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Report No. 710/458

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ARMOR PLATE

Metallurgical Examination of Section of German

Face-Hardened Armor from the Front of a PZ. KW. III Tank

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by

A. Hurlich
Junior Metallurgist

[illegible] 1955
date

M. C. WOODS
W. A. Laboratory
Sec Adm

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October 15, 1942

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Report No. 710/458
Watertown Arsenal

November 10, 1942

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ARMOR PLATE

Metallurgical Examination of Section of German
Face-Hardened Armor from the Front of a PZ. KW. III Tank

OBJECT

To conduct a metallurgical investigation of the subject armor including chemical analysis, hardness survey, determination of physical properties, and macroscopic and microscopic examination.

REFERENCES

O.O. 470.5/11289 - W.A. 470.5/4880
O.O. 470.5/11290 - W.A. 470.5/5040
A.P.G. Firing Record No. A4022

The basic correspondence pertaining to this report is contained in Appendix A, and data extracted from A.P.G. Firing Record No. A4022 are contained in Appendix B.

SUMMARY OF RESULTS

1. The subject armor is a medium high carbon chromium-molybdenum alloy steel that was probably deoxidized with aluminum and titanium.

2. The plate was heat-treated as homogeneous armor to a Brinell hardness of approximately 375-430 after which the face was flame hardened to an average depth of approximately 1/8" yielding a face hardness of 653 Brinell. The flame hardening depth is reasonably uniform across the plate.

3. The metal is of good quality with respect to cleanliness and lack of pronounced macroscopic segregations and absence of directional properties. The plate contains considerable microscopic segregation as evidenced by extensive banding in both the longitudinal and transverse sections.

4. The physical properties of the midsection of the base metal of the German armor are as follows:

	Y.S.P. 0.1% Set	T.S.	% Elong.	% R.A.	Izod	BHN
Longitudinal	153,000	180,000	12.9	44.5	28.0	375
Transverse	154,000	180,500	11.4	35.4	21.4	375

These indicate reasonable uniformity, probably as a result of cross rolling.

5. The steel from which this armor was made has been extremely well processed and evidences proper care and the best of techniques throughout the operations. The flame hardening operation has also been carefully performed; the resulting hardness gradients are uniform and show the characteristic sharp transition from the hardened face to the softer back passing through a narrow softened zone.

A. Hurlich

A. HURLICH
Assistant Metallurgist

APPROVED:

H. H. ZORNIG
Colonel, Ord. Dept., U.S.A.
Director of Laboratory

A-1, 24, 23

INTRODUCTION

In accordance with instructions from the Office, Chief of Ordnance, a specimen of face-hardened armor plate, 1-1/4"x13-1/2"x31-1/2", from the front of a PZ KW. III Tank was forwarded to this arsenal from Aberdeen Proving Ground for metallurgical investigation.

The plate was ballistically tested at Aberdeen Proving Ground. Figures 1 and 2, respectively, show the face and back of the plate after the ballistic test.

TEST PROCEDURE

Strips were cut from the plate in both the longitudinal and transverse directions for hardness surveys, macro-etching, and microscopic examination. The composition and the physical properties of the base metal were determined.

DATA AND DISCUSSION

1. Markings

The following markings were noted stamped on the back surface of the plate:

"66" with additional marking obliterated by impact of Round No. 13.

"71 41 325E02994" stamped in approximately 1/2" high figures.

Two stylized German eagles grasping globes containing the swastika emblem were stamped on the back of the plate, one at each end of the above series of numbers. The serial number "WaA79" was stamped beneath the eagle to the left of "71" and the symbol "WaA7" was stamped under the eagle to the right of the last number.

2. Chemical Analysis

The chemical analysis of the subject armor was found to be as follows:

C	Mn	Si	S	P	Ni	Cr	Mo	Cu	V	Al	Ti
.55	.81	.51	.019	.028	nil	1.63	.35	.06	trace	.03	.065

The German armor is essentially a medium high carbon chromium-molybdenum alloy steel that was probably deoxidized with a complex deoxidizer containing aluminum and titanium. The carbon content is considerably higher than that of current American homogeneous armor of comparable thickness, which averages approximately 0.30% carbon.

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3. Hardness Survey

Hardness surveys were made of the hard case and of the base metal using both the Rockwell and Vickers machines, see Figures 3 and 4. The specimens for hardness survey were first etched in 5% nitric acid solution to delineate the hardened zone. The appearance of the hardened zone was typical of those produced by flame-hardened processes. This fact was subsequently confirmed.

The Rockwell C survey on a transverse section of the armor, Figure 3, shows that the surface hardened zone has an extremely uniform hardness level of Rockwell C 57.5-60. This uniformity of hardness is superior to that observed on numerous flame-hardened plates of American manufacture examined at this Arsenal. A similar hardness survey conducted on a longitudinal section of the subject armor showed results identical to those obtained on the transverse section.

The Vickers hardness survey was conducted to detect the hardness gradient from case to core, see Figure 4. A very sharp hardness gradient from case to core exists, the hardness dropping from 643 to 354 Vickers Pyramid Hardness in 0.02 inches.

Brinell hardness readings were also made on the face and the back of the German armor.

The results of the hardness surveys are summarized in Table I:

TABLE I

	Rockwell C Hardness	Vickers Pyramid Hardness	Brinell Hardness
Flame-hardened zone	57.5-60	643-681	653
Base metal	38-43	354-397	375-429

4. Physical Properties

Physical properties determined on test specimens cut from the midsection of the base metal of the German armor are listed in Table II:

TABLE II

	Y.S.P. 0.1%Set	T.S.	% Elong.	% R.A.	Izod	BHN
Longitudinal	153,000	180,000	12.9	44.5	28.0	375
Transverse	154,000	180,500	11.4	35.4	21.4	375

The subject armor is considerably harder and consequently less ductile than present production American plate of comparable thickness, which would probably lead to poorer shock properties than those possessed by American armor. The Izod impact values are normal for steel at the hardness level of the subject armor, and the relatively consistent results in the longitudinal and transverse directions indicate proper cross-rolling of the steel,

5. Macro-Examination

Strips cut from both the longitudinal and transverse directions were macro-etched, see Figure 5. The metal is dense, free from pronounced segregation, except at the right hand end of the transverse section which may represent residual secondary piping. The hardened zone, except where it tapers off at the ends of the transverse section, is extremely uniform in thickness compared to those of flame-hardened plates of American manufacture examined at this Arsenal. Compared to rolled American armor of the same thickness, the subject armor is of excellent quality with respect to soundness of the metal.

The macro-etch, because of the characteristic shape of the hardened layer, confirms the fact that the German armor was flame hardened. Several cracks were observed in the hardened layer, see Figure 5, which were present before macro-etching. It is possible that these cracks resulted from the ballistic testing, because numerous cracks were found radiating from the penetrations. These cracks are confined to the hardened, more brittle, zone.

A 1" wide strip, Section A, Figure 1, was cut through the large counter-sunk hole in the center of a flame-cut end of the plate and through a rivet hole. This section was macro-etched on both cut surfaces, see Figures 6A and B.

Figure 6A is a photograph of the etched surface cutting through the rivet hole. Away from the rivet hole, the flame-hardened zone averages 0.09" in depth. At the right edge of the rivet hole the zone is 0.11" deep, and at the left edge the zone is 0.04" deep. In the rivet hole the zone varies in depth from 0.0" to 0.13". Figure 6B is a photograph of the etched surface parallel to and 1" away from the surface shown in Figure 6A. Approximately opposite the rivet hole, the flame-hardened zone decreases to a depth of 0.06" for a distance of approximately .7". This decrease in the depth of the flame-hardened zone may have been the result of having a plug of metal of high heat conductivity such as copper in the rivet holes during flame-hardening. The drilled holes were probably filled with plugs during the flame-hardening to prevent excessive hardening of the interior of the holes and consequent danger of cracking through the holes as a result of projectile impact.

At the edge of the plate surface next to the large counter sunk hole, the depth of the hardened zone increases to 0.20" (Figure 6A) and 0.16" (Figure 6B). The counter sunk surface is not flame-hardened and was presumably covered by a plug of metal during the face-hardening process.

6. Micro-Examination

An Oberhoffer etch on transverse and longitudinal sections of the subject armor, Figures 7A and B, indicates that the plate was cross-rolled, and that the principal direction of rolling was in the same direction as the longer dimension of the plate.

The steel is moderately clean, Figure 7C, with a very few elongated nonmetallics. The back face of the plate was slightly decarburized, and was covered with a layer of scale approximately 0.004" thick, Figure 7D. The metal is severely banded in both the transverse and longitudinal directions, Figures 7E and F.

The micro-structure of the junction of the hardened zone and the base metal is shown in Figure 8A. The steel is extremely banded and darker etching bands can be seen on the base side of the junction. These darker etching bands represent a very shallow layer of metal immediately below the hardened zone that was tempered by the flame hardening of the surface layer. Reference to the Vickers Pyramid hardness survey, Figure 4, shows a zone marked "C" that is lower in hardness than the base metal. This zone comprises the darker etching bands seen in Figure 8A.

The micro-structure of the base metal consists of a tempered martensite, Figure 8B. The junction zone contains a mixture of a hard untempered martensite and patches of martensite tempered at a temperature sufficiently high to cause spheroidization of the carbides, Figure 8C. The micro-structure of the flame-hardened zone consists of a very hard, untempered acicular martensite, Figure 8D.

To further establish the fact that the armor was flame-hardened, a section of the plate was annealed from 1700°F. The microstructure of the surface zone was the same as that of the base metal after annealing. From all the preceding evidence, it is established that the face hardening was undoubtedly accomplished by flame-hardening.

7. Ballistic Considerations

Table III contains data summarizing the ballistic testing of the German face-hardened armor as abstracted from Aberdeen Proving Ground Firing Record No. A4022 of July 30, 1942. Complete data covering the ballistic test of the subject armor is contained in Appendix B.

TABLE III

Angle of Plate	Projectile	Lowest Velocity Complete Penetration Ft./Sec.	Highest Velocity Partial Penetration Ft./Sec.	Ballistic Limit Ft./Sec.
normal	37 MM M51 A.P.C.	1387	1333	1360
20°	"	1446	1405	1426

Current American rolled homogeneous low alloy armor plate of the same thickness as the subject armor is normally heat-treated to a Brinell hardness of 280-320, and the average ballistic limit of production plate is in the neighborhood of 1400 ft/sec when impacted with the 37 MM M51 A.P.C. projectile. The German armor had a ballistic limit of 1360 ft/sec with a base hardness of 375-430 Brinell and a face hardness of 653 Brinell. Against the capped projectile, therefore, the German armor is not superior to considerably softer homogeneous American plate.

The high hardness of the 1-1/4" thick German armor would undoubtedly cause poorer shock resistance to the impact of heavier projectiles. American armor of comparable thickness withstands the impact of the 75 MM T21 slug (a 15-pound soft steel projectile) at a velocity of approximately 800-900 ft/sec, whereas it is doubted that the German face-hardened plate would resist the same projectile without excessive cracking or complete breakage.

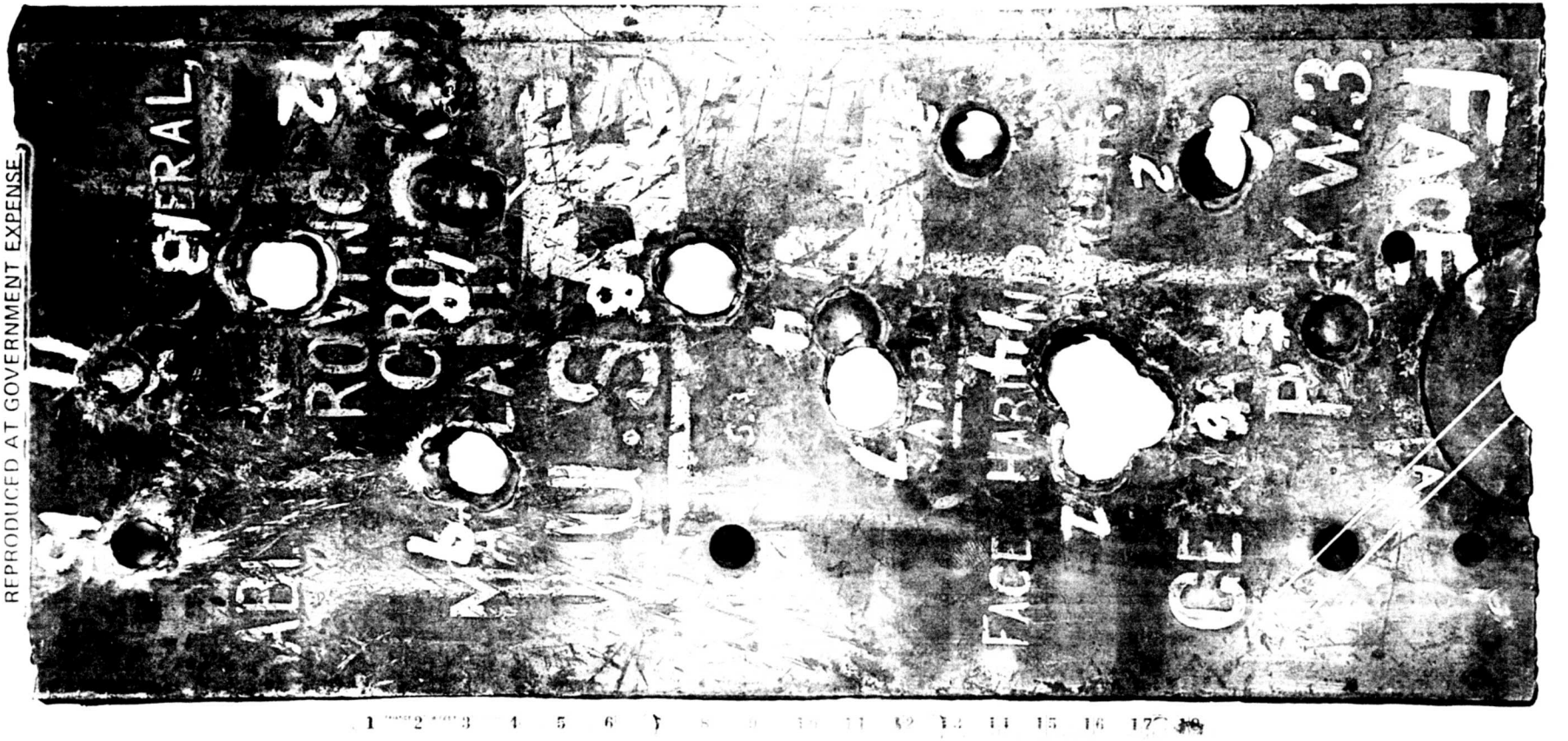
The chief advantage of face-hardening armor plate is its superior ballistic characteristics over homogeneous plate when subjected to the impact of matching uncapped projectiles such as the 37 MM M74 and the 20 MM M75. The effect of a hard face is to break up uncapped projectiles, thereby destroying their penetrating ability. Since several British uncapped armor-piercing projectiles are used in the field, notably their 2 and 6-pounders, the German plate was probably designed to afford maximum protection from the attack of these projectiles.

In view of the consideration that capped armor-piercing projectiles are coming into more prominent use on the field of battle, the use of face-hardened armor plate in these thicknesses is to be questioned. The difficulty of making repairs in the field, the fabrication problems, and the fact that face-hardened armor of the type of the subject armor is not easily weldable; all point to the underlying reasons for the greater use of softer homogeneous armor.

It has been recognized in this country that face-hardening, by any process whatsoever, is not justified on plate greater than

thickness. The German face-hardened armor, which is of as good quality as may be produced commercially, bears out this contention by virtue of its inferior performance against the 37 MM M51 A.P.C. projectile.

REPRODUCED AT GOVERNMENT EXPENSE



WATERTOWN ARSENAL

FACE OF FLAME HARDENED ARMOR PLATE $1\frac{1}{4}$" X $13\frac{1}{2}$" X $31\frac{1}{2}$", FROM THE FRONT OF A GERMAN PZ. KW. III TANK AFTER BALLISTIC TEST PERFORMED AT ABERDEEN PROVING GROUND. AUGUST 14 1942 (FRONT) W.A.710-1924

FIGURE

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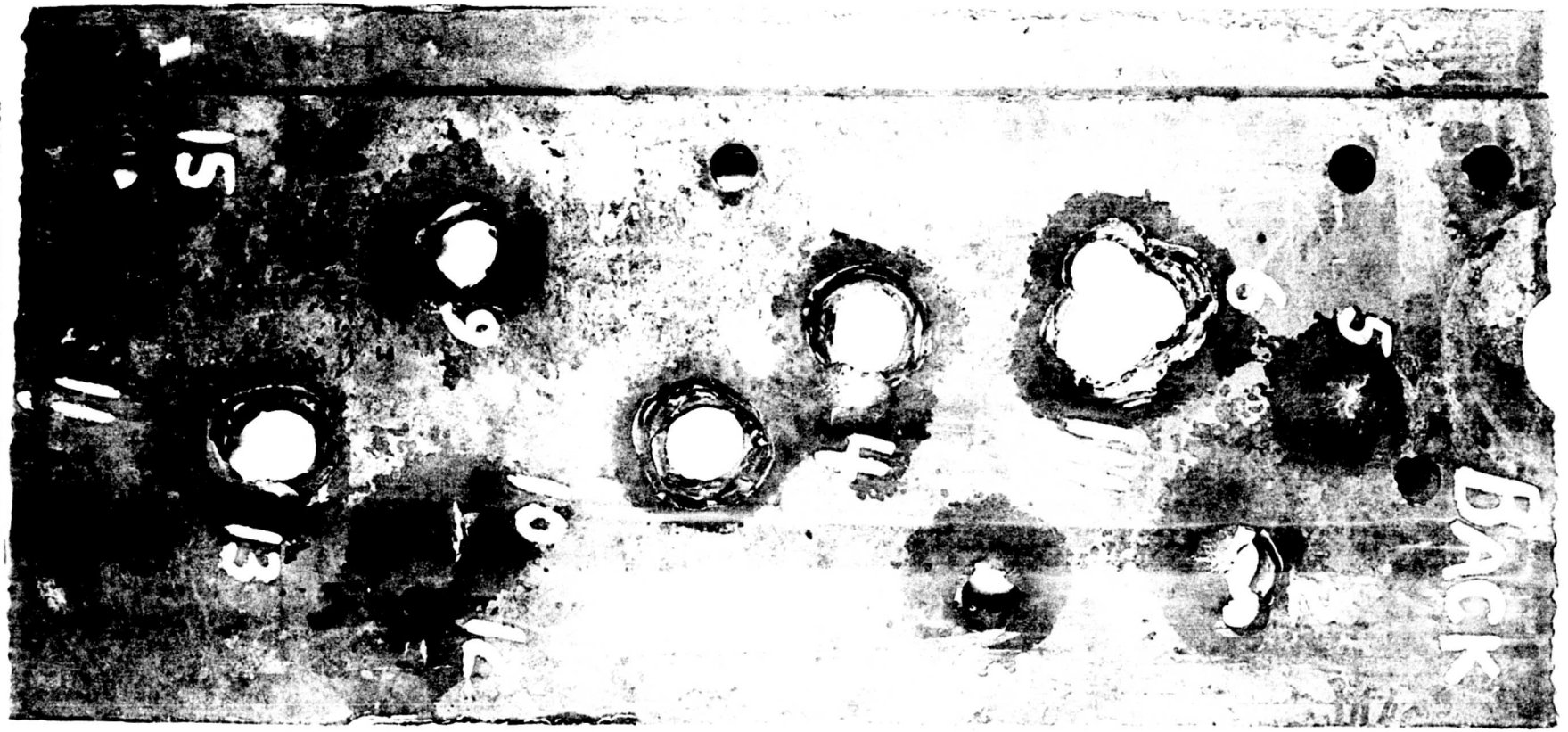
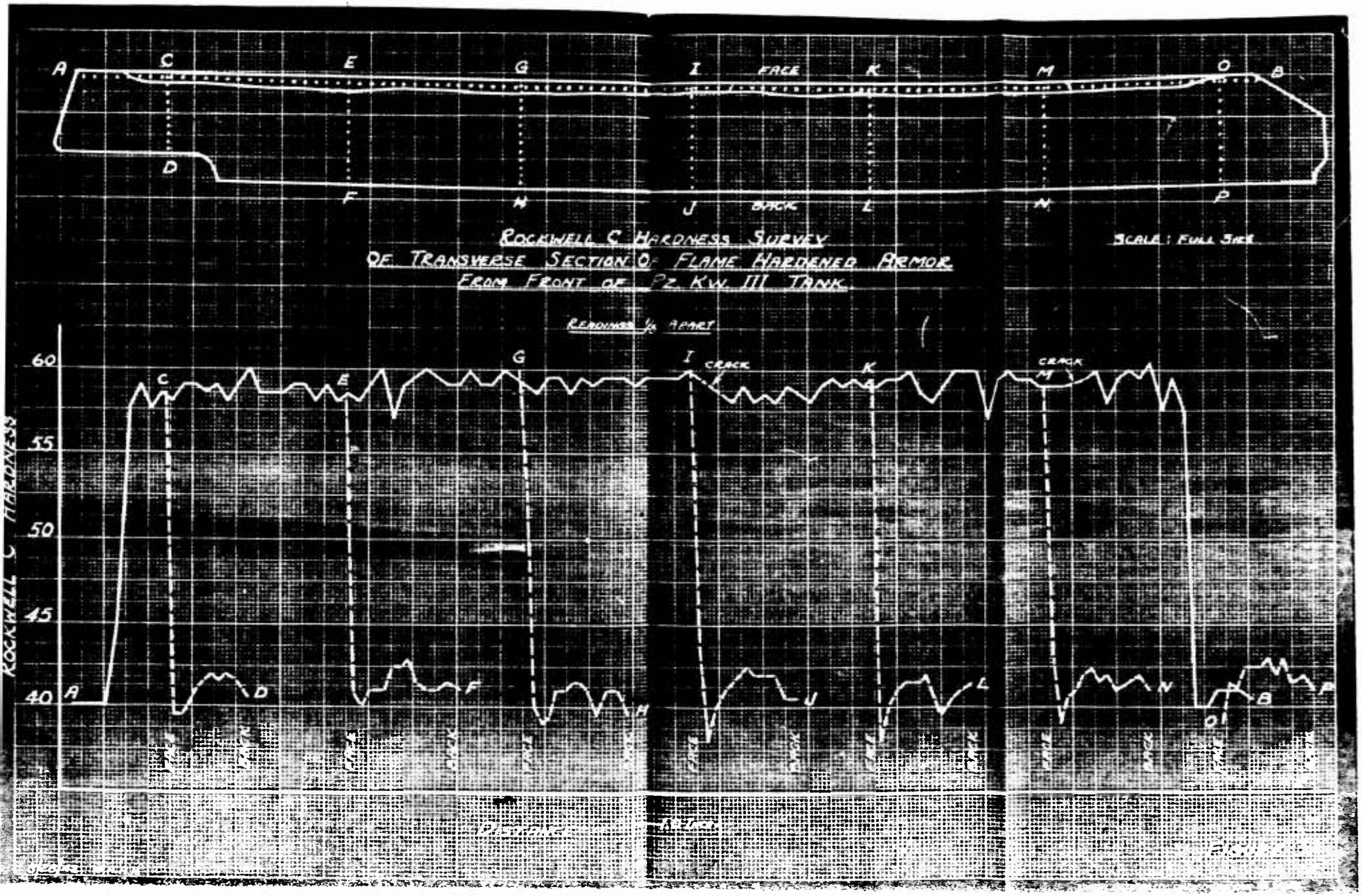
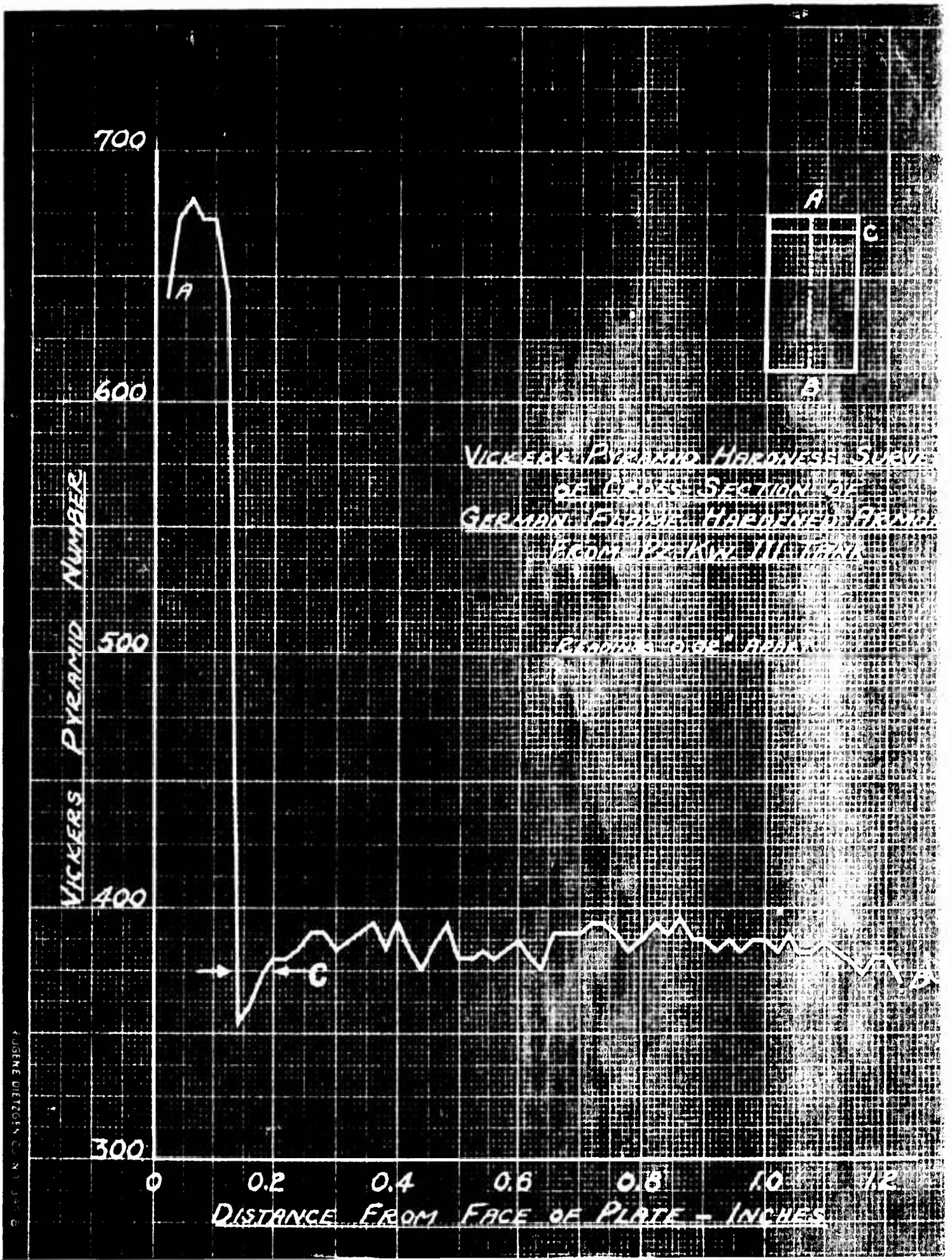


WATERTOWN ARSENAL

FACE OF FLAME HARDENED ARMOR PLATE $1\frac{1}{4}$" X $13\frac{1}{2}$" X $31\frac{1}{2}$", FROM THE FRONT OF A GERMAN PZ. KW. III TANK AFTER BALLISTIC TEST PERFORMED AT ABERDEEN PROVING GROUND. AUGUST 14 1942 (REAR) W.A.710-1925

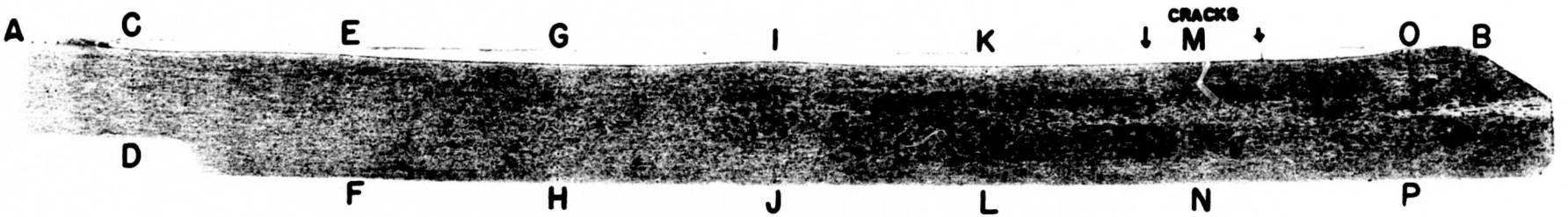
FIGURE


A
C
E
G
I
FACE
K
M
O
B
D
F
H
J
BACK
L
N
P
ROCKWELL C HARDNESS SURVEY
OF TRANSVERSE SECTION OF FLAME HARDENED ARMOR
FROM FRONT OF PZ KW III TANK
SCALE: FULL SIZE
READINGS 1/16 APART
ROCKWELL C HARDNESS
60
55
50
45
40
CRACK
CRACK



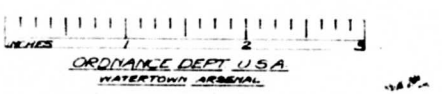
700
600
500
400
300
VICKERS PYRAMID NUMBER
0
0.2
0.4
0.6
0.8
1.0
1.2
DISTANCE FROM FACE OF PLATE - INCHES
A
C
B
VICKERS PYRAMID HARDNESS SURVE
OF CROSS SECTION OF
GERMAN FLAME HARDENED ARMO
FROM PZ.KW. III TANK
READINGS 0.02" APART

REPRODUCED AT GOVERNMENT EXPENSE



TRANSVERSE

LONGITUDINAL



WATERTOWN ARSENAL

MACROETCHED SECTIONS OF FLAME HARDENED GERMAN ARMOR PLATE
1 ¼" X 13 ½" X 31 ½" FROM THE FRONT OF A PZ. KW. III TANK
AUGUST 24 1942 W.A.710-1931

FIGURE 5

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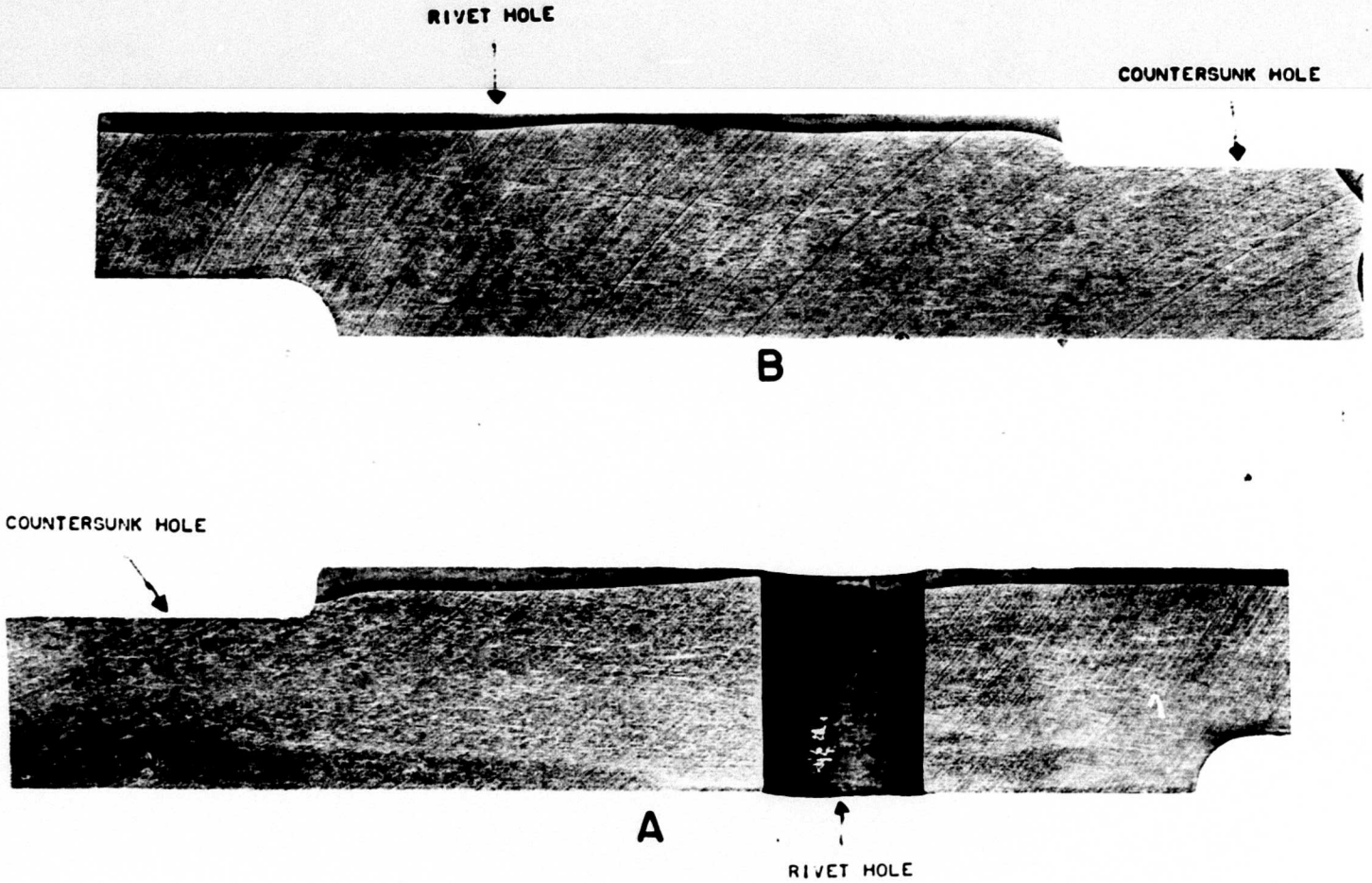


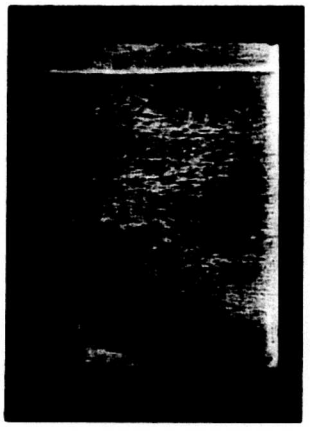
WATERTOWN ARSENAL

SECTION A

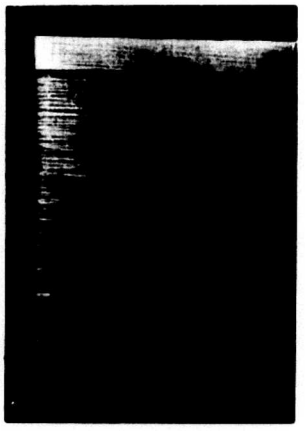
MACROETCHED SECTION OF FLAME HARDENED GERMAN ARMOR PLATE
FROM THE FRONT OF A PZ.KW III TANK. MAG. X 1
OCTOBER 3 1942 WTN.710-1937

FIGURE

GERMAN FLAME-HARDENED ARMOR FROM P2. KW III TANK.



X1½ —A— OBERHOFFER ETCH TRANSVERSE



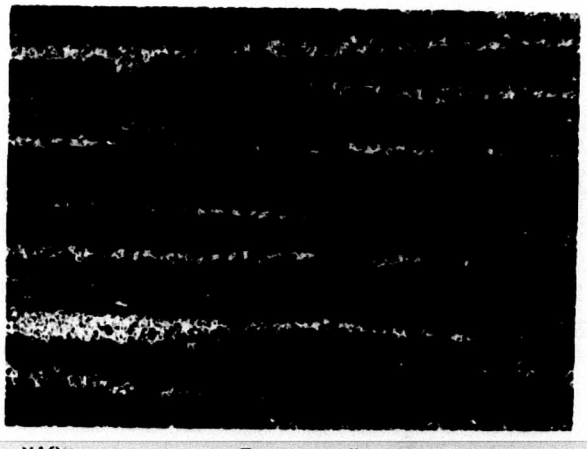
X1½ —B— OBERHOFFER ETCH LONGITUDINAL

X100 —C— UNETCHED

LONGITUDINAL. DISTRIBUTION OF NON-METALLICS. MODERATELY CLEAN STEEL.

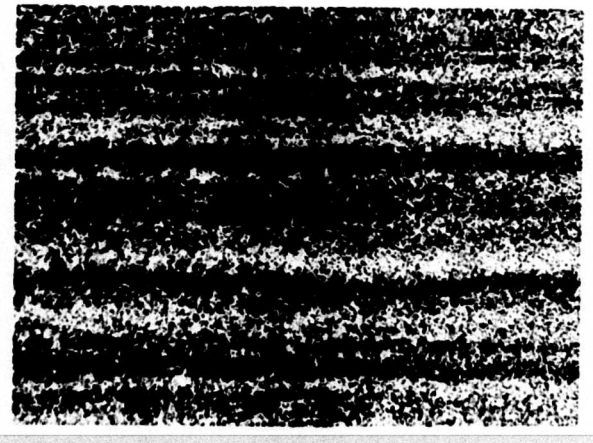
X100 —D— NITAL PICRAL ETCH

SLIGHT DECARBURIZATION AND SCALING OF BACK SURFACE OF ARMOR.



X100 —E— NITAL PICRAL ETCH

TRANSVERSE. BANDED STRUCTURE OF BASE METAL.



X100 —F— NITAL PICRAL ETCH

LONGITUDINAL. BANDED STRUCTURE OF BASE METAL.

W.A.636-4807

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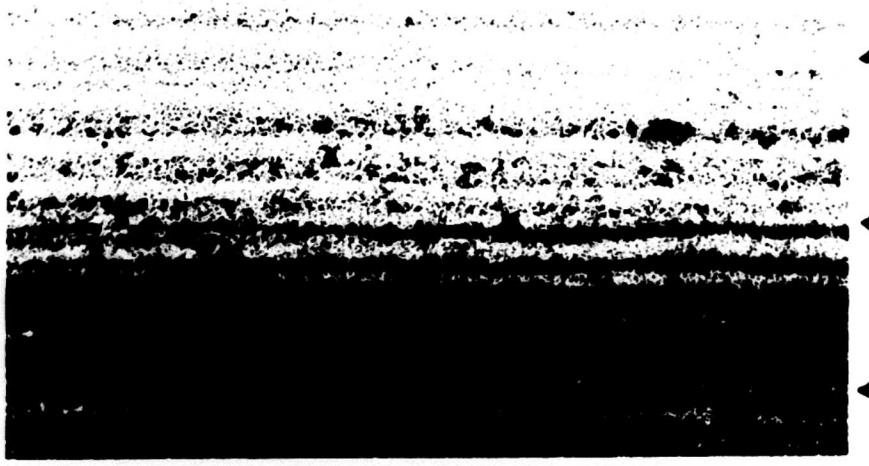
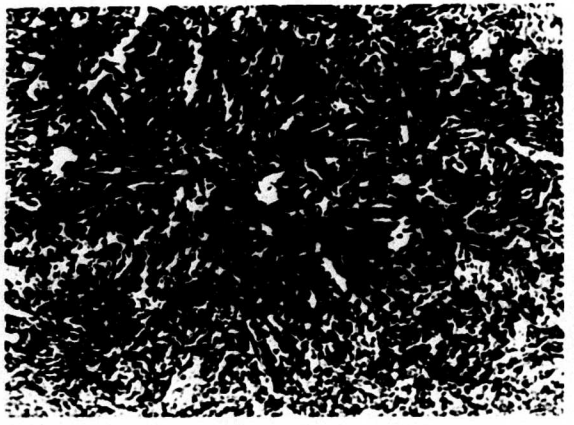
REPRODUCED AT GOVERNMENT EXPENSE

FIGURE 8



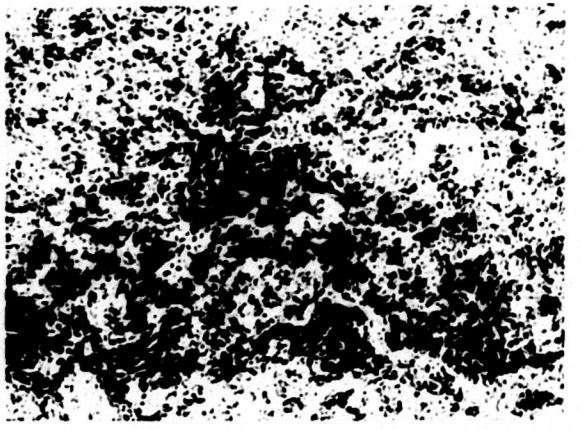
X100 -A- NITAL PICRAL ETCH

JUNCTION OF FLAME-HARDENED ZONE AND BASE METAL



X1000 -B- NITAL PICRAL ETCH

BASE METAL. TEMPERED MARTENSITE



X1000 -C- NITAL PICRAL ETCH

JUNCTION. MARTENSITE AND SPHEROIDIZED CARBIDES

X1000 -D- NITAL PICRAL ETCH

FLAME-HARDENED ZONE. MARTENSITE

APPENDIX A

COPY

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WAR DEPARTMENT
Office of the Chief of Ordnance
Washington

O.O. 470.5/11290
SPOTB - Intel.
A.P.G. 470.5/3024
W.A. 470.5/5040

July 27, 1942

Subject: Shipment of Armor Plate to Watertown Arsenal

To: The Commanding Officer
The Proving Center
Aberdeen Proving Ground, Md.

Attn: Captain A. W. Jordon

1. It is requested that the Proving Center ship to Watertown Arsenal, attention of Colonel Zornig, a specimen of face-hardendd armor plate, 1 1/4" x 13 1/2" x 31 1/2", from the front of a Pz.Kw. III Tank.

2. This piece of armor plate was received by Ferry Command from the Middle East and is in storage at the Proving Center.

3. It is requested that copies of any correspondence covering this shipment of armor plate to Watertown Arsenal be sent to the Ordnance Intelligence Unit.

By order of the Chief of Ordnance:

(s/t) E. S. DAVIS
1st Lt., Ord. Dept.

COPY

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Davis/mks

COPY

WAR DEPARTMENT
Office of the Chief of Ordnance
Washington

July 27, 1942

O.O. 470.5/11289
SPOTB - Intel.
W.A. 470.5/4880

Subject: Shipment of Armor Plate to Watertown Arsenal

To: The Commanding General
Watertown Arsenal
Watertown, Massachusetts

Attn: Colonel, Zornig

1. Attached is copy of letter to the Proving Center, Aberdeen Proving Ground, requesting them to ship to Watertown Arsenal a specimen of face-hardened armor plate, 1 1/4" x 13 1/2" x 31 1/2", from the front of a Pz.Kw III Tank.

2. Colonel W.A. Borden, Deputy Chief of the Technical Division, has requested this shipment be forwarded to you for analysis and study, with eight (8) copies of the report prepared at the conclusion of the tests.

3. A copy of the new Ordnance Department Order, covering the hardling of foreign ordn ance materiel, will be sent to Watertown Arsenal within two weeks. This Order will contain instructions for the distribution of the eight (8) copies of the report.

By order of the Chief of Ordnance:

(s/t) E. S. DAVIS
1st Lt., Ord. Dept.

1 Incl.
Copy of letter to Aberdeen Proving Center

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COPY

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O.O. 470.5/11289
W.A. 470.5/4880

NAM/amv

Watertown Arsenal, Watertown, Massachusetts, August 20, 1942.
To: Chief of Ordnance, U. S. A., Pentagon Building, Washington, D. C.
Attn: SPOTB - Intel.

1. A preliminary analysis of the subject German armor has revealed that the material is of good quality and of the following chemistry:

C	Mn	Si	S	P	Ni	Cr	Mo	Al	Ti
.55	.81	.51	.019	.028	nil	1.63	.37	.03	.065

2. The plate was heat treated as homogeneous armor to a Brinell hardness of approximately 429 after which the face was flame hardened to a depth of approximately 3/16" yielding a face hardness of 653 Brinell. The flame hardening depth is uniform across the width of the plate.

3. It is requested that this file be returned for future reference and the submission of the final report.

For the Commanding Officer:

(s/t) G. L. COX,
Lt. Col., Ordnance Dept.,
Assistant.

1 Incl. n/c
Copy of letter to Aberdeen Proving Ground

W.A. 470.5/4880 (R)
O.O. 470.5/11289 2nd Ind. Davis/mks

War Department, Ordnance Office, Ordnance Intelligence Unit, Washington, D. C., August 26, 1942.
To: Watertown Arsenal, Watertown, Massachusetts

1. Noted and this file returned for submission of final report.

By order of the Chief of Ordnance:

(s/t) E. DAVIS
1st Lt., Ordnance Dept.

1 Incl. Added
Ord. Dept. Ord. 327 (in dup.)

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COPY

APPENDIX B

Ballistic Test of

German Face-Hardened Armor Plate

from the Front of a PZ. KW. III Tank

The following data regarding the ballistic testing of the German face-hardened armor are abstracted from Aberdeen Proving Ground Firing Record No. A4022 of July 30, 1942:

Round No.	Projectile	Velocity Ft/Sec.	Remarks
		Angle of Plate - Normal	
1	37 MM M51 A.P.C.	1414	CP - 2 cracks of light around punching started.
2	"	1360	Disregard results. Hit right edge of machine hole. Tore away metal between impact and machine hole.
3	"	1387	CP -Diameter of penetration 1-3/4"x 1-7/16".
4	"	1317	PP - Depth of penetration 1-1/8", SC on MB. Punching started.
5	"	1333	PP - Depth of penetration 1-5/16", SC on MB.
6	"	2534	Disregard result. Hit at edge of round No. 1. CP -Diameter of penetration including BS 2-3/8"x2-1/2".
7	"	2547	Disregard result. Hit at edge of round No. 4. CP - Diameter of penetration with lamination 2-7/16"x 2-11/16".
8	"	2538	CP - Diameter of penetration with lamination 2-9/16"x3".
		Angle of Plate - 20° from Normal	
9	"	1535	CP -Diameter of penetration 1-21/32"x 1-27/32".
10	"	1446	CP - Crack of light 1/8"x1" MB. Punching started. Nose and body of projectile destroyed.

Round No.	Projectile	Velocity Ft/Sec.	Remarks
		Angle of Plate - 20° from Normal	
11	37 MM M51 A.P.C.	1405	PP - SB. Nose of projectile destroyed in plate. Projectile shattered.
12	"	1446	Disregard results. Hit in machine hole.
13	"	2535	CP. Diameter of penetration including BS and lamination 2-7/16"x2-25/32".
14	"	2534	Disregard. Hit in impact No. 6.
15	"	2535	Disregard. Hit clamp.

Key to Abbreviations

CP - Complete penetration
PP - Partial penetration
SB - Slight bulge on back
MB - Medium bulge on back
BS - Back spall
SC - Star crack