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Report No. 710/451
Watertown Arsenal

July 24, 1942

ARMOR PLATE

Further Studies of the Mechanism of Penetration of Homogeneous Armor Plate

OBJECT

To continue the study, by metallographic means, of the nature of the deformation produced in 1/2" thick homogeneous rolled armor plate by caliber .30 armor-piercing bullets.

REFERENCES

W. A. Report No. 710/197
W. A. Letter 470.5/3371
W. A. Letter W.A. 470.5/4731

Correspondence pertaining to this report is contained in Appendix A.

CONCLUSIONS

1. No discernable difference was found between deformations resulting from penetration of rotating and non-rotating armor piercing bullet cores.

2. Alternate light and dark etching rings around the penetration are revealed by an Oberhoffer etch on armor plate sectioned perpendicular to the direction of impact. These rings result from any one or the combination of the two following effects:

   a. Severe lateral compression of the segregation bands in the metal.

   b. Upward or downward bending of the bands so that the examined surface cuts transversely through the bands in the vicinity of the bullet hole.

3. From the evidence presented in this report, it would appear that the formation of "white layer" is related to impact, or high rates of deformation; whereas static penetration is characterized by the absence of the "white layer", indicating that there is a limiting velocity below which the "white layer" is not formed.

[illegible]. Hurlich
Jr. Metallurgist

Approved:

R. H. [illegible]
Colonel, Ordnance Dept.
Director of Laboratory

INTRODUCTION

Previous metallographic study (W.A. 710/197) of penetration of thin homogeneous armor by caliber .30 armor-piercing bullets has revealed severe distortion in the vicinity of the penetrations. On planes perpendicular to the direction of bullet penetration, the distortion revealed by Oberhoffer's* macroetching reagent shows itself in the form of thin concentric rings about the bullet hole. These rings gradually merge into the normal banded structure of the metal away from the vicinity of the penetration. On planes parallel to the direction of bullet impact, the distortion consists of the bending downward of the flow lines, or banding, to merge into the contour of the penetration.

In the vicinity of the penetrations are found randomly distributed "white layers", which are believed to be martensite formed by highly localized heating and rapid cooling of the metal in regions where severe slip and faulting of the armor plate has occurred.

It was considered desirable to continue the study of deformation produced in armor plate upon bullet impact to gain further information on the mechanism of penetration by armor piercing projectiles.

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Stannous Chloride	0.5 g.
Cupric Chloride	1.0 g.
Ferric Chloride	30 g.
Hydrochloric acid	50 c.c.
Ethyl Alcohol	500 c.c.
Water	500 c.c.

TEST PROCEDURE AND MATERIALS

ARMOR PLATE

Penetrations were obtained in two 1/2" thick homogeneous armor plates cut from a 36"x36" plate of the following chemical analysis:

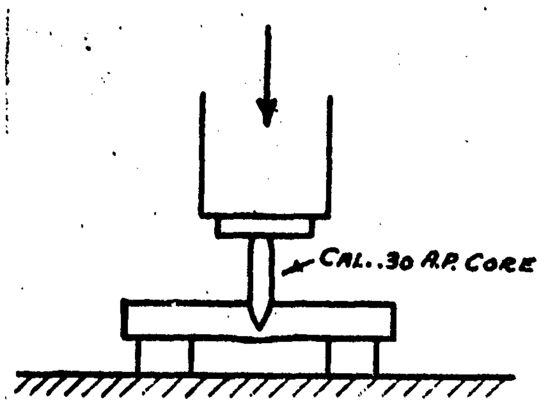
C	Mn	Si	S.	P	Ni	Cr	Mo	V
.26	.53	.25	.015	.011	3.47	1.47	.51	.07

The two plates had the following properties:

Plate No.	Brinell Hardness	Ballistic Limit-ft/sec.	Projectile
8831	363	2450	Cal. .30 A.P.
620-2	366	2466	Cal. .30 A.P.

TEST PROCEDURE

Plate No. 8831 was ballistically tested at Watertown Arsenal using preloaded caliber .30 A.P. ammunition at normal impact, after which a section was cut from the plate and penetrations made in the section by pushing caliber .30 A.P. cores into the plate under the head of a tensile machine, as illustrated in the following diagram:



The deformation around the statically produced penetrations was compared to that around impact penetrations.

The following penetrations made in plate SS31 were sectioned either in planes transverse to the armor plate or parallel to the surfaces of the plate:

Penetration Number	Velocity Ft/sec.	Method of Obtaining Penetration	Depth of Penetration	Plane Sectioned
SS31-Z	2500	Fired from Mann* Barrel	Complete	Parallel to surface
SS31-2100	2100	" "	.470"	Transverse
SS31-2150	2150	" "	.485"	Transverse
SS31-ST1	Static	Statically under tensile machine	.198"	Transverse
SS31-ST2	Static	" "	.424"	Transverse
SS31-SL	Static	" "	Complete	Parallel to surface

Plate No. 620-2 was sent to Frankford Arsenal to obtain penetrations with rotating and non-rotating caliber .30 A.P. cores to observe the differences, if any, in the deformations produced. The rotating cores were copper plated to take the rifling while the non-rotating cores were unplated.

The following penetrations in plate No. 620-2, produced by firing caliber .30 A.P. bullet cores at the plate, were studied in this investigation:

Penetration No.		Velocity	Weapon	Depth of Penetration	Plane Sectioned
W.A. No.	**F.A. No.**				
4	1/29/42 A	2475	Smooth Bore	Complete	Parallel to surface
5	1/30/42 A	2113	.257 Remington	.371	Parallel to surface
11	2/26/42 A	1876	Smooth Bore	.367	Transverse
14	2/26/42 D	2386	.257 Remington	Complete	Parallel to surface

In general, three plane sections were examined in the case of penetrations studied on planes parallel to the plate surfaces; one within 0.020" of the impacted surface of the plate, one within 0.020" of the back face of the plate, and one approximately in the middle of the cross-section of the plate.

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* Springfield action rifle with heavy cylindrical barrel fired from a V-block rest.

The penetrations were first examined at high magnification etched with nital to observe the existence and distribution of "white layer", after which they were etched with Oberhoffer's macroscopic reagent to reveal the deformation of the metal in the vicinity of the bullet hole.

RESULTS AND DISCUSSION

Examination of transverse sections of penetrations made by jacketed caliber .30 A.P. bullets and stripped caliber .30 A.P. cores shows the effect of the jacket on the ridge built up on the face of the plate during penetration. Figure 1B shows a cross-section of a penetration caused by a caliber .30 A.P. core fired from a smooth-bore gun. The metal at the face of the plate has piled up around the bullet similar to the ridge built up around a Brinell ball impression in soft metal. Figures 1A and 1C show the wave formation at the surface of the plate caused by the slight penetration of the jacket metal into the plate. In very soft armor plate, the jacket will penetrate to a considerable depth.

Figures 1B and 1D are transverse sections of static penetrations caused by pushing caliber .30 A.P. cores into the plate under the head of a tensile machine. The deformation of the banding is similar to that produced by dynamic impact with both rotating and non-rotating bullets.

No "white layer" was observed in the transverse sections of the static penetrations examined. Figure 2A, a view of the bottom of penetration SS31-SS1, shows only pronounced displacement of the banding near the penetration. On the other hand, considerable "white layer" was observed in dynamic penetrations of both rotating and non-rotating bullets, (see Figure 2C, nital etch, of the transverse section of the bottom of penetration SS31-2100.) The formation of "white layer" seems to be, therefore, a function of the rate of deformation.

Views of planes parallel to the surface of the plate containing typical deformation produced by dynamic impact of caliber .30 bullets is shown in Figure 3, penetration No. SS31-2. A, B, and C are respectively sections cut near the top, middle and bottom of the penetration. The white material at the edge of the bullet hole in Figure 3A consists of portions of the copper jacket lining the penetration. Figure 3B shows considerable "white layer" branching off from the edge of the penetration at angles of roughly 45°. The displacement of the banding on either side of the "white layers" are evidence of the slip of the metal that caused the extremely localized heating that resulted in "white layer" formation. Figure 3C shows a crack radiating from the bullet hole that contains several sections of "white layer".

Views of planes parallel to the surface of the plate containing typical deformation produced by static penetration of caliber .30 A.P. cores are shown in Figure 4, penetration No. SS31-SL. A, B, and C again represent sections from the top, middle, and bottom of the penetration. Both penetrations No. SS31-2 and SS31-3L are complete to about the same degree, i.e. the nose of the bullet projecting through the back of the plate to about the same extent in each penetration. The thin concentric rings around the bullet hole of the static penetration are very similar to those around the dynamic penetration.

The obvious difference between dynamic and static penetrations is again the lack of "white layer" in the static penetration. One exception was, however, found in the case of the longitudinal section of the bottom layer of penetration No. SS31-SL. Figures 5A and B are views at higher magnification of the plane section 0.019" above the back face of the plate around penetration No. SS31-SL, showing occurrence of what must be considered "white layer" at the edge of the bullet hole and along cracks radiating from the bullet hole. The probable explanation of this phenomenon follows: As the core was pushed through the plate under the head of the tensile machine, the load built up to a maximum value and remained relatively constant. When the point of the core emerged through the back of the plate, the plate resistance decreased abruptly and the core accelerated forward (due to the resilience of the plate which had been elastically deflected under the applied force) at a speed great enough to cause formation of "white layer". This "white layer" would necessarily be restricted to the last portion of the plate penetrated; i.e. the bottom of the bullet hole, where it was actually found.

The "white layer" illustrated in Figure 5B, photographed under oblique illumination, shows the characteristic furrowed and distorted appearance of these layers.

Penetrations produced by both rotating and non-rotating cores show identical formation of "white layer" and concentric rings, suggesting that rotation of the bullet core has negligible influence upon the mechanism of penetration of armor plate. This is to be expected since calculations have shown that the energy of rotation of a bullet in flight is a very small value compared to the energy of translation.

Figures 6A, B, C, are respectively views of sections parallel to the plate surface through the top, middle, and bottom of penetration No. 14 (2/26/42 D) in plate No. 620-2, produced by firing a copper-plated caliber .30 A.P. core from a caliber .257 Remington rifle. The pitted white band around the edge of the bullet hole in Figure 6C is a portion of the copper plating. Some copper has also filled up a crack in the vicinity of the penetration.

Figure 6 illustrates a phenomenon that has been previously noted in W.A. Report No. 710/197; namely, the hour-glass shape of the volume of metal that is distorted during a complete penetration. Figure 6A, which is a view of a section 0.006" below the top of the plate shows distortion to an average distance of 0.13" away from the bullet hole. A section 0.228" below the impacted surface, Figure 6B, shows distortion to an average distance of but 0.10" from the bullet hole. A section 0.482" below the impacted surface, Figure 6C, shows distortion to an average distance of 0.18" away from the bullet hole. The metal in the middle of the cross-section of homogeneous plate undergoes severe lateral compression, but very little upward or downward displacement, while the metal near the extremities of the cross-section is displaced upward at the impacted surface and downward at the back surface of the plate to form the familiar bulges around penetrations. It is the upward and downward bending of the metallic fibers (segregation bands) near the plate surfaces that are responsible for the hour-glass shape that is revealed by metallographic means.

Transverse sections through segregation bands appear, when etched, as alternate light and dark streaks. Severely compressed metal will appear exactly the same; so that it is impossible to determine, by metallographic means alone, if either compression or bending of the fibers is alone responsible for the distortion or whether they both are responsible.

The hour-glass pattern of deformed metal seems to be associated with the formation and breaking off of front and back petals, the shape of which invariably conforms to the outline of the volume of the deformed metal.

Views of sections cut parallel to the surface of the plate through a penetration made by a non-rotating caliber .30 armor piercing bullet core are shown in Figure 7. The formation of "white layer" and deformation consisting of concentric rings are identical with those produced by impact of a rotating armor piercing core, as in Figures 5 and 6.

A yawed impact of a caliber .30 core against 1/2" homogeneous plate produced an interesting deformation pattern, as seen in Figure 8, which shows layers parallel to the plate surface through penetration No. 5 (1/2"/48 A). Figure 8A reveals a plane section 0.006" below the impacted surface. The bullet entered the plate from a direction that corresponds to the lower right hand region of the photograph.

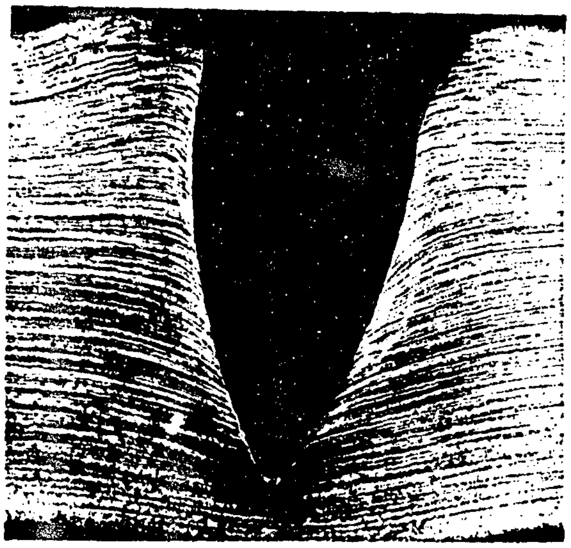
The deformation is most severe in the upper left of the photograph, which is the portion of the metal that the bullet displaced upward as it entered the plate at an angle. On a layer 0.228" below the top surface of the plate, see Figure 8B, the deformation is most severe in the lower right of the photograph, which corresponds to the portion of the metal that is in compression beneath the armor piercing core, while the deformation in the upper left of the photograph represents the metal above the axis of the projectile which is deformed by a combination of compression and tension stresses. This variation in the distribution of the deformed metal with the depth of penetration suggests the reversal of stresses to which the body of the armor piercing core is subjected as it penetrates a piece of armor of this thickness.

Figure 8C shows a plane section 0.482" below the impacted surface and 0.019" below the bottom of the bullet hole. The deformation in this region consists of the bending of the remnants of the dendritic axes, which had previously been deformed and aligned by hot working, into a circular pattern around the center of impact.

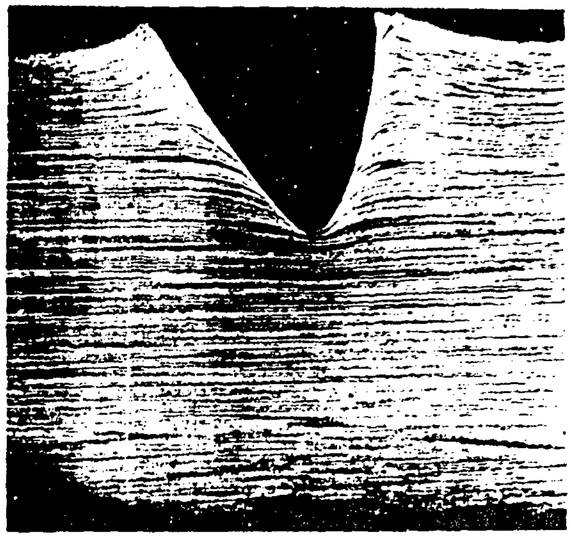
The thin concentric rings of alternate light and dark etching constituents consist of highly deformed and compressed segregation bands that are displaced by the bullet during penetration. These same bands are present in their undisturbed condition away from the penetration, and in this region consist of parallel light and dark etching streaks oriented in the direction of rolling of the plate.

Figure 1

Etched in Oberhoffer's Reagent — Transverse Sections of Penetrations — Original Magnification [illegible]

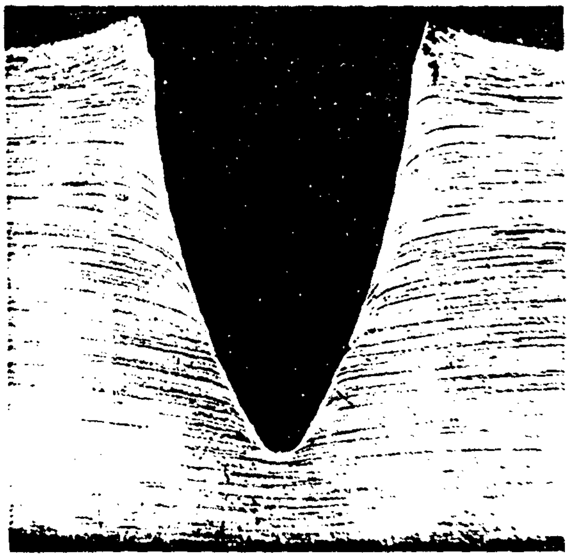


A. Impact Penetration — No. SS31-2100
Velocity - 2100 Ft/sec.
Bullet - Cal. .30 AP Fired from Mann Barrel

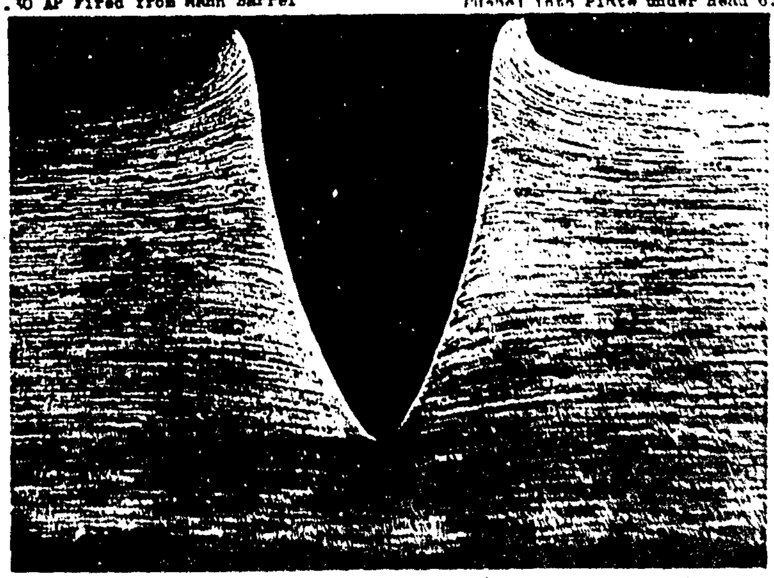


B. Static Penetration — No. SS31-[illegible]
Bullet - Cal. .30 Core
Pushed into Plate under Head of Tensile Machine

C. Impact Penetration — No. SS31-2150
Velocity - 2150 Ft/sec.
Bullet - Cal. .30 AP Fired from Mann Barrel



D. Static Penetration — No. SS-[illegible]
Bullet - Cal. .30 Core
Pushed into Plate under Head of Tensile Machine



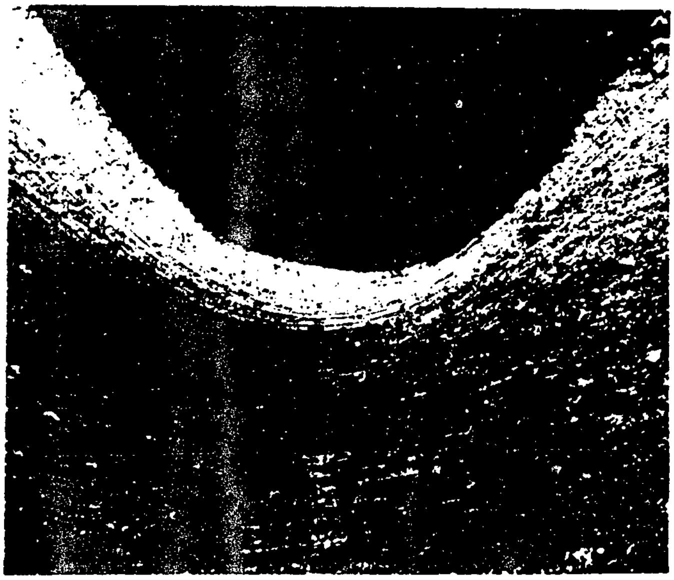
E. Impact Penetration — Velocity - [illegible] Ft/sec. — No. [illegible]
Bullet - Cal. .30 Core (Unplated) Fired from Smith [illegible] Rifle

Figure 2

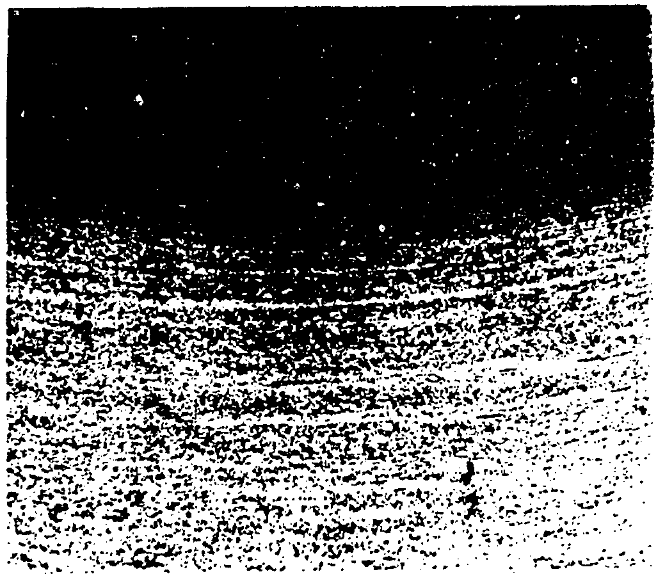
Static Penetrations

Etched in Nital

Original Magnification X10



A. Penetration SS31-ST1
Static Penetration. Transverse Section through Bottom of Bullet Hole.



B. Penetration SS31-SL
Static Penetration. Section Parallel to and 0.246" Below Front Surface of Plate.

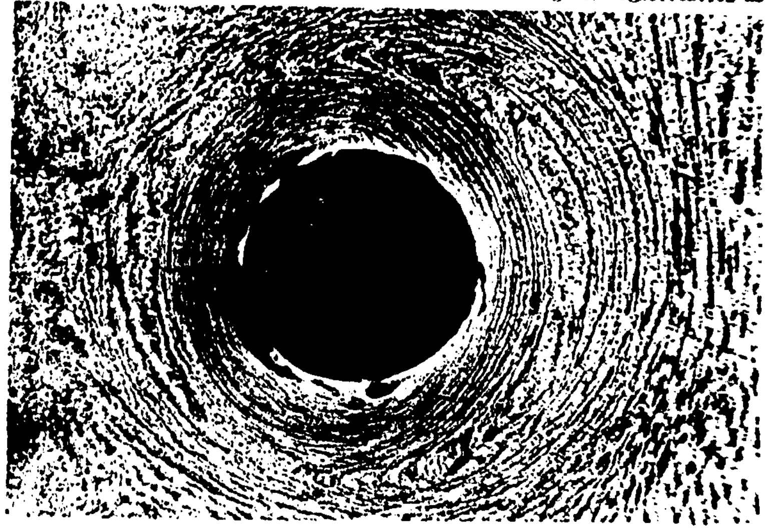
Impact Penetrations

C. Penetration SS31-2100
Dynamic Penetration - 2100 Ft/sec.
Transverse Section through Bottom of Bullet Hole.

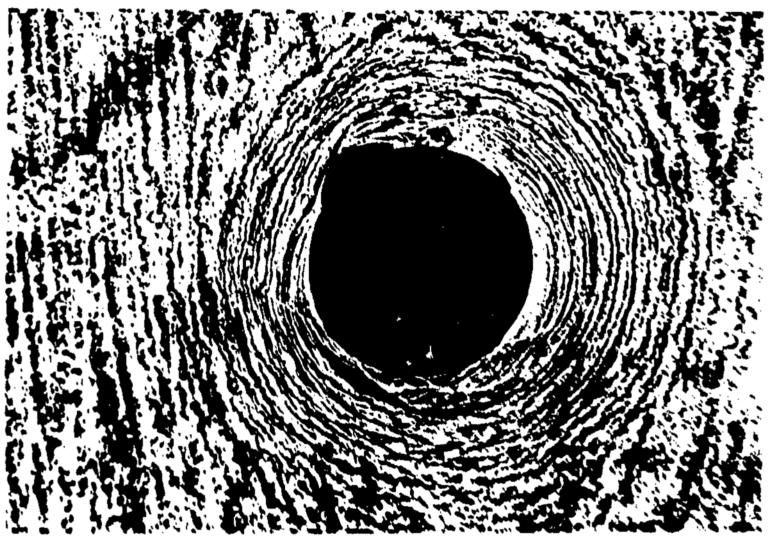
D. Penetration SS31-2
Dynamic Penetration - 2500 Ft/sec.
Section Parallel to and 0.[illegible]" Below Front Surface of Plate

Figure 3

Etched in Oberhoffer's Reagent | Original Magnification X5



A. Section Parallel to and 0.017" Below Front Surface of Plate.



B. Section Parallel to and 0.257" Below Front Surface of Plate.

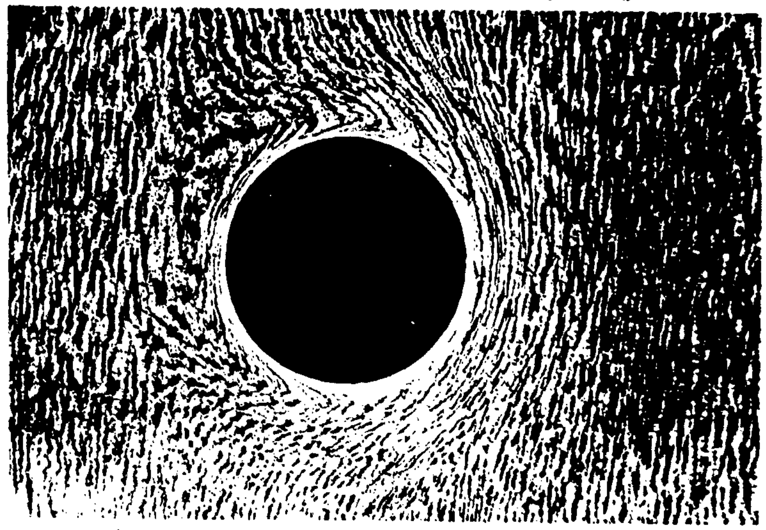
Penetration No. 5531-2
Velocity - 2990 Ft/sec.
Bullet - Cal. .30 A.P. Fired from Mann Barrel
Normal Impact

C. Section Parallel to and 0.[illegible]" Below Front Surface of Plate and 0.[illegible]" Above Back Surface of Plate.

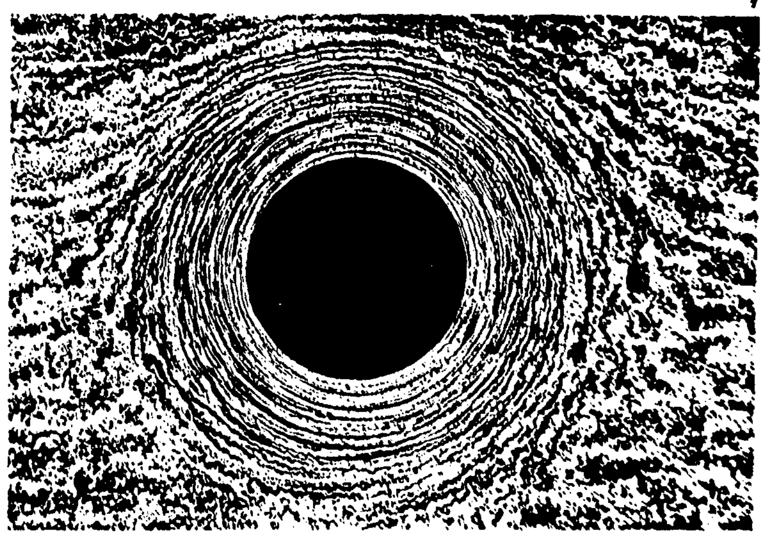
Figure 4

Etched in Oberhoffer's Reagent

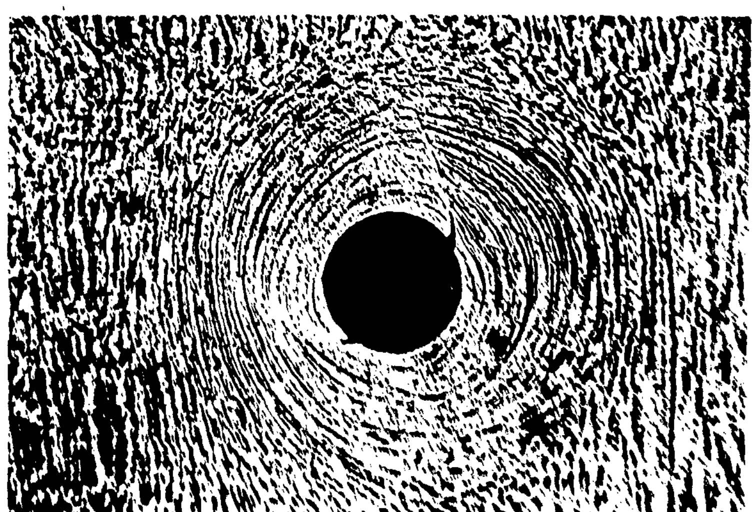
Original Magnification X5



A. Section Parallel to and 0.025" Below Front Surface of Plate.



B. Section Parallel to and 0.246" Below Front Surface of Plate.

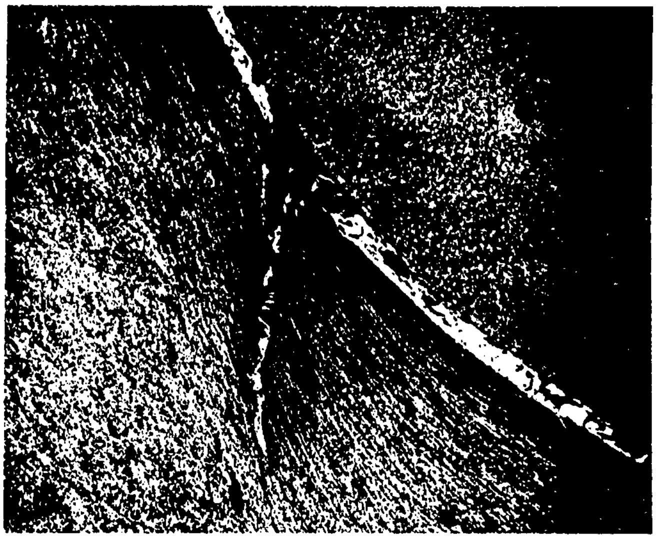


C. Section Parallel to and 0.[illegible]" Below Front Surface of Plate and 0.[illegible]

Penetration No. 5531-SL
Velocity - Static Penetration Under Head of Tensile Machine
Bullet - Cal. .30 Core (Jacket Stripped off Prior to Penetration)
Normal Penetration

Figure 5

Static Penetration



Bullet
Core

A. Orig. Mag. X100 Penetration SS31-SL Nital Etch
Static Penetration. Section Parallel to and 0.019"
Above Back Surface of Plate.

Penetration No. SS31-SL

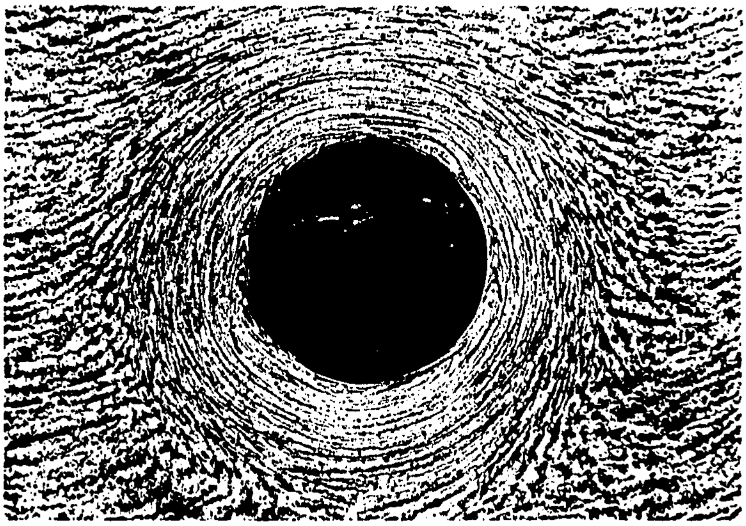
Armor
Plate

Bullet
Core

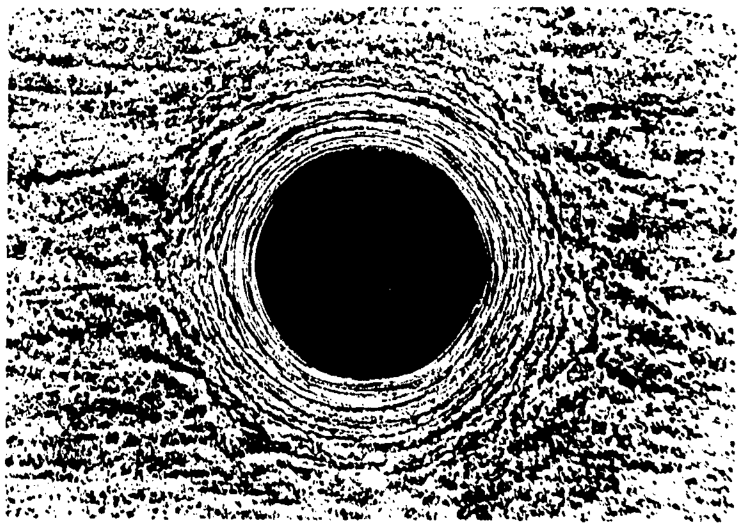
B. Orig. Mag. X1000 Oblique Illumination SS31-SL Nital Etch
Cracks and Severe Distortion in "White Layer" Adjacent to Bullet Core

Figure 6

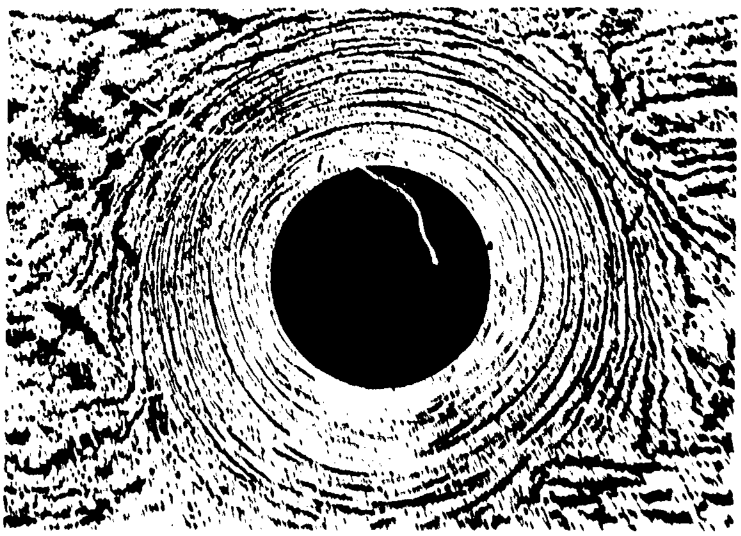
Etched in Oberhoffer's Reagent — Original Magnification X5



A. Section Parallel to and 0.006" Below Front Surface of Plate.



B. Section Parallel to and 0.228" Below Front Surface of Plate.



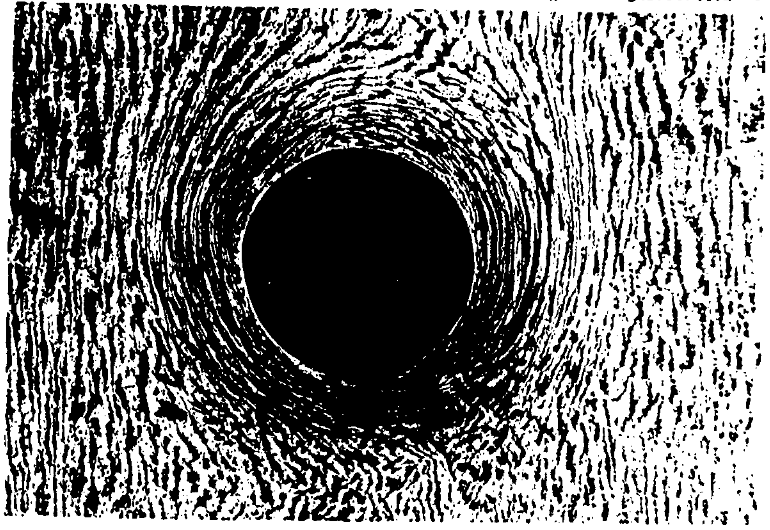
C. Section Parallel to and 0.482" Below Front Surface of Plate and 0.018" Above Back Surface of Plate.

Penetration No. 14(2/26/42D)
Velocity - 2356 Ft/sec.
Bullet - Cal. .20 Core (Copper Plated) Fired from Cal. .257 Remington Rifle.
Normal Impact

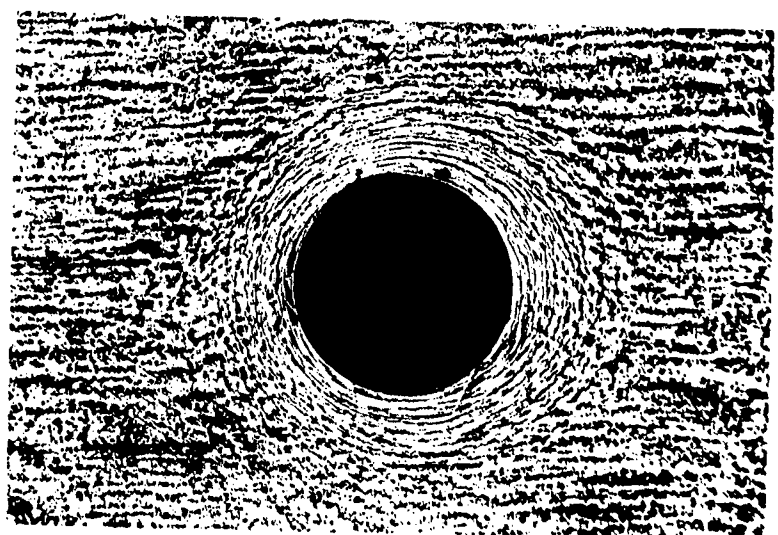
Figure 7

Etched in Oberhoffer's Reagent

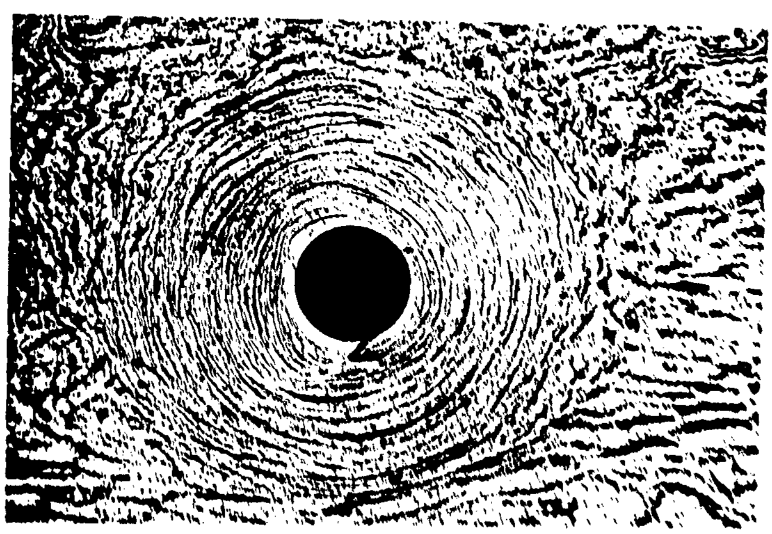
Original Magnification X8



A. Section Parallel to and 0.014" Below Front Surface of Plate.



B. Section Parallel to and 0.247" Below Front Surface of Plate.

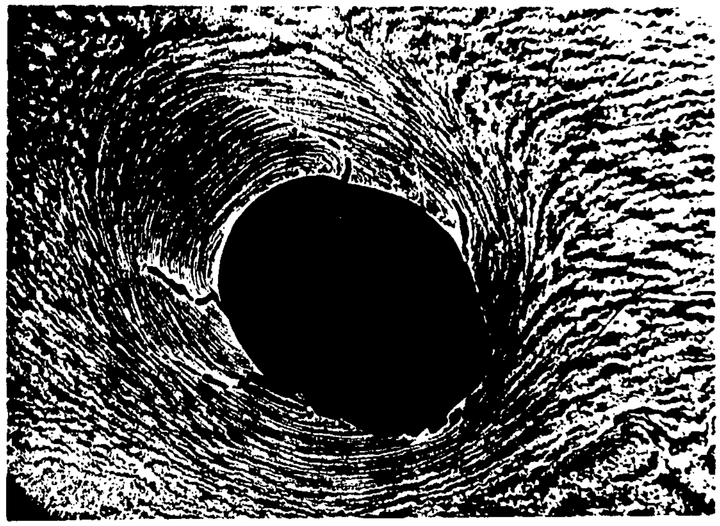


C. Section Parallel to and 0.500" Below Front Surface of Plate and 0.013" Above Back Surface of Plate.

Penetration No. 4(1/29/42A)
Velocity - 2475 Ft/sec.
Bullet - Cal. .30 Core (Unplated) Fired from Smooth Bore Rifle.
Normal Impact

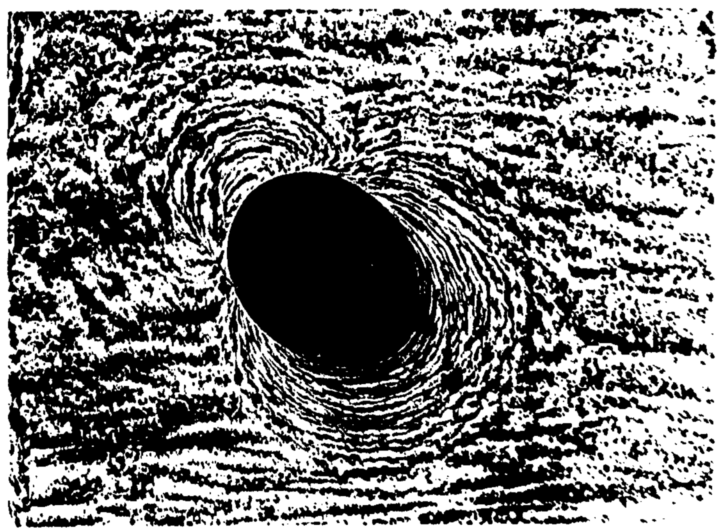
Figure 8

Etched in Oberhoffer's Reagent | Original Magnification X8

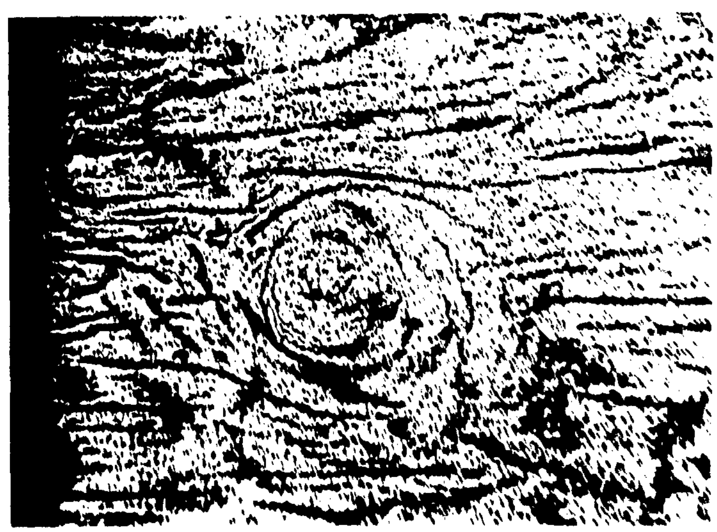


A. Section Parallel to and 0.006" Below Front Surface of Plate.

↖ Direction of Impact



B. Section Parallel to and 0.228" Below Front Surface of Plate.



C. Section Parallel to and 0.482" Below Front Surface of Plate, and 0.019" Above Back Surface of Plate. 0.111" Below Bottom of Bullet Hole

Penetration No. 5(1/30/42A)
Velocity - 2113 ft/sec.
Bullet - Cal. .30 Core (Copper Plated) Fired from Cal. .257 Remington Rifle.
Bullet Yawed Prior to Impact.

Thickness of Plate = .501"
Depth of Penetration = .371"

APPENDIX A

C O P Y

[illegible]

WAR DEPARTMENT

WATERTOWN ARSENAL

WATERTOWN, MASS.   December 19, 1941

Attention of:
Laboratory

Major L. [illegible] Fletcher
Frankford Arsenal
Philadelphia, Pennsylvania

Dear Major Fletcher:

As a result of the conference recently held at your laboratory with Lt. Matthews, Dr. Reed, and your technical staff on the subject of penetration of armor, we invite your attention to the following:

1. ...

2. Making a Penetration Test on 1/2" Thick Homogeneous Armor Plate No. 620-2 with Nonjacketed Bullet - Cooperative Work between Watertown Arsenal and Dr. Smith.

We are sending to you by mail a sample of heat treated Ni-Cr-Mo armor plate, 5"x2-1/8"x1/2", for making penetrations with a nonjacketed, nonrotating bullet in order that we may study the deformation in the vicinity of the impact with this type of a projectile. It is suggested that penetrations be made at such velocities as to cause complete penetration, that is, with the nose of the bullet core just projecting through the rear face of the plate and also a penetration in which the bullet core has completely passed through the plate. The chemical analysis of this material is:

C	Mn	P	S	Ni	Cr	Mo
.25/.30	.35/.40	.016	.012	3.25/3.50	1.4/1.6	.40/.60

The Brinell hardness of the sample is 366 and the ballistic limit of this plate is 2466 f/s, Cal. .30 A.P.

...

For the Commanding General:

Very truly yours,

(signed) G. L. [illegible],
Major, Ord. Dept.,
Acting Director of Laboratory

C O P Y

FRANKFORD ARSENAL

Philadelphia, Pa. CMH:mlw

February 28, 1942

W.A. 470.5/3871
Attn: Laboratory

Major C. L. Cox,
Watertown Arsenal,
Watertown, Mass.

Dear Major Cox:

The armor sample which you sent December 19, 1941 has been penetrated as was planned, with rotating and with non-rotating cal. .30 cores. The sample [5" x 2-1/8" x 1/2" of plate No. 620-2] is being mailed under separate cover, and data pertaining to these penetrations are given on the attached sheet.

The smooth-bore weapon which was modified for firing bullets without rotation gives a maximum velocity of less than 2500 ft/sec and produced two complete penetrations, but not a complete perforation of the armor sample. The cartridge has already been completely filled with powder having the highest potential available, and the velocity can be appreciably increased only by increasing the powder volume.

Velocities were measured for the first rounds by means of the optical chronograph, which uses a rotating mirror to record the bullet position as a function of time. The values are believed to be correct to within 1% probable error. The later values, measured by a ballistic pendulum, may be somewhat less accurate, since the equipment has not yet been fully checked.

It will be noted that the bullets for the Remington .257 are heavier, because of the copper plating which was needed to take the rifling.

We hope that this sample of armor will be of use to Dr. Reed and Lt. Matthews in the study of the effect of bullet spin upon the armor during penetration. We are, of course, interested in the details which the etchings show regarding any notable

COPY

FRANKFORD ARSENAL

Philadelphia, Pa. CMH:mlw

February 28, 1942

W.A. 470.5/3871
Attn: Laboratory

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Watertown, Mass.

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The armor sample which you sent December 19, 1941 has been penetrated as was planned, with rotating and with non-rotating cal. .30 cores. The sample /5" x 2-1/8" x 1/2" of plate No. 620-2/ is being mailed under separate cover, and data pertaining to these penetrations are given on the attached sheet.

The smooth-bore weapon which was modified for firing bullets without rotation gives a maximum velocity of less than 2500 ft/sec and produced two complete penetrations, but not a complete perforation of the armor sample. The cartridge has already been completely filled with powder having the highest potential available, and the velocity can be appreciably increased only by increasing the powder volume.

Velocities were measured for the first rounds by means of the optical chronograph, which uses a rotating mirror to record the bullet position as a function of time. The values are believed to be correct to within 1% probable error. The later values, measured by a ballistic pendulum, may be somewhat less accurate, since the equipment has not yet been fully checked.

It will be noted that the bullets for the Remington .257 are heavier, because of the copper plating which was needed to take the rifling.

We hope that this sample of armor will be of use to Dr. Reed and Lt. Matthews in the study of the effect of bullet spin upon the armor during penetration. We are, of course, interested in the details which the etchings show regarding any notable differences in the metal flow between penetrations by spinning and non-spinning bullets. Suggestions of any similar cooperative work on the mechanics of armor penetration will be very welcome; however it is doubtful that we will have much time for it in the immediate future.

Sincerely yours.

(signed) L. S. FLETCHER,
Lt. Col., Ord. Dept.
Assistant

Incl: w/c

ROUND	WEIGHT	WEAPON	METHOD OF MEASUREMENT	VELOCITY
1/28/42 A	3	Cal..257 Remington	Optical Chronograph	Faint record
1/28/42 B		Cal..257 Remington	Optical Chronograph	Missed
1/28/42 C		Smooth bore	Optical Chronograph	Missed
1/29/42 A		Smooth bore	Optical Chronograph	2475 ft/sec
1/30/42 A		Cal..257 Remington	Optical Chronograph	2113 ft/sec
1/30/42 B		Cal..257 Remington	Optical Chronograph	2000 ft/sec
1/30/42 C		Cal..257 Remington	Optical Chronograph	193[illegible] ft/sec
1/31/42 A		Smooth bore	Optical Chronograph	2400 ft/sec
2/25/42 A	90.7 gr.	Cal..257 Remington	Ballistic Pendulum	2261 ft/sec
2/25/42 B	93.4 gr.	Cal..257 Remington	Ballistic Pendulum	2152 ft/sec
2/26/42 A	82.85 gr.	Smooth bore	Ballistic Pendulum	1876 ft/sec
2/26/42 B	82.8 gr.	Smooth bore	Ballistic Pendulum	1797 ft/sec
2/26/42 C	82.7 gr.	Smooth bore	Ballistic Pendulum	1632 ft/sec
2/26/42 D	94.7 gr.	Cal..257 Remington	Ballistic Pendulum	23[illegible] ft/sec