. .50 APM2, STUCK IN PLATE, BASE OFF
HARDNESS PATTERN OF SURROUNDING ARMOR
REMINGTON NO. 1 TITANIUM ARMOR PLATE, 5/8" THICK
Hardness Values: Vickers Pyramid (10 kg)
Etch: HF, 1 Part; Glycerine, 1 Part
Magnification: 2X
Oblique Illumination

NPG 40082

CONFIDENTIAL

Figure 12



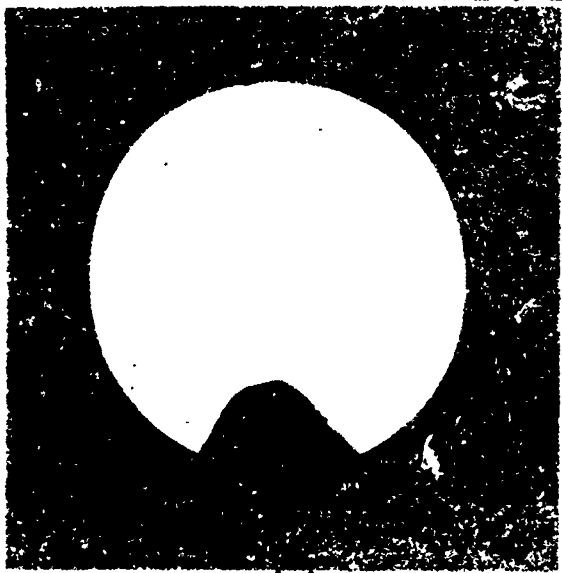
Etched Section Through Round No. 10, Cal. .50 APM2, Stuck in Plate, Base off

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



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.

(a)

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.

(b)

Plastic Titanium

(a)

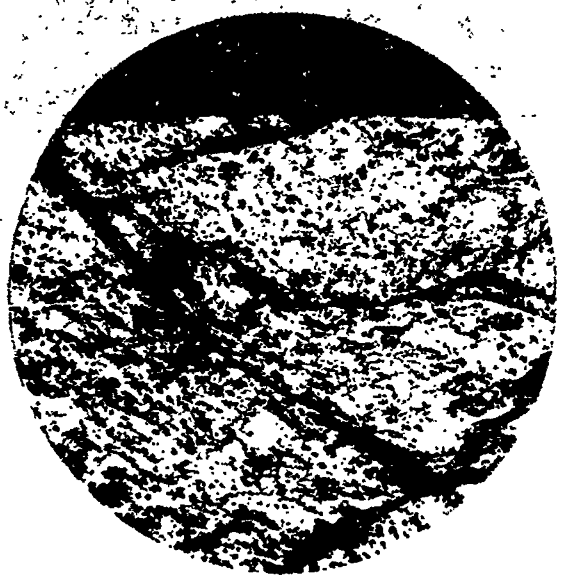
NP9-40617

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)

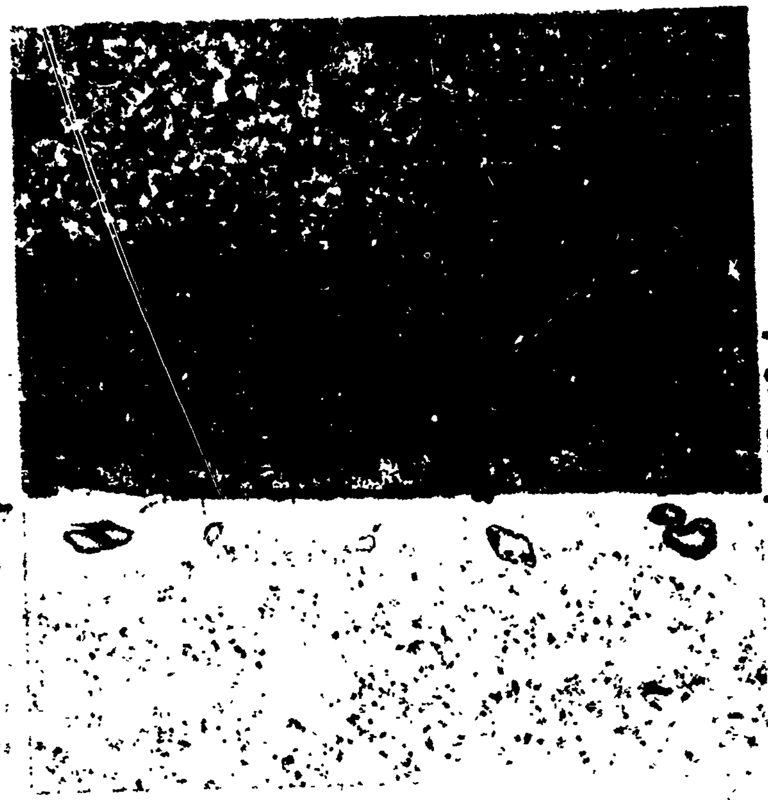
NP9-40618

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

Cal. .50 APM2
Steel
Dart

Titanium

985 KHN

980 KHN

980 KHN

850 KHN

630 KHN

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

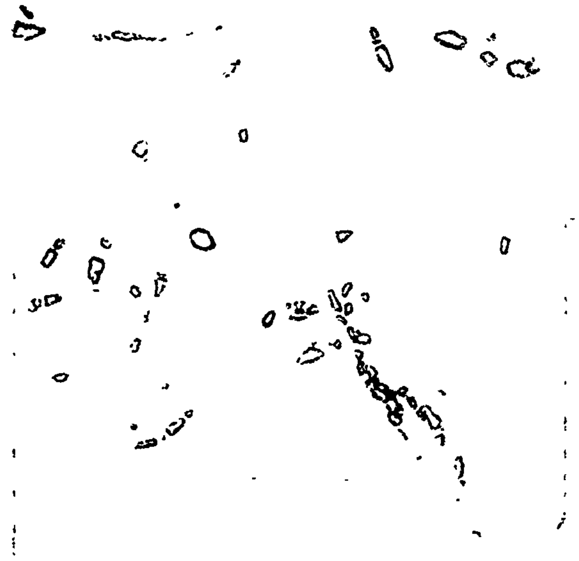
Corner of Plate

Magnification: 100X

Unetched.

Similar to (a) above.

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



NP9-40621

Center of Plate

Magnification: 100X

Unetched.

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

(a)

NP9-40622

Corner of Plate

Magnification: 100X

Unetched.

Similar to (a) above.

(b)

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

(a)

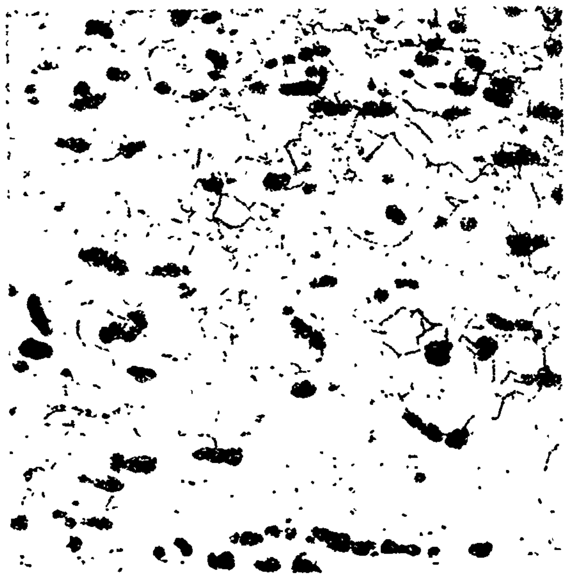
NP9-40623

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

(a)

NP9-40626

Center of Plate

Magnification: 100X

Etch: 3% HF, 3% HNO_3, H_2O

Equi-axed alpha titanium grains.

(b)

NP9-40627

Corner of Plate

Magnification: 100X

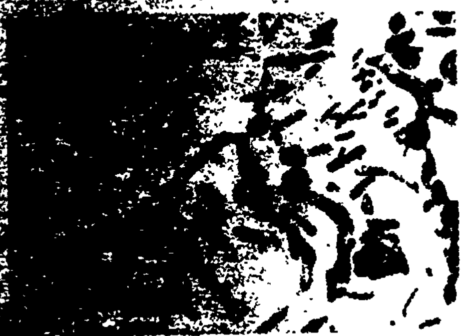
Etch: 3% HF, 3% HNO_3, H_2O.

Equi-axed alpha titanium grains.

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

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

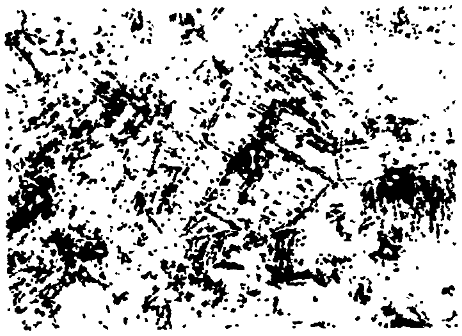
1625°F
5% Transformed
D-4.52
R_A-58.4



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

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

(a)

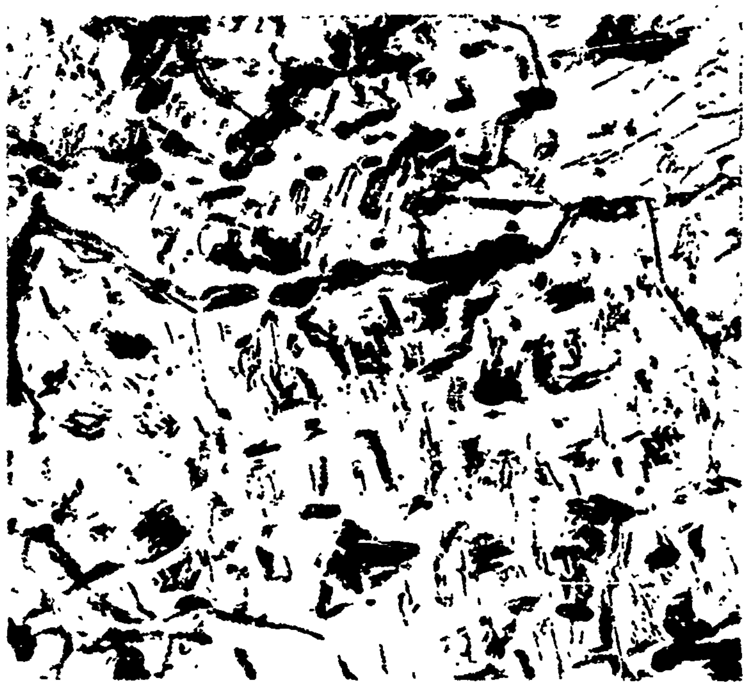
NP9-40629

Titanium Plate 1R
Material as received.

Magnification: 250X

Etch:

Equi-axed alpha grains.



(b)

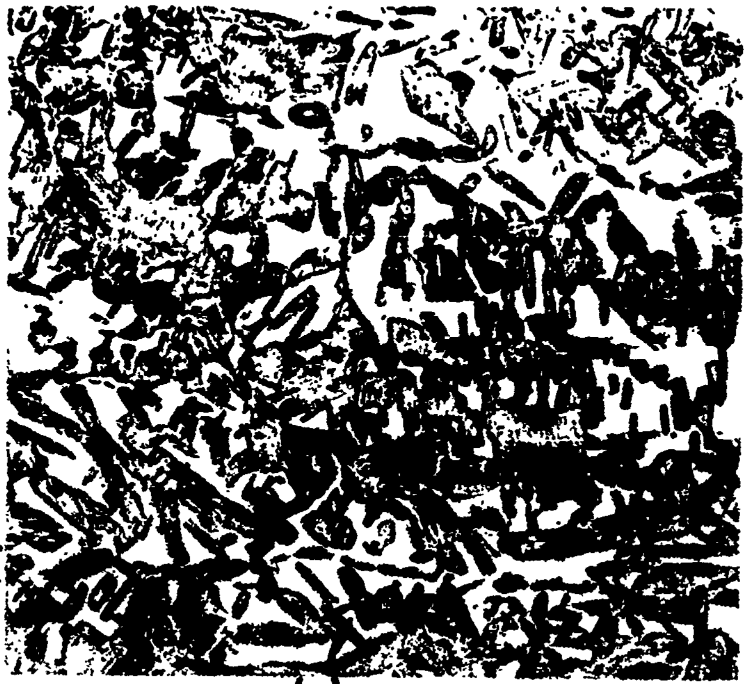
NP9-40630

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)

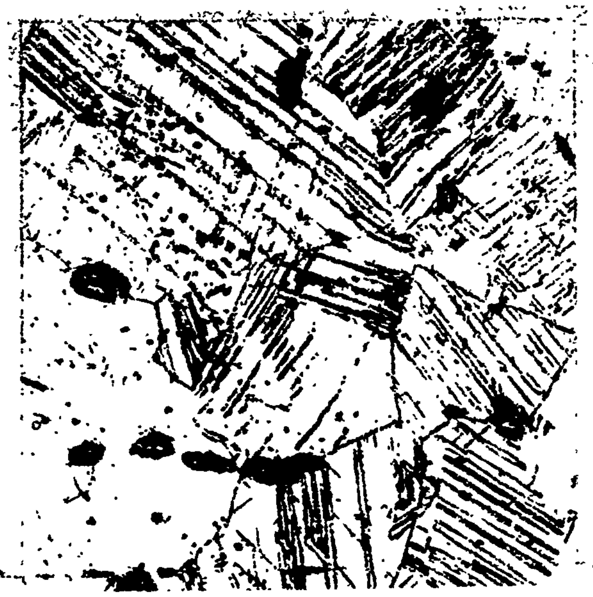
NP9-40726

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

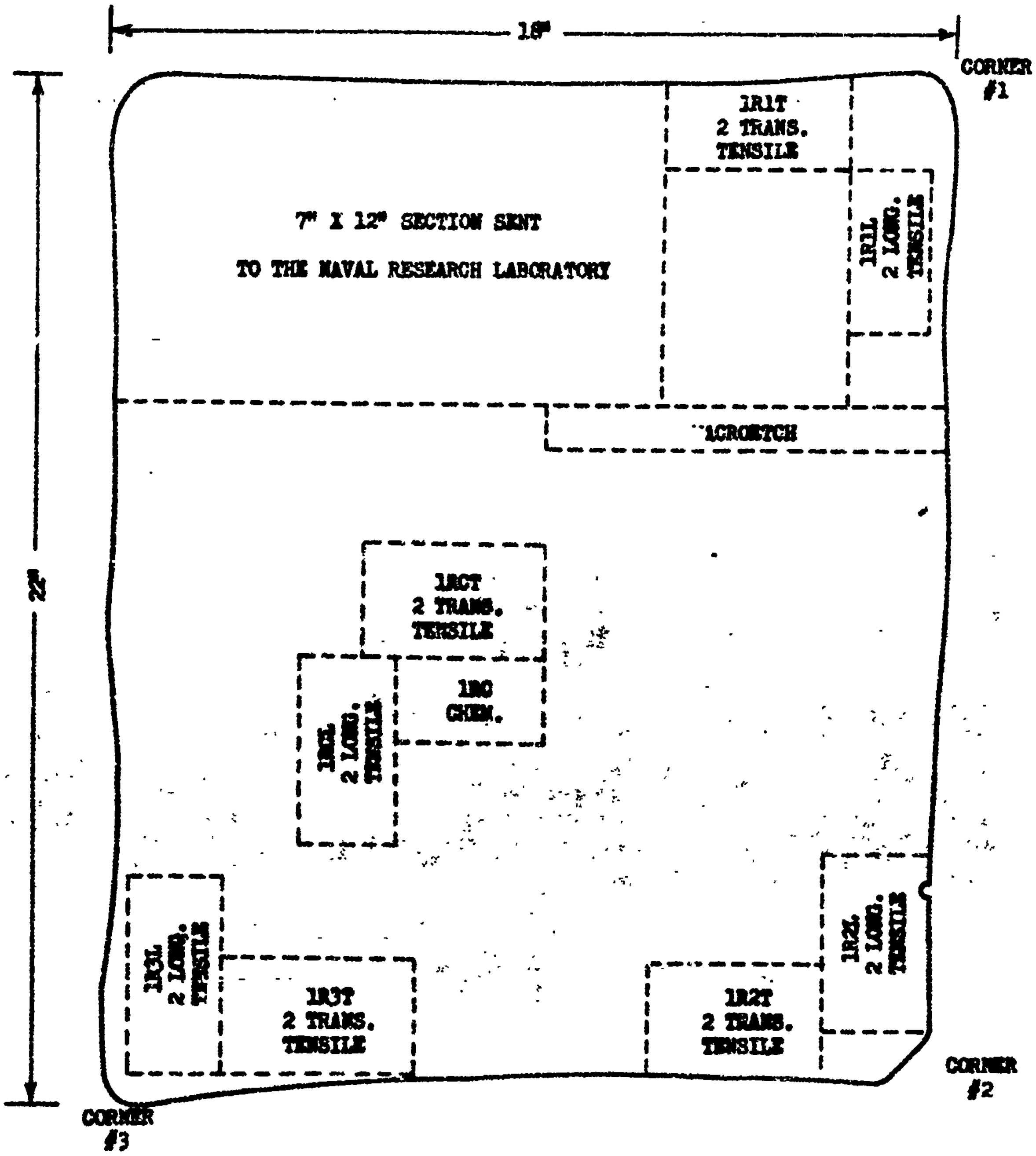
Titanium Plate 1R

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.



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

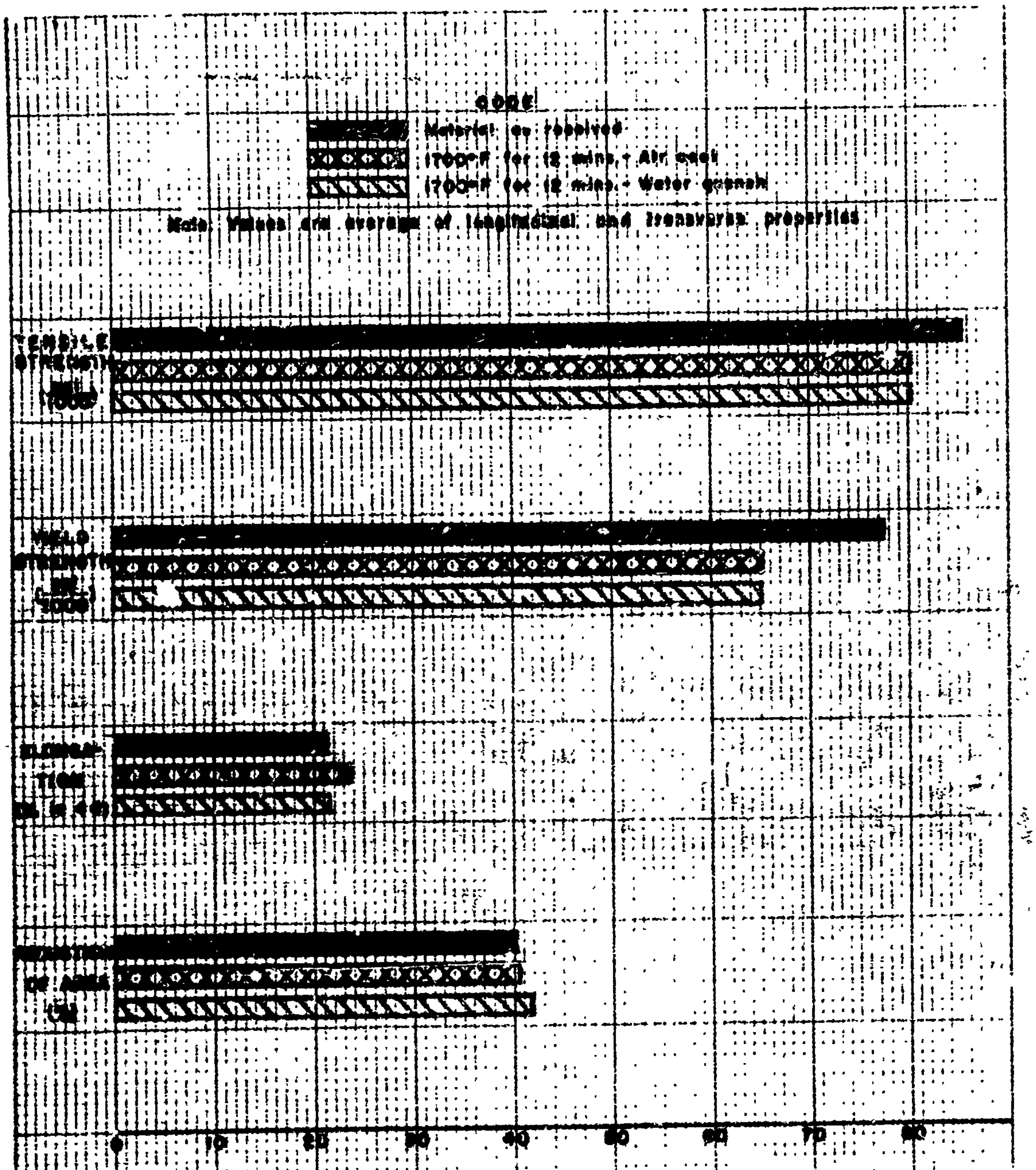
CORNER OF PLATE
(CODE 1R3)
HEAT TREATED AT NPG
1700°F FOR 12 MINS.
WATER QUENCH

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

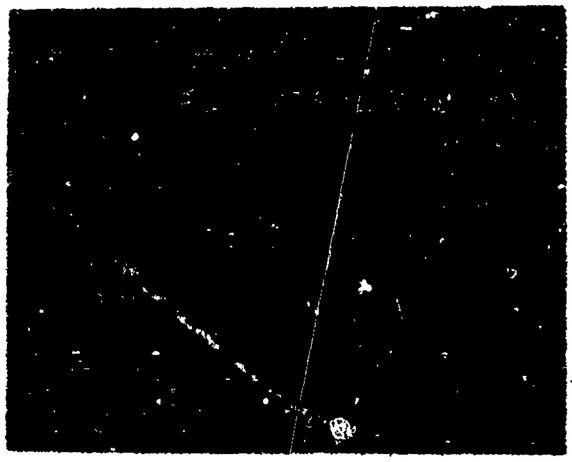
CONFIDENTIAL

NP9-40607

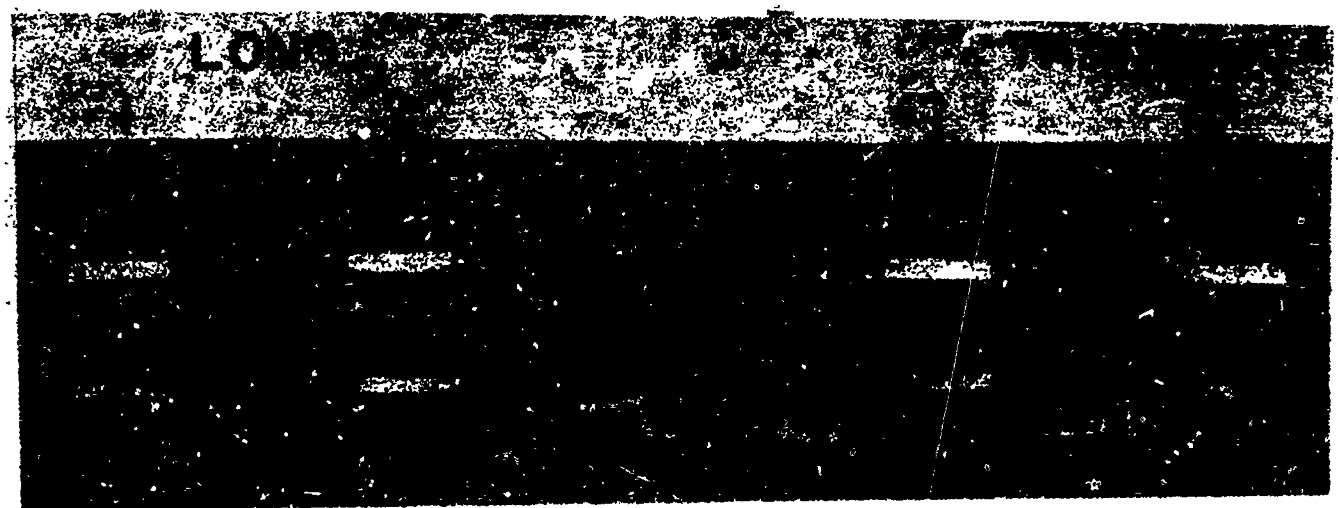
Titanium Plate No. 1R

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

Scale: Actual size.



(a)

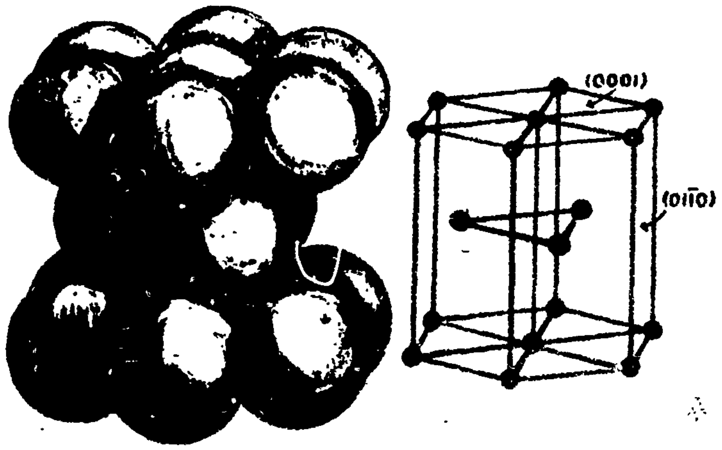


(b)
NP9-40608

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



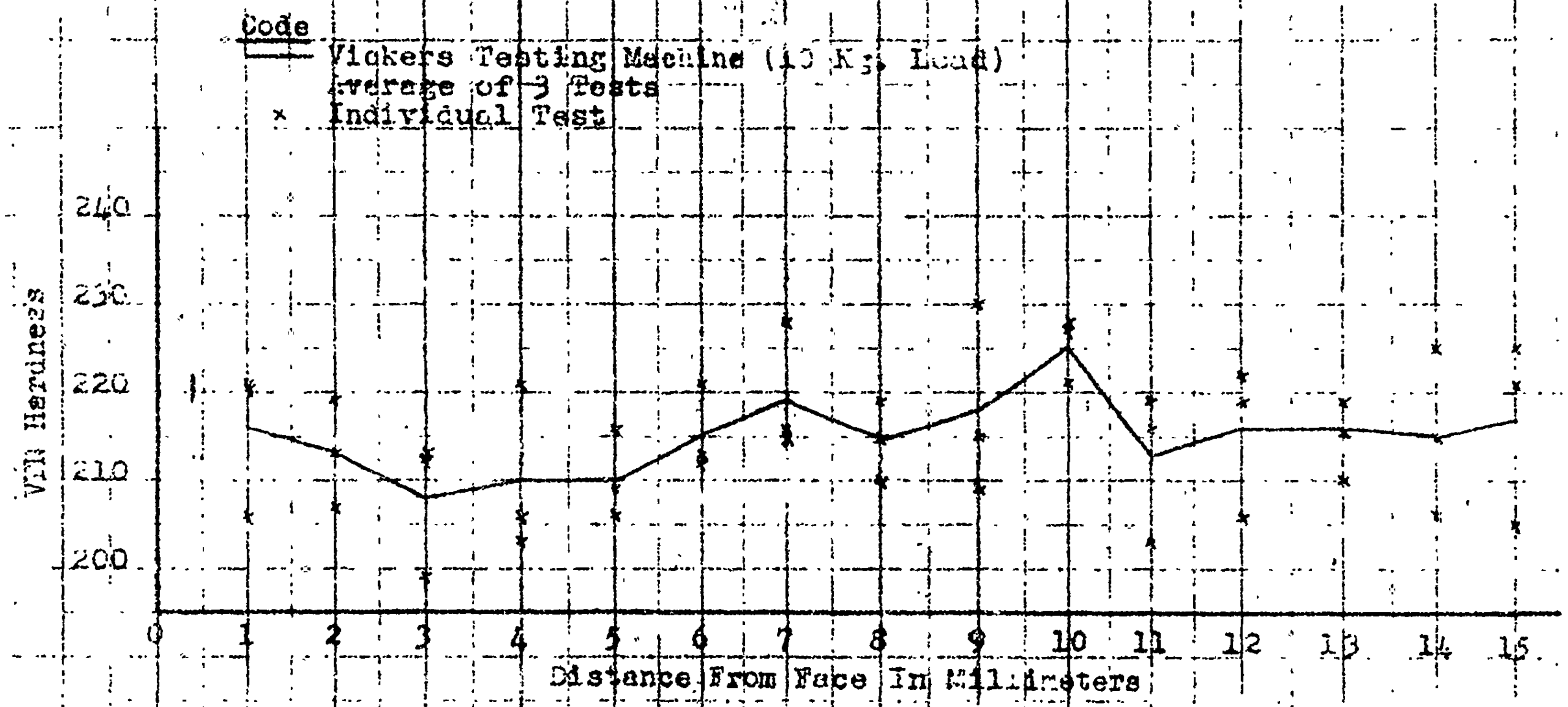
(from "The Structure of Metals and Alloys" by Wm. Hume-Rothery)

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).

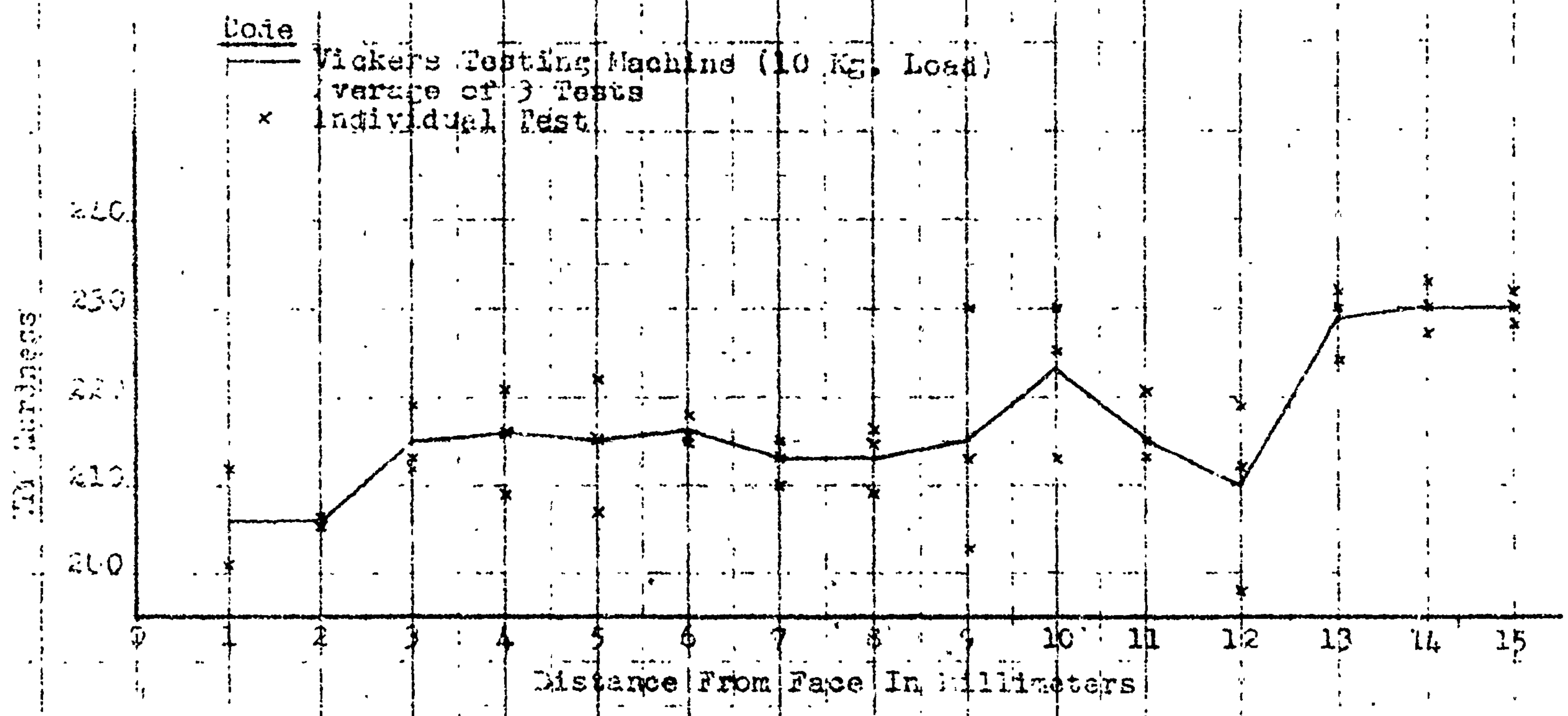
NP9-40628



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

Figure 11

MPO 40089 11 January 1950 CONFIDENTIAL



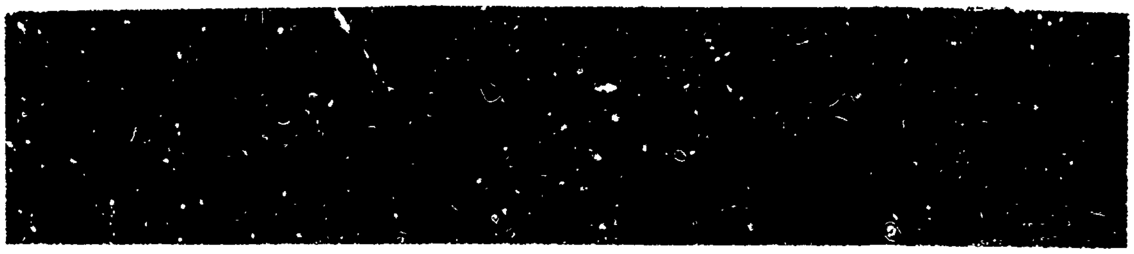
SERIES OF HARDNESS TESTS ACROSS TRANSVERSE SECTION
OF REMINGTON NO. 1 TITANIUM ARMOR PLATE, 5/8" THICK

NF9 40090

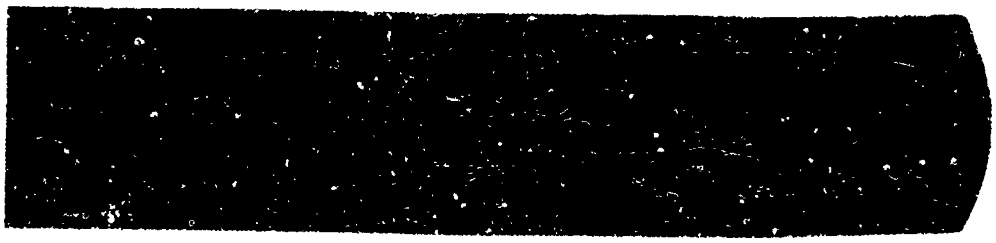
11 January 1950

Figure 32

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

Center  I

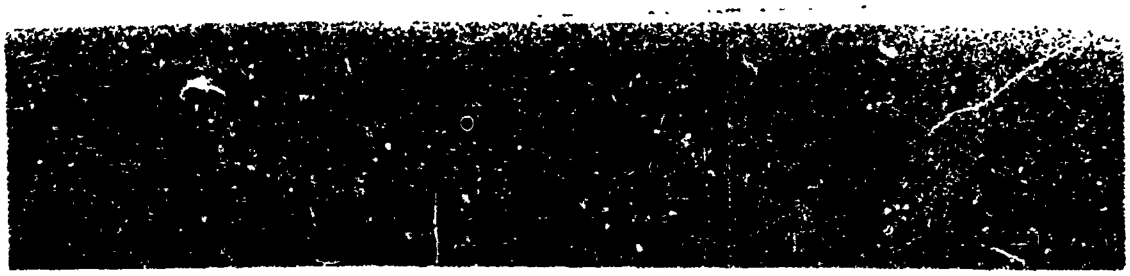
I  II

II  Edge

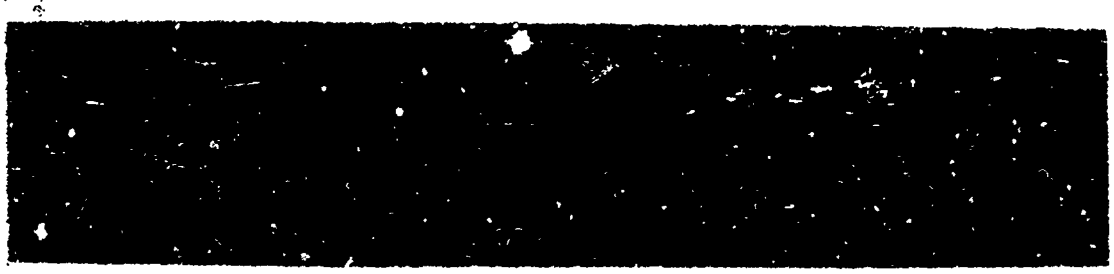
Macroetched Sections Extending from Center to Edge.
Remington No. 1 Titanium Armor Plate, 5/8" Thick.
Etch: Boiling 50% HCL
Magnification: 2X
Streaks indicate slight segregation.

NP9-40615

Center

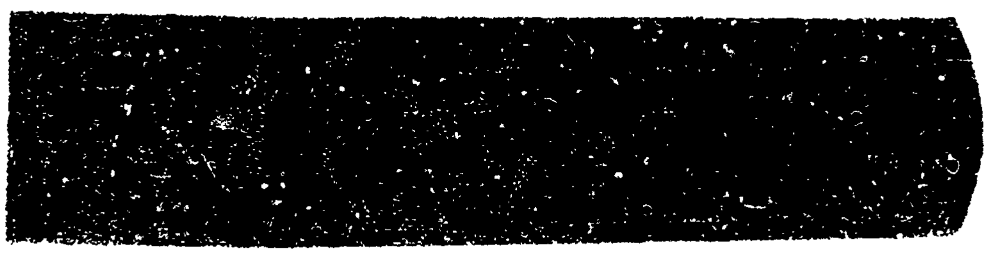


I



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
	Long.	1	77,400	66,000	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	4[illegible].9	9.8	36.7
CORNER OF PLATE (CODE 1R1)	Trans.	1	84,600	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
	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
CENTER OF PLATE (CODE 1RC)	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.	Trans.	1	81,200	67,900	24.4	40.4	7.6	35.6
Air Cool		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.	Trans.	2	78,700	63,100	23.6	41.6	9.2	35.8
Water Quench		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 NPG

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	Minor Axis
CENTER OF PLATE (CODE 1RC)	Long.	1	44	20.4	6.0	15.9
		2	48	23.6	7.2	17.7
		Ave.	46	22.0	6.6	16.8
MATERIAL AS RECEIVED	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 (CODE 1RC)	Long.	1	15	99.2
		2	15	100.0
		Ave.	15	99.6
MATERIAL AS RECEIVED	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).

X X X X X	TEMPERATURE	TIME					
ANNEAL			YP				
NORM			TS				
HARDEN			EL		PLATE		
QUENCH			RA		SIZE	12 x 21.5	
DRAW					WEIGHT	[illegible]	
GAUGE	[illegible]	[illegible]	[illegible]	C	DATE	27 Oct. 1949	
PROJ.	Cal. .50 AP M2	Cal. .30 AP M2	20 mm HE	Mn	MFR.	Remington Arms Co.	
GUN	273	129-373	104723	S	CONTR.	NORD 10583 (Exp.)	
RANGE	1	1	3	P	TYPE	Jato nozzle	
OBL.	0	0	70	Si	SPECS.		
RC	Vpmin	Vpmin	Vpmin	Ni	PLATE	NPG.1	
LC	1637	2216	2401	Cr	GROUP		
HI	— 1/50	2207	2554	Mo	HEAT		
LIMIT	1635 1701	2212 2212	[illegible]		BHN	235	
RESULT	Vpmin 1709	2212			STEEL		T-3004-1

RD.	BULLET	CHARGE	STR. VEL	OBL.	YAW	PENET	BULLET	CONDITION OF PLATE
1	Cal. .50 M2	9.9	1745	0	0	X	RJ	Disregard Hit plate frame 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	2246	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

CONFIDENTIAL

Encl. (   )

PLATE

1 - [illegible]

T-3014-1

RD.	BULLET	CHARGE	STRIKING VELOCITY	OBL.	YAW	PENET.	BULLET	CONDITION OF PLATE
19	Cal. 30 [illegible]	2.68	2226	0	0	C	NR	1/4" Hole 1/3 PO
20	"	2.68	2202	0	0	I	C/P	1/8" Nose G. Pot
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.						

LIGHT ARMOR FIRING RECORD

FRAC-... -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 #31
[illegible]	[illegible]	[illegible]	[illegible]			[illegible]	[illegible]	[illegible] 2/3 PO
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible] Nose 2/3 PO
[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] Nose 1/3 PO
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] 1/4 PO
[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	[illegible]	92	165[illegible]	0	[illegible]	I	CIP	3/8" Nose 2/3 PO
9	"	92	1678	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	1/4" 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	1/4" Hole G Pat.
17	"	275	[illegible]5	0	0	C	NR	1/4" Hole 1/4 PO
18	[illegible]	[illegible]	[illegible]	0	0	I	CIP	[illegible]

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FRAC-3-10-60-4000

[illegible]

SHEET NO.

Encl. (   )

PLATE

417

14 Jan 1950

T-3014-1

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.

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PRBC-3-10-40-8000

SHEET NO.

X X X X X	TEMPERATURE	TIME					
ANNEAL				YP			
NORM				TS			
HARDEN				EL		PLATE	
QUENCH				RA		SIZE	18"x18"
DRAW						WEIGHT	35.5
GAUGE	0.622	0.622	0".622	C		DATE	9, 19 Jan. 1950
PROJ.	Cal. 50 APM2	Cal. 30 APM2	20MMHE	Mn		MFR.	Remington Rand Co
SUM	297	[illegible]	104733	S		CONTR.	[illegible]
RANGE	1	1	2	P		TYPE	Titanium
OBL.	0	0	2-13	Si		SPECS.	
RC	Torm n	Torm n		Ni		PLATE	407
LC	1542	2348		Cr		GROUP	
HI	1527 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 AP	8.6	1555	0	0	I	CIP	5/16" Nose 1/3 PO
2	"	8.7	1542	0	0	X	FCIP	5/16" Nose 1/3 PO
3	"	8.7	1555	0	0	I	RJ	1/8" Hole 1/4 PO
4	"	8.7	1527	0	0	I	RJ	1/8" Hole G. Pet
5	"	8.8	1604	0	0	I	CIP	5/16" Nose 1/3 PO
6	"	8.9	1641	0	0	X	FCIP	5/16" Nose 1/3 PO
7	"	8.8	1600	0	0	X	CIP	1/2" Nose PO
8	"	8.9	1650	0	0	C	NR	1/2" Hole 1/3 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 1¾" from edge of plate causing 5" [illegible]
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 AP 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
PSBC-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 [illegible]	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		0	I	CIP	1/4" Nose G. Pet
24	"	275	2282		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	20MM HE	400	2272	20	—	I	HO	~~9" Thru Crack~~ HB 2", 1" Cracks
28	"	410	2311	20	—	I	HO	1/8" open ~~9" 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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PSBC-3-19-48-3300

LIGHT ARMOR FIRING RECORD

PRVC-APG-69 SHEET NO.

X X X X X	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. 30 M2	[illegible]	[illegible]	Mn	MFR. [illegible] Arms Co.
GUN	[illegible]	[illegible]	[illegible]	S	CONTR.
RANGE	1	1	2	P	TYPE [illegible]
OBL.	0	0	20	Si	SPECS.
RC	VPmin	VPmin		Ni	PLATE 415
LC	1565	2319	2331	Cr	GROUP
HI	1576 VP50	2313 VP50	2285	Mo	HEAT
LIMIT	1555 1564	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. 30 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" Front spall on 3 Cal. 50 rounds 3/4" Spall on most Cal. 30 rounds [illegible]

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PRVC-S-30-48-C[illegible]

LIGHT ARMOR FIRING RECORD
PRNC-NPG-69A

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 M3	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", 5" rotated in front 2", 2",
21	"	410	2321	20	—	C	HO	3" x 5" Section out 2" Thin Crack H… 5" From edge of Plate

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PNF-3-10-40-6000

LIGHT ARMOR FIRING RECORD
PRRC-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[illegible]	0.548	C	DATE 9 Jan 1950
PROJ.	Cal 50 M2	Cal 30 M2	Mn	MFR. DUPONT - NGF - AL
GUN	299	[illegible]	S	CONTR.
RANGE	1	[illegible]	P	TYPE TITANIUM
OBL.	0	[illegible]	SI	SPECS.
RC	V50 MIN	V50 MIN	Ni	PLATE 13
LC	1497	2376	Cr	GROUP
HI	1455 V50 [illegible]	2311 V50	Mo	HEAT
LIMIT	1471 [illegible]	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 Started
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 30 APT 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 2/3 PO
17	Cal 30 M2	27.0	2287	0	0	I	CIP	1/8" Nose 1/2 PO
18	"	26.5	2256	0	0	I	CIP	PPB

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PRRC-B-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.

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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 [illegible]	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 NP
LC	[illegible]	2378	Cr		GROUP	
HI	[illegible] V50	2336 V50	Mo		HEAT	
LIMIT	1586 1538	2357 2357			BHN	
RESULT	V50 1616	2357			STEEL	

T-3014

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 1½" x 1¾" B Spall
3	"	8.7	1562	0	0	I	RJ	1/8" Hole ½ PO
4	"	8.7	1574	0	0	X	CIP	5/16" Nose ½ 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 ½ PO
9	Cal 30 M2	275	2272	0	0	I	RJ	1/32" Nose
10	"	275	2258	0	0	I	CIP	1/8" Nose ½ 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	FCIP	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	2391	0	0	X	CIP	7/16" Nose 2/3 PO

LIGHT ARMOR FIRING RECORD
PRRC-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 M2	280	2328	0	0	I	CIP	1/8" Nose 1/4 F O

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	0.518		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-max 1633				STEEL	

T-[illegible]-1

RD.	BULLET	CHARGE	STR. VEL.	OBL.	YAW	PENET	BULLET	CONDITION OF PLATE
1	Cal.50ML	8.5	1561	0	0	I	CIP	3/8" Nose G Pet.
2	"	8.6	1508	0	0	I	RS	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

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LIGHT ARMOR FIRING RECORD

PRRC-RPN-69

SHEET NO.

X X X X X	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 V50	Mo		HEAT	2ND Test.
LIMIT	1611 1630			BHN	
RESULT	V50 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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LIGHT

X X
ANNEAL
NORM
HARDEN
QUENCH
DRAW
GAUGE
PROJ.
GUN
RANGE
OBL.
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RESULT

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CON

LIGHT ARMOR FIRING RECORD

PRNC-EPC-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 ...	Mn	MFR. Remington Arms Co.
GUN	209	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			STEEL

V50 NAV 1655

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

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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 AP M2	Cal.30 M2	MN	MFR. Remington Arms Co.
GUN	299	1224973	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 1630	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.50 AP M2	8.8	1576	0	0	I	RJ	1/4" Hole
2	"	9.0	1668	0	0	C	NR	7/16"x1/2" Hole PO
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

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

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.

ΣV = 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

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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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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DIV: Ordnance (22)

SECT: Armor (2)

SUBJECT HEADINGS

Armor plate - Physical properties

Titanium - Physical properties

(Copies obtainable from ASTIA-DSC)

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