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Watertown Arsenal Laboratory  
Report Number WAL 710/539  
Problem Number B-4.12

UNCLASSIFIED

25 October 1943

ARMOR

Metallurgical Examination of Eleven Sections of Enemy Armor  
Including Homogeneous, Flame-Hardened,  
Carburized, and Welded Components

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OBJECT

To conduct a metallurgical investigation consisting of chemical analysis, hardness and hardness distribution of face hardened plates, macroetching for determination of steel quality, and microscopic examination.

SUMMARY OF RESULTS

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1. Flame Hardened Armor

a. The pistol port cover is a forging made from a medium carbon Cr-Mo steel heat treated to a hardness of 388 Brinell and flame hardened to an average depth of 0.09".

b. The two flame hardened rolled armor sections are made of well processed medium carbon Cr-Mo-V steel heat treated to hardnesses of 363-388 Brinell and flame hardened to a depth of 0.155" for the 50 mm. plate and 0.11" for the 31.4 mm. plate.

2. Carburized Armor

a. The carburized armor section was processed from a Mn-Cr-Mo steel. The case has a depth of 0.21" and has a maximum carbon content of 0.81%. The face hardness is 627 Brinell and the core hardness 331 Brinell. The carbon content of the core is 0.26%. The back surface of the plate exhibits severe decarburization extending into the metal for a distance of 0.15".

3. Homogeneous Armor

a. Two of the homogeneous plates are of the common medium carbon Cr-Mo analysis heat treated to 363 Brinell.

b. One homogeneous plate described as armor from a landing boat, was processed from a relatively low carbon Cr-Ni-Mo analysis and is not

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## INTRODUCTION

In accordance with instructions from the Office, Chief of Ordnance<sup>1</sup>, eleven pieces of enemy armor were forwarded to this Arsenal for metallurgical examination.

Enemy armor sections similar in nature to several of the subject plates have been previously examined at this laboratory;<sup>2,3,4</sup> consequently the metallurgical examination to which the eleven sections were subjected is not as detailed as would otherwise be the case. Data, covering chemical analyses, types of armor, hardnesses, and analyses of weld deposits, abstracted from previous reports covering metallurgical examinations of German armor are contained in Appendix A.

### MATERIALS AND TEST PROCEDURE

The armor components consist of the following items:

<u>Serial Number</u>	<u>Description</u>
FMPL-1 ✓	Cover, Pistol Port, PZ III Tank
FMPL-3 ✓	Plate, Top Engine, PZ III Tank, 17 mm.
FMPL-11 ✓	Plate, Armor, Approx. 3/4"x3/4"x3/4", used on Landing Boats
FMPL-14 ✓	Plate, Armor, Homogeneous, 16.3 mm., 14"x12"
FMPL-20 ✓	Plate, Armor, Flame Hardened, 50 mm., 4 1/2"x3"
FMPL-21 ✓	Plate, Armor, Flame Hardened, 31.4 mm., 6 1/2"x5"
FMPL-23 ✓	Plate, Armor, Homogeneous, 31.7 mm., 19"x15"
FMPL-25 ✓	Plate, Armor, Carburized, 31.0 mm., 10 1/2"x8 1/2"
FMPL-27 ✓	Plate, Armor, Homogeneous, 30.0 mm., 11"x6"
FMPL-28 ✓	Plate, Armor, Homogeneous 26.1 mm., 12 1/2"x4"
FMPL-29 ✓	Plate, Armor, Homogeneous 8.1 mm., 9"x6 1/2"

Of the above items; three FMPL-1, FMPL-20, and FMPL-21 are flame hardened; one, FMPL-25, is carburized, and the remainder are homogeneous armor plates. In addition, homogeneous plates FMPL-27, FMPL-28, and FMPL-29 contain either weld deposits or welded attachments, and homogeneous plate FMPL-3, which consists of an entire door section, has a locking device as well as two hinges attached to it by means of threaded bolts. The top engine plate was apparently attached in such a manner as to facilitate accessibility to the engine.

1. O.O. 470.5/14377, W.A. 470.5/7152, See Appendix B.
2. "Armor - Metallurgical Examination of Section of German Face-Hardened Armor from the Front of a PZ.KW III Tank." W.A. Report 710/458, A. Hurlich, 15 October 1942.
3. "Armor - Metallurgical Examination of Armored Vehicle Components (Armor Attachment Bolts and Welded Armor Sections) from a German PZ.KW III Tank." W.A. Report 710/472, P.V. Riffin, 2 January 1943.
4. "Armor - Metallurgical Examination of German Armor from a PZ.KW III Tank." W.A. Report 710/485, P.V. Riffin, 15 March 1943.

Longitudinal and transverse sections were cut from each piece for hardness surveys, macroetching, and microscopic examination. The chemical analyses of the armor sections, weld deposits, and attachments were determined as completely as possible.

In the following discussion, the plates are grouped and considered according to type.

## DATA AND DISCUSSION

### 1. Flame Hardened Armor

#### a. Chemical Analysis

The analyses of the three flame-hardened armor components are the following:

TABLE I

Chemical Analyses of Flame-Hardened Armor Sections

<u>Plate No.</u>	<u>C</u>	<u>Mn</u>	<u>Si</u>	<u>S</u>	<u>P</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>	<u>V</u>	<u>Cu</u>	<u>Al</u>
FMPL-1	.45	.60	.715	.012	.011	.12	1.34	.42	-	.14	.015
FMPL-20	.47	.66	.29	.015	.010	.13	1.30	.55	.33	.16	.015
FMPL-21	.60	.66	.43	.013	.023	.05	1.33	.29	.33	.06	.02

These analyses are typical of the Cr-Mo and the Cr-Mo-V compositions widely used for the armor components of the German PZ KW III tank, note the data in Appendix A.

#### b. Hardness Surveys

Rockwell C and Vickers hardness surveys were made upon cross-sections of the flame-hardened armor components. The graphs of the hardness patterns of plates FMPL-1, 20, and 21 are contained in Figures 1 and 3, and the data summarized in Table II. Brinell hardness impressions were also made on the face and the core of the plates.

TABLE II

Hardness Surveys of Flame-Hardened Armor

<u>Plate No.</u>	<u>Hardness of Face</u>			<u>Hardness of Core</u>			<u>Depth of Flame-Hardened zone to 400 VPN-inches</u>
	<u>BHN</u>	<u>VPN</u>	<u>Rc</u>	<u>BHN</u>	<u>VPN</u>	<u>Rc</u>	
FMPL-1	-	572	54	388	401-421	41	0.09
FMPL-20	627	690-707	58.5	363	370	37.5	0.155
FMPL-21	601	707-724	58	388	394	41	0.11

### c. Macrostructure

Sections of the flame hardened armor components were etched in a hot 50% hydrochloric acid solution. Photomicrographs of the etched sections are shown in Figures 8 and 9. The grain flow pattern of item FMPL-1, which is a pistol port cover, reveals that the cover was produced by a forging operation. The steel quality of plates FMPL-20 and 21 is good; the metal being sound, well worked, and relatively clean. The cracks in the flame hardened layer of plate FMPL-21 are believed caused by ballistic impacts in adjacent areas.

### d. Microstructure

The microstructures of the flame-hardened components are typical of previously examined plates of the same type. The structures of the cores of the three components consist of fine, tempered martensite, see Figures 11a, 12f, and 12g. The flame hardened zones consist of martensite, below which is a narrow band of high temperature tempered martensite of reduced hardness which merges into the harder tempered martensite of the base metal.

The probable heat treatment of the flame-hardened components consisted of oil quenching from above the  $A_3$  temperature, tempering back to a hardness of Rockwell C 37.5-41, and a subsequent flame-hardening of the outer surfaces.

## 2. Carburized Armor

### a. Chemical Analysis

The base analysis of the one carburized armor section is the following:

<u>Plate No.</u>	<u>C</u>	<u>Mn</u>	<u>Si</u>	<u>S</u>	<u>P</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>	<u>Cu</u>	<u>Al</u>
FMPL-25	.26	1.05	.29	.016	.016	.09	.86	.33	.11	.01

This steel is a Mn-Cr-Mo alloy possibly derived from the basic Cr-Mo analysis by lowering the chromium and raising the manganese.

A piece of plate FMPL-25 was annealed, and chips were milled from ten consecutive layers, each 0.020" thick, and analyzed for carbon. The curve of the carbon gradient is shown in the upper portion of Figure 4. The surface is slightly decarburized, with the first 0.020" layer having a carbon content of 0.68%. The maximum carbon content of the case is 0.81%, with a gradual decrease to 0.32% C at a distance of 0.180-0.200" below the plate surface.

### b. Hardness Survey

Vickers and Rockwell C hardness surveys through the cross-section of plate FMPL-25 are shown in Figure 4 and, together with Brinell surveys, are summarized in Table III.

TABLE III

Hardness Surveys of Carburized Armor

<u>Plate No.</u>	<u>Hardness of Face</u>			<u>Hardness of Core</u>			<u>Hardness of Back Surface</u>	
	<u>BHN</u>	<u>VPN</u>	<u>Rc</u>	<u>BHN</u>	<u>VPN</u>	<u>Rc</u>	<u>BHN</u>	<u>Rc</u>
FMPL-25	627	700-720	58.5	331	375	35	269	26

The depth of the case to the point where the Vickers hardness decreased to 400 VPN is 0.21". The hardness gradient of the carburized armor at the transition zone between case and core is much less steep than that of the flame-hardened plates, compare Figures 3 and 4.

c. Macrostructure

Macrophotographs of the hot acid etched sections of plate FMPL-25 are shown in Figure 10. The steel is dense, well-worked and free of segregations. The cracks are believed caused by ballistic impacts in adjacent areas of the plate.

d. Microstructure

The microstructure of the case of carburized plate FMPL-25 consists of hypereutectoid carbide particles in a matrix of fine martensite, see Figure 13c. The microstructure of the core consists of grains of tempered martensite with clusters of acicular ferrite segregated in larger ferrite grains, see Figure 13d. This microstructure is believed to result from incomplete quenching from below the upper critical range, so that ferrite is formed in two manners; some because the steel had not been completely austenitized so that some ferrite remained out of solution upon heating, and some resulting from high temperature transformation during cooling. The back surface of the plate has a layer 0.15" thick that is severely decarburized, Figure 13e.

A probable method of manufacture of this armor consists of carburizing the armor in a relatively heavy section, then subsequently rolling it to the final gauge. This method of production produces a good diffusion of carbon, breaks up any hypereutectoid carbide grain boundary network formed upon carburizing, and generally results in some decarburization at the plate surface such as was observed in the subject plate. The plate was probably oil quenched from a temperature that was above the  $A_3$  temperature of the high carbon case, but below the  $A_3$  temperature of the low carbon core, and tempered at a moderately low temperature.

3. Homogeneous Armor

a. Chemical Analysis

The analyses of the homogeneous armor components are contained in Table IV.

TABLE IV

Chemical Analyses of Homogeneous Armor Components

<u>Plate No.</u>	<u>C</u>	<u>Mn</u>	<u>Si</u>	<u>S</u>	<u>P</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>	<u>Cu</u>	<u>Al</u>
FMPL-3	.51	.65	.45	.010	.030	Trace	1.40	.42	.05	.03
FMPL-11	.25	.34	.28	.019	.011	.57	2.67	.19	.17	.07
FMPL-14	.50	.66	1.77	.018	.031	.07	.84	.21	.11	.015
FMPL-23	.48	.61	1.42	.021	.018	.08	.88	.20	.14	.015
FMPL-27	.50	.59	1.38	.017	.019	.08	.87	.18	.16	.015
FMPL-28	.53	.67	.42	.016	.022	.07	1.31	.44	.09	.02
FMPL-29	.49	.59	1.69	.010	.009	.14	1.00	.29	.13	.03
Hinge from Plate FMPL-3	.47	.65	.43	.010	.026	Trace	1.34	.39	.04	.04

Plates FMPL-3, FMPL-28, and the hinge from plate FMPL-3 are of the common Cr-Mo analysis. Plate FMPL-11, reported as being armor from a landing boat, is not believed to be of German manufacture because it contains nickel and has an unusually high chromium content; being somewhat similar in composition to armor produced in Italy.

Plates FMPL-14, 23, 27, and 29 represent a new type composition not previously encountered in German armor, namely a Si-Cr-Mo analysis. This analysis is a modification of the older Cr-Mo alloy with the chromium content reduced 0.30-0.50%, the molybdenum content reduced .15-.25%, and the silicon content raised to 1.40-1.70% to offset the decrease in hardenability occasioned by lowering the chromium and molybdenum. This modification may represent an attempt to conserve the more strategic alloying elements, and may be symptomatic of decreasing German stockpiles.

b. Hardness Surveys

Rockwell C hardness surveys were made upon cross-sections of the homogeneous plates, and Brinell impressions were made on both surfaces and on cross-sections cut from the plates. Graphs of Rockwell C hardness surveys of the homogeneous armor are contained in Figures 1, 2, and 4, and the data summarized in Table V.

TABLE V

Hardness Surveys of Homogeneous Plates

<u>Plate No.</u>	<u>Hardness of Front Surface, BHN</u>	<u>Hardness of Core BHN</u>	<u>Hardness of Back Surface Rc</u>	<u>Hardness of Back Surface BHN</u>
FMPL-3	363	341	35	341
FMPL-11	-	-	36.5	-
FMPL-14	363	388	41.5	363
FMPL-23	321	341	36.5	311
FMPL-27	331	341	38	285
FMPL-28	363	363	39	363
FMPL-29	444	444	45	444
Hinge from Plate FMPL-3	341	341	--	341

German armor is found to be generally considerably harder than American armor of comparable thickness.

### c. Macrostructure

Photomicrographs of the hot acid etched sections of the homogeneous plates and some of their attachments are shown in Figures 8, 9, 10, and 11. The hinge from plate FMPL-3 was produced by forging. The macro-photograph of the hinge shown in Figure 8 is of a surface perpendicular to the flow lines and thus reveals only the end-grain condition. Plate FMPL-3 contains many short scattered nonmetallics which have been etched out by the hot acid, see Figure 8. Details of the assembly of the locking device attached to top engine plate FMPL-3 are shown in Figure 11e.

Homogeneous plate FMPL-14 has been well processed and thoroughly cross-rolled, see Figure 8. Plate FMPL-23 has a greater nonmetallic content than most of the other homogeneous plates, Figure 9. Plates FMPL-27, 28, and 29 are all very clean, sound, and well processed, see Figure 10.

### d. Microstructure

#### Plate FMPL-3

The steel is relatively dirty, containing many slightly elongated inclusions, Figure 11b. The microstructure consists of tempered martensite with relatively severe banding, Figures 11c and d. The microstructure of the hinge consists of tempered martensite similar to that of the plate. The threaded bolt has a microstructure of tempered martensite, Figure 11f, and is very similar in all respects to the bolt studied and reported in WAL Report No. 710/4723. The plate, hinge, and bolts were probably oil quenched and tempered back to their respective hardnesses.

#### Plate FMPL-11

The steel of the landing boat armor is relatively clean, but one large centerline defect, consisting of residual piping and/or thermal cracking was found extending to a sheared end of the plate, see Figure 12a. The microstructure consists of martensite and acicular ferrite, Figures 12b and c, probably resulting from quenching from a temperature between the  $A_1$  and  $A_3$  temperatures without subsequent tempering. The reason for the deliberate production of this microstructure, if such were the case, is uncertain; for the properties developed are unsatisfactory for armor applications.

#### Plate FMPL-14

The steel is relatively dirty, with many short stringers distributed throughout the cross-section, Figure 12d. The microstructure consists of acicular tempered martensite, Figure 12e, probably resulting from oil quenching and tempering.

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3. See footnote on Page 3.

### Plate FMPL-23

The plate surfaces are decarburized to an unusually severe extent for homogeneous armor, having decarburized layers averaging 0.025" deep, Figure 13a. The microstructure consists of a mixture of tempered martensite, ferrite, and pearlite, Figure 13b, resulting from incomplete quench hardening. This plate represents one of the very few cases of poor heat treatment observed in German armor. Almost all the samples of German armor which have been examined at this Arsenal have indicated excellent heat treatments and satisfactory tempered martensitic microstructures.

### Plate FMPL-27

The microstructure consists of spheroidized carbides in a matrix of tempered martensite which exhibits slight banding, Figures 14b and c. One surface of the plate is severely decarburized, having a total depth of decarburization of 0.04" with a 0.008" layer completely decarburized to ferrite, Figure 14d.

### Plate FMPL-28

The microstructure consists of a well spheroidized sorbito, Figure 15c.

### Plate FMPL-29

The microstructure consists of acicular tempered martensite, Figure 16b, probably resulting from oil quenching and tempering at a relatively low temperature to produce high hardness.

## 4. Weldments

### a. Description

Homogeneous plate FMPL-27 had a thin structural steel member welded to the back surface with two single bead passes to form a T joint, see the macrophotograph in Figure 10. Homogeneous plate FMPL-28 included a two bead weld along one end of the plate, see Figure 10, and homogeneous plate FMPL-29 had a strip welded completely around the plate by means of two single bead passes forming an L joint, Figure 10.

The structural members and weld deposits were numbered as follows:

### Plate FMPL-27

- A - Structural steel member
- B - Weld deposit (It was determined spectrographically that the two deposits were laid on with electrodes of the same analysis.)

Plate FMPL-28

- C - Outer weld deposit
- D - Inner weld deposit

Plate FMPL-29

- E - Inside weld
- F - Outside weld (It was determined spectrographically that the two deposits, E and F, were laid on with electrodes of the same analysis).
- G - Steel strip welded to plate

b. Chemical Analysis

The analyses of the welded attachments and the weld deposits are contained in Table VI.

TABLE VI

Chemical Analyses of Welded Attachments and Weld Deposits

<u>Item No</u>	<u>C</u>	<u>Mn</u>	<u>Si</u>	<u>S</u>	<u>P</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>	<u>W</u>	<u>Cu</u>
Strip A	.05	.46	.01	-	-	.13	.10	-	-	.09
Weld B	.11	.82	.10	-	-	--	.25	Trace	-	.10
Weld C	.37	1.50	.195	-	-	2.25	2.04	.66	.63	.20
Weld D	.26	4.32	--	-	-	1.04	9.44	.27	-	.14
Welds E & F	.34	.82	.89	-	-	.12	.59	.19	-	.19
Strip G	.47	.69	1.66	-	-	.21	1.20	.39	-	.12

The carbon analyses are probably unreliable, and may often incorporate carbon pick-up from the base metal.

Plate FMPL-27

The weldment on this plate consists of a low-carbon structural steel member attached to the plate with two single bead weld deposits using low carbon steel electrodes.

Plate FMPL-28

The weldment consists of a duplex weld deposit, containing an inner weld deposit of a Mn-Ni-Cr-Mo alloy containing sufficient amounts of the austenite forming elements to produce a substantially austenitic weld, and an outer weld deposit of a Mn-Ni-Cr-Mo-W alloy rich in the hardening elements which form substantially martensitic deposits.

Reference to Appendix A shows that both these weld rod compositions are widely used in German manufacture. Analyses of five welds of the austenitic type follow:

	Mn	Ni	Cr	Mo	V	Source of Data
	4.32	1.04	9.44	.27	-	Weld D
	5.0	1.00	12.9	.23	-	R.D. Met. Report 232/42, Appendix A
	6.5	1.26	15.6	.10	-	" " " " " "
	4.81	.81	10.36	Trace	.32	W.A.L. Report 710/472, Appendix A
	5.19	.99	11.46	Trace	-	W.A.L. Report 710/485, Appendix A
Average	5.1	1.0	12.0	-	-	

The basic analysis of the austenitic weld rod appears to be 5.0 Mn, 1.0 Ni, 12.0 Cr, either with or without small amounts of Mo or V. In this alloy, manganese replaces the more strategic nickel; but the composition does not provide as stable an austenite as the 18 Cr- 8 Ni analysis, and sufficient martensite is formed during cooling from the welding temperature to raise the hardness of the weld deposit to approximately 400 Vickers Pyramid Number.

The analyses of several typical hard facing weld deposit compositions are as follows:

	Mn	Ni	Cr	Mo	W	Source of Data
	1.50	2.25	2.04	.66	.63	Weld C
	1.93	3.33	2.42	.61	.62	R.D. Met. Report 232/42 Appendix A
	1.93	2.38	3.44	.57	.20	W.A.L. Report 710/472, Appendix A
	2.00	2.44	3.54	.58	.36	" " " "
	1.67	3.05	1.40	.64	Present	" " " "
Average	1.8	2.7	2.5	.60	.45	

The hard facing weld deposit has been found to have a hardness of 500-550 Vickers, and is frequently severely cracked. The usual welding procedure when the two different types of weld deposits are used together, is to first deposit the austenitic weld, then cover it with a layer of the hard facing weld which becomes the portion of the weldment exposed to ballistic attack.

### FMPL-29

The weldment consists of a strip of armor steel welded around the armor plate with two single pass deposits employing a low alloy Cr-Mo weld rod containing some residual nickel.

#### c. Hardness Surveys

Vickers hardness surveys made across the weld deposits, heat affected zones, welded attachments, and base metal of the weldments on plates FMPL-27, 28, and 29 are shown graphically in Figures 5, 6, and 7 respectively. Pertinent data are summarized in Table VII.

TABLE VII

Hardness Surveys of Weldments

<u>Plate #</u>	<u>Av. Hardness of Base Metal VPN</u>	<u>Max. Hardness Heat Affected Zone of Base Metal-VPN</u>	<u>Av. Hardness of Weld Deposit-VPN</u>	<u>Av. Hardness of Welded Attachment VPN</u>	<u>Max. Hardness of Heat Affected Zone of Attachment-VPN</u>
FMPL-27	375	690	325 Outer	160	200
FMPL-28	375	625	weld-525 Inner	-	-
FMPL-29	450	734	weld-400 275	375	690

That German armor steels are not well adapted to welding is indicated by the extremely high hardnesses developed in the heat affected zones of the base metal. The steels have been found to be very susceptible to cracking, see Appendix A.

d. Microstructure

Plate FMPL-27

The microstructure of the weld deposit consists of ferrite and carbides, Figure 14f, which would be expected considering the low carbon weld rod used. The microstructure of the mild steel structural member welded to the plate consists of ferrite and a small amount of carbides, Figure 14e.

Plate FMPL-28

The microstructure of weld bead C, the outer weld, consists of martensite with small amounts of austenite; and that of weld bead D, the inner weld, consists of austenite with small amounts of martensite. The hard weld is severely cracked, with the crack extending into the heat affected zone of the base armor, Figures 15a and b.

Plate FMPL-29

The microstructure of the armor steel composition strip welded to the base armor consists of martensite and ferrite resulting from quenching from an intercritical temperature, Figure 16c. The microstructure of the two weld deposits is identical, consisting of ferrite, carbides, and some martensite, Figure 15d. The weld metal contains a large degree of dendritic segregation; with many cracks associated with the segregation, Figure 15f.

## GENERAL CONSIDERATIONS

The eleven armor sections submitted for examination fall into five type analyses, as follows:

<u>No. of Plates</u>	<u>Type Analysis</u>
3	Cr-Mo
2	Cr-Mo-V
1	Mn-Cr-Mo
1	Cr-Ni-Mo
4	Si-Cr-Mo

Of these types, two, the Cr-Mo, and the Cr-Mo-V composition have been frequently encountered in previous examinations of German armor from the PZ KW III Tank, see Appendix A, and are believed to represent the basic compositions most widely employed. The Mn-Cr-Mo steel, used for the carburized armor, represents a slight modification of the Cr-Mo analysis, with the chromium content lowered and the manganese raised to maintain the hardenability.

The Cr-Ni-Mo alloy is not believed to be of German manufacture, and more closely resembles armor analyses developed in Italy.

Of striking interest is the Si-Cr-Mo analysis, encountered for the first time in the subject armor. The reduction of the chromium and molybdenum contents indicates an attempt at conservation of these strategic alloying elements. The hardenability of the steel is maintained by an increase in silicon, a non-strategic alloying element.

Some of the weldments consisted of attachments welded to armor sections by means of low-carbon low alloy weld deposits. These weldments are apparently not subject to ballistic attack. In weldments subject to ballistic attack, the Germans employ a well standardized welding procedure. The first beads are laid on using an electrode of an analysis which produces a predominately austenitic deposit with sufficient martensite to produce an average hardness of approximately 400 Vickers. The electrode has an analysis of substantially 5 Mn, 1 Ni, 12 Cr, with or without small quantities of Mo or V. A deposit of a hard facing alloy weld metal is laid on over the first deposit. The hard facing alloy electrode has an average analysis of approximately 1.8 Mn, 2.7 Ni, 2.5 Cr, .60 Mo, and .45 W and produces a predominately martensitic deposit having a hardness of 500-550 Vickers.

German armor is not well adapted to welding operations. The high carbon content usually employed, 0.40-0.60 C, results in the formation of extremely high hardnesses in the heat affected zone (frequently higher than 700 Vickers) with consequent danger of cracking. Cracks in heat affected zones of German weldments have been frequently reported. The hard facing alloy is an extremely poor welding material, rarely being found free of cracks. The hard facing deposit is very brittle, breaking off readily under ballistic attack.

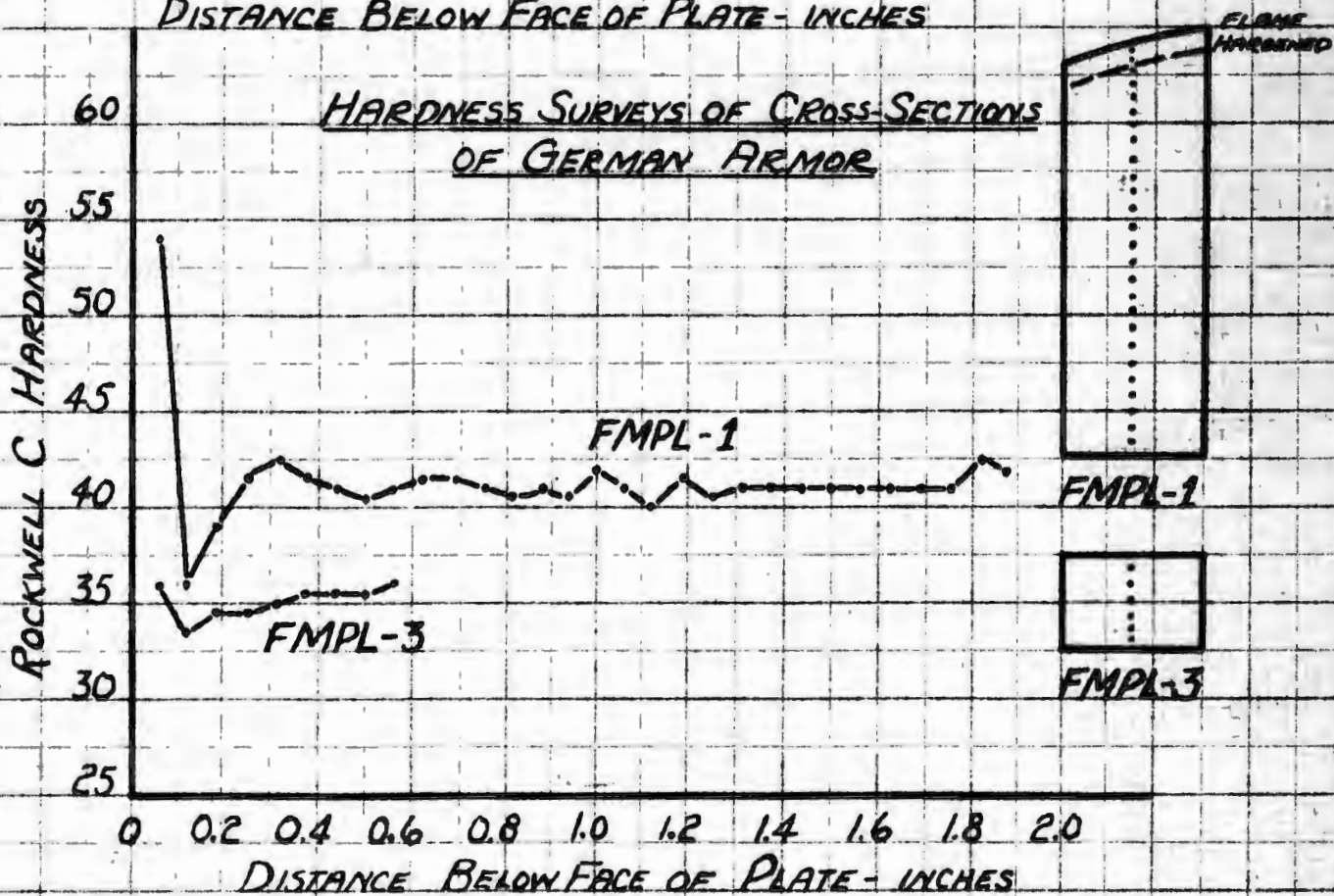
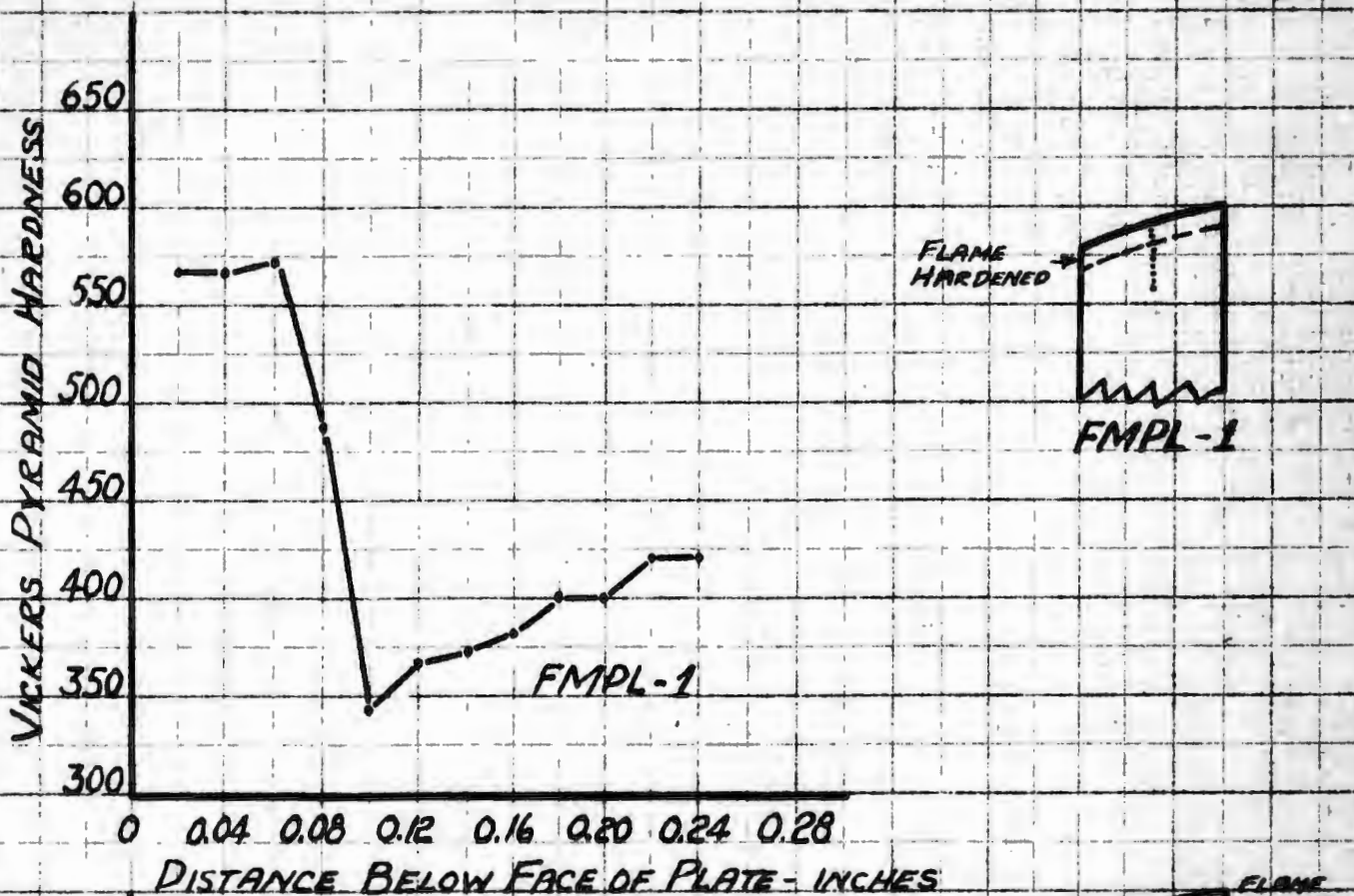
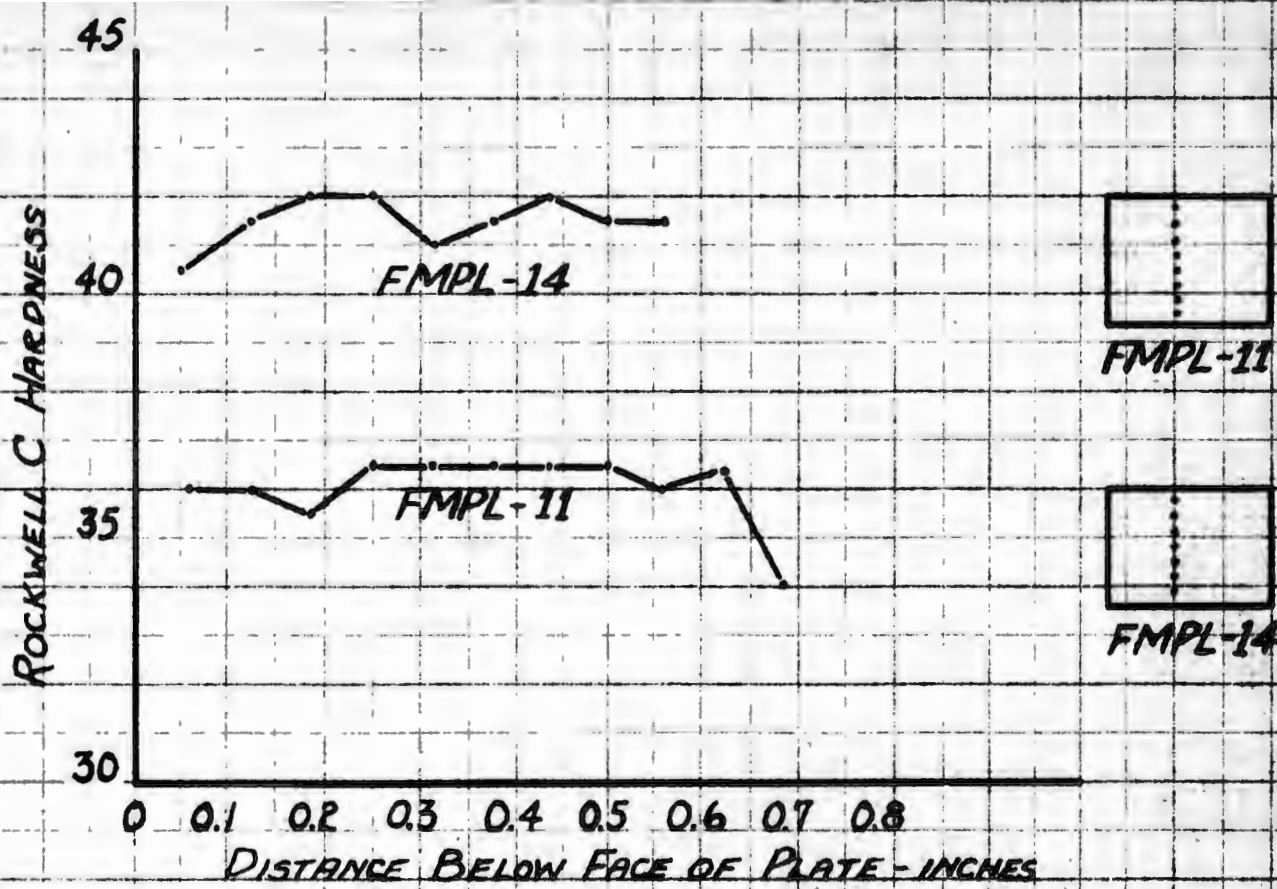


FIGURE 1



HARDNESS SURVEYS OF CROSS-SECTIONS OF GERMAN ARMOR

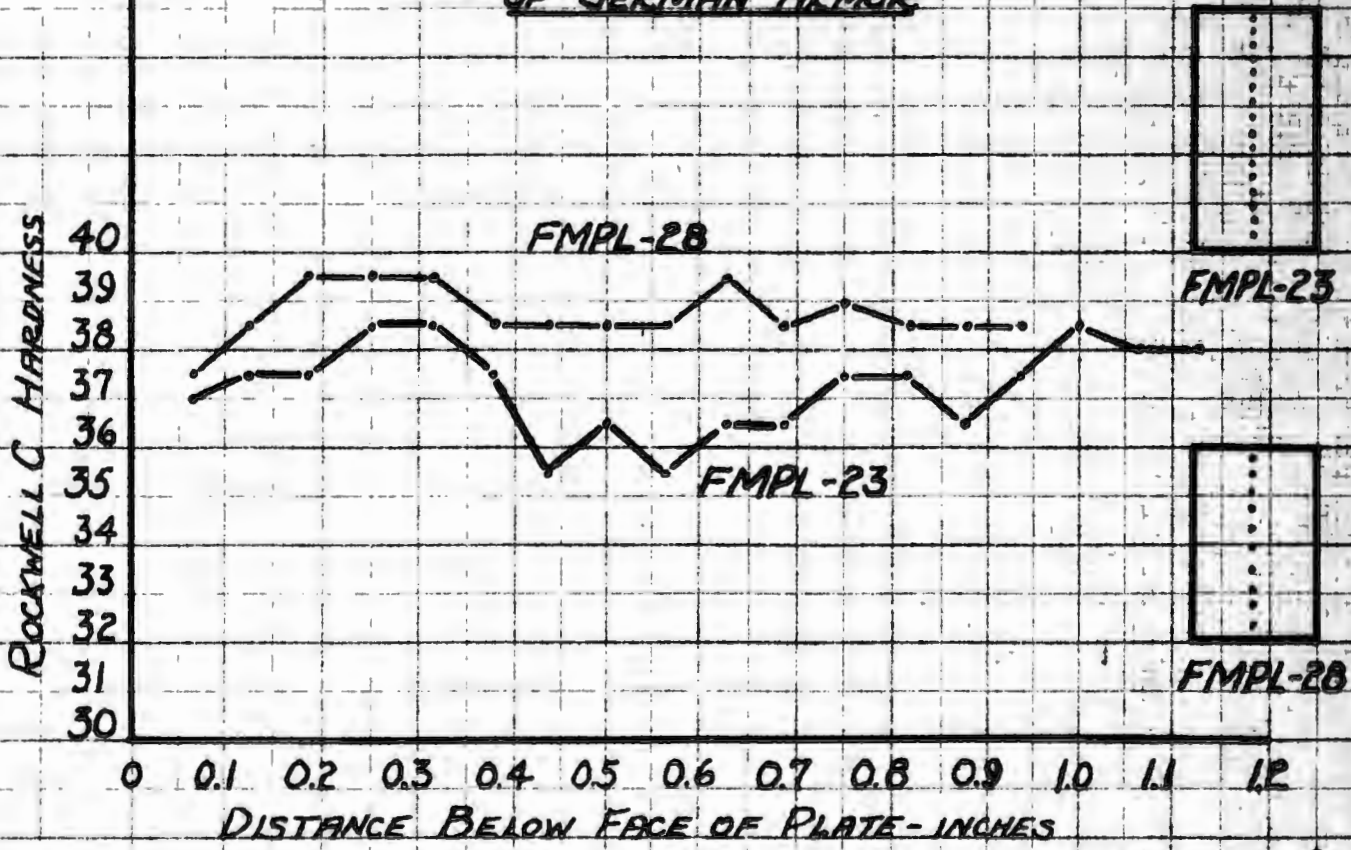
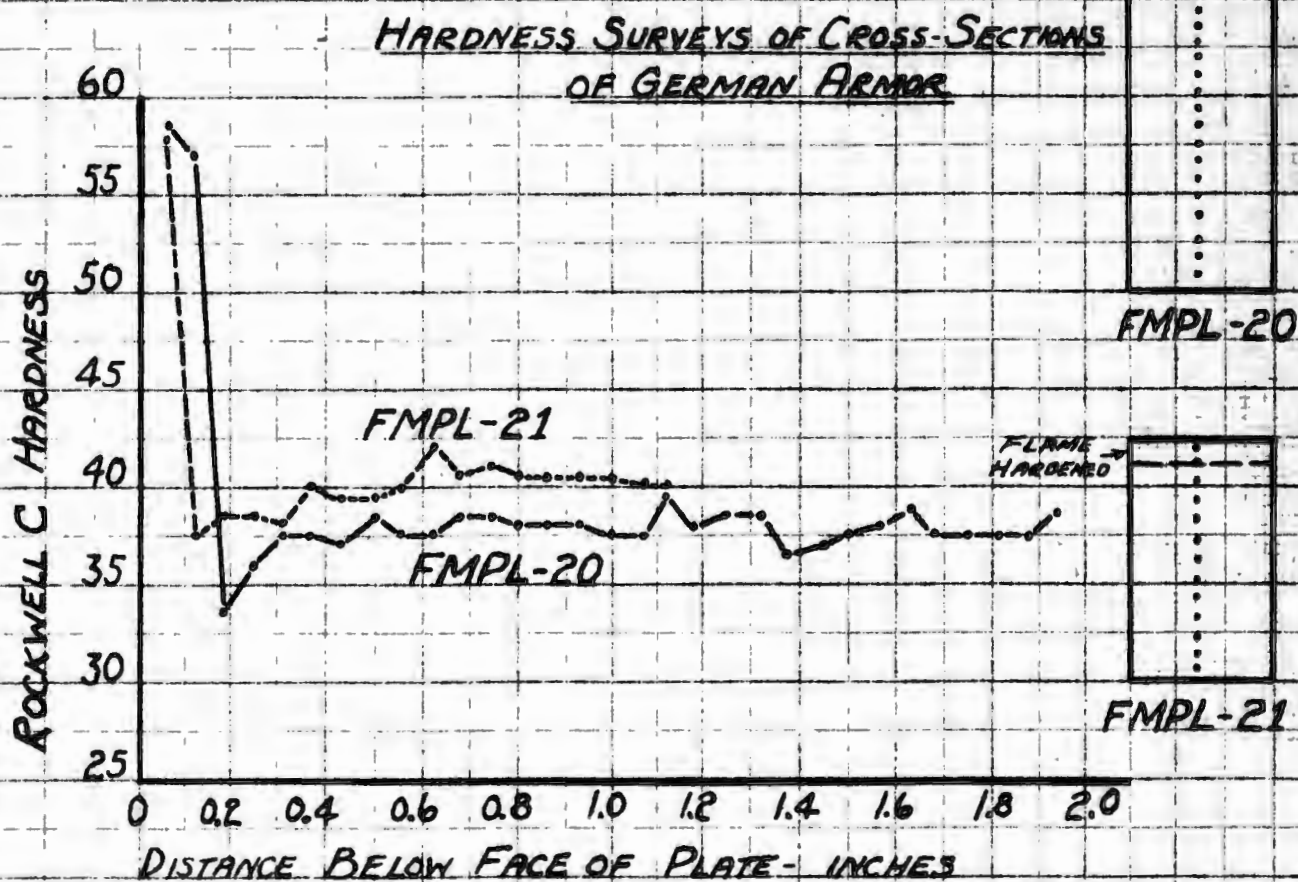
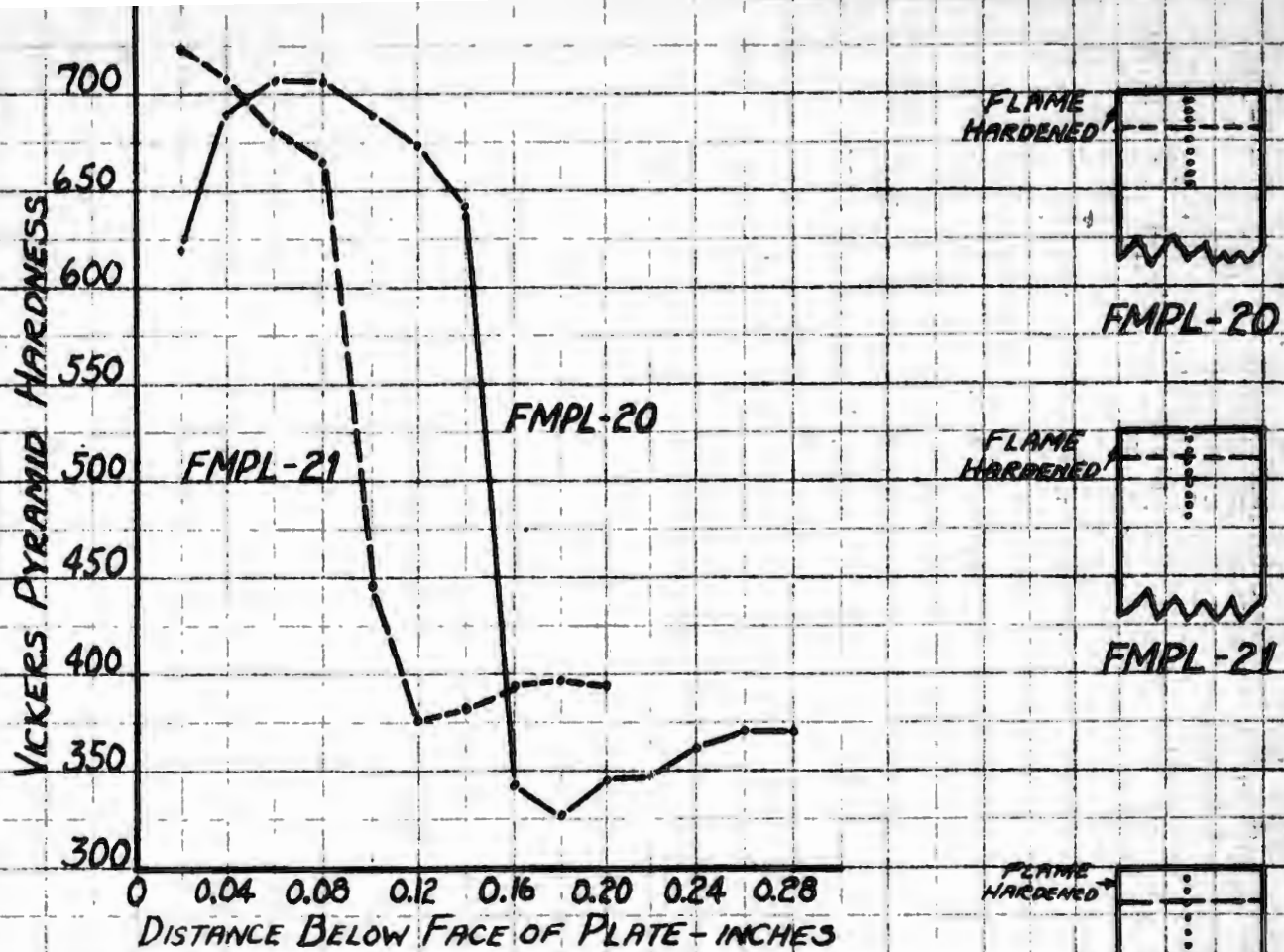


FIGURE 2



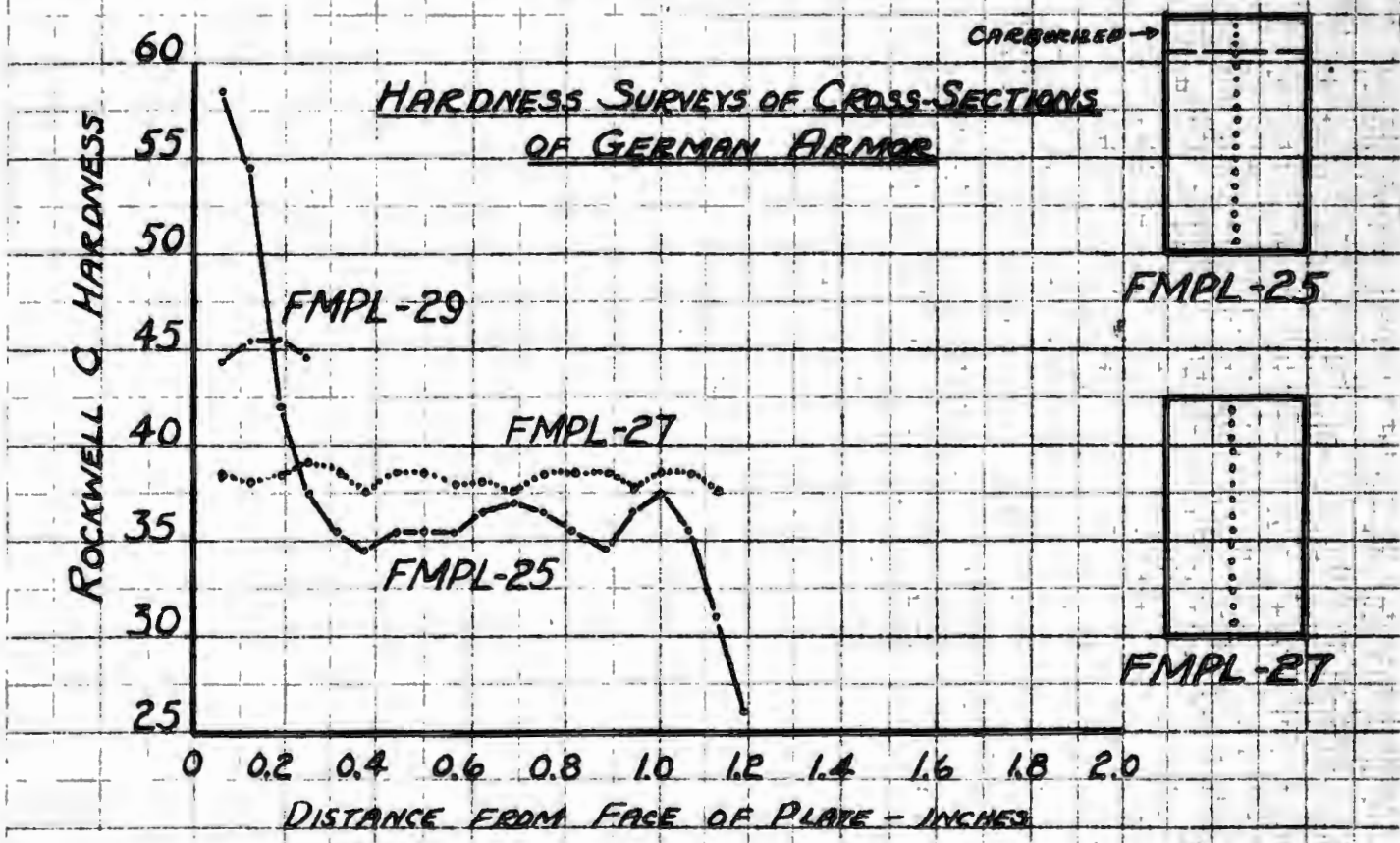
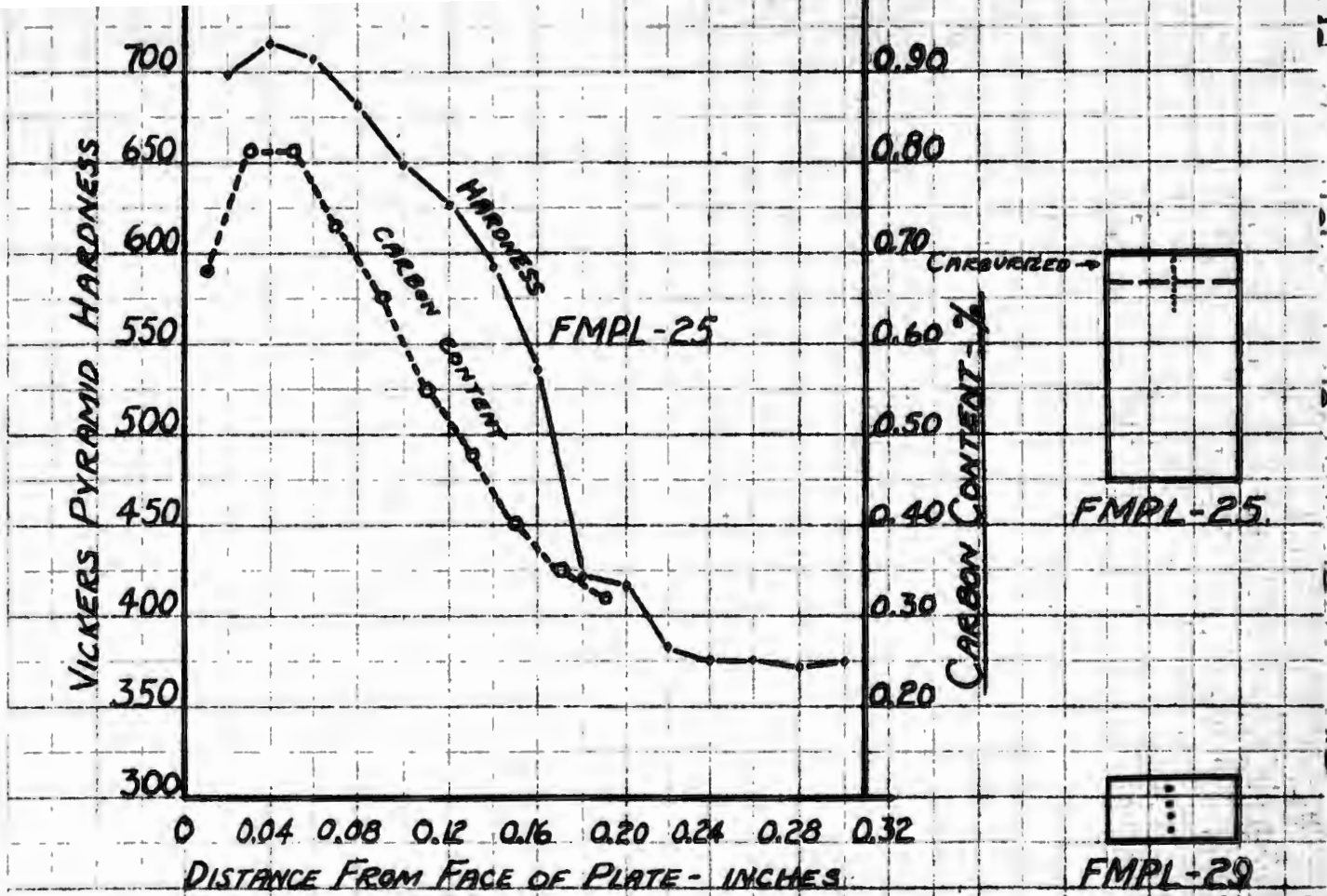


FIGURE 4

W.A. AH 10/7/43

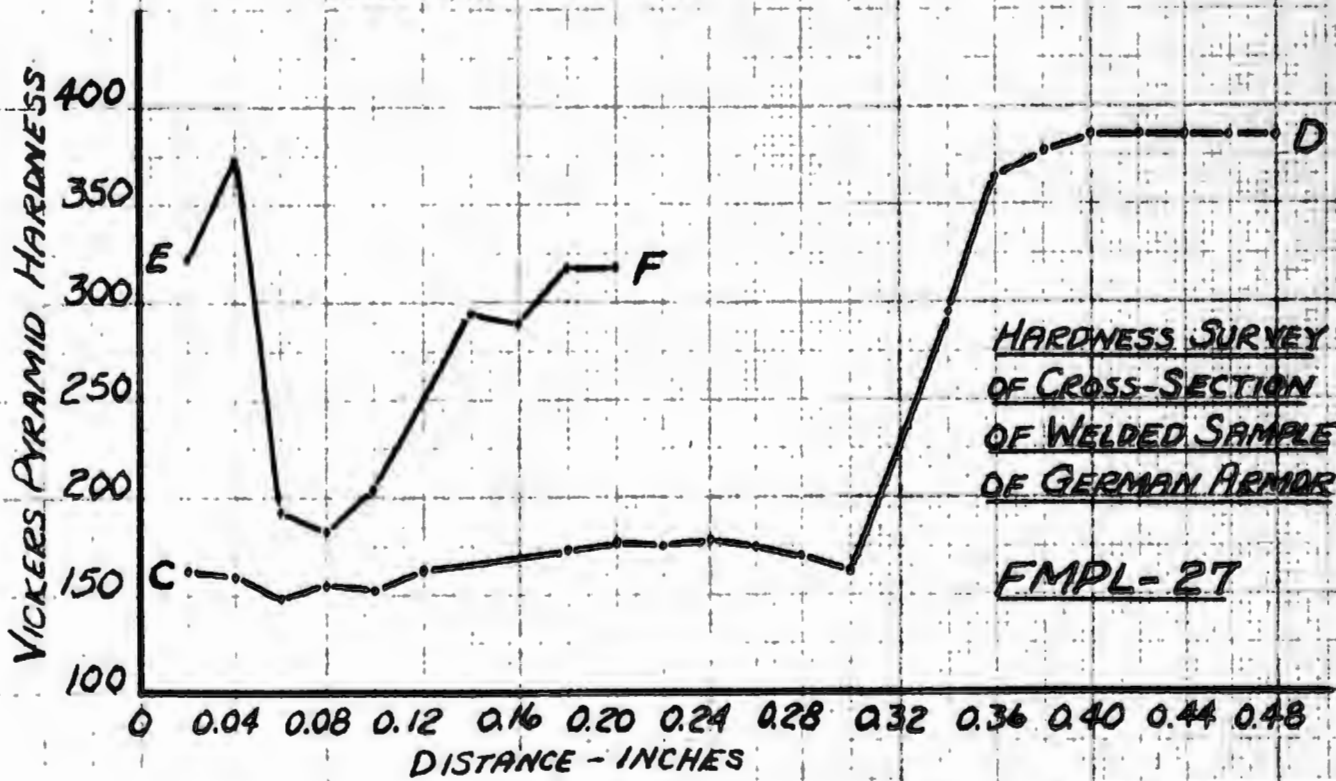
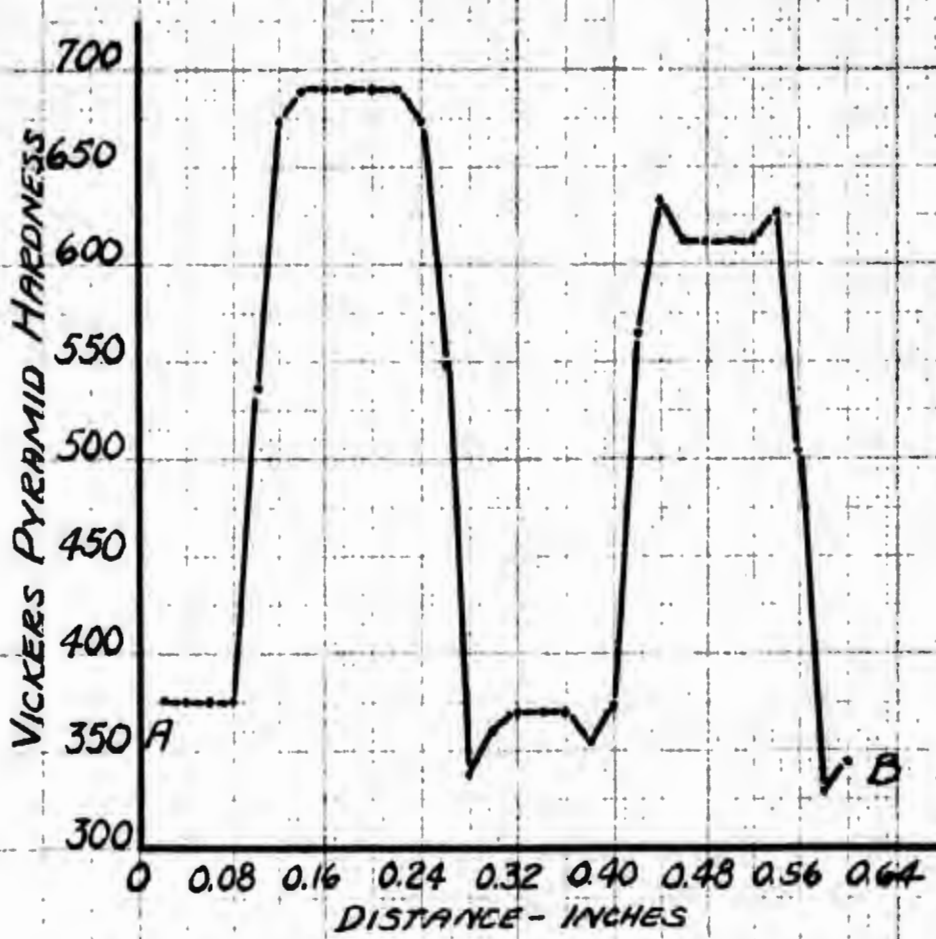
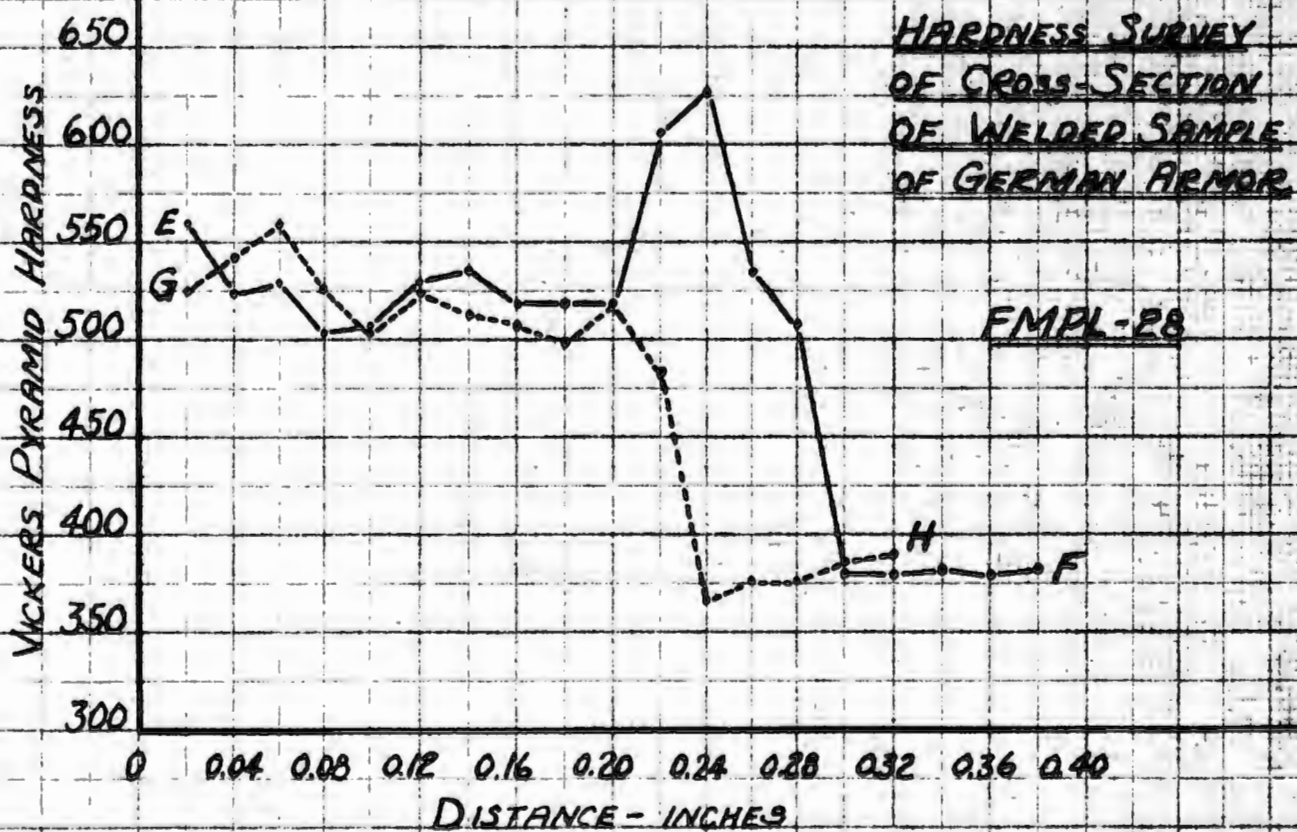
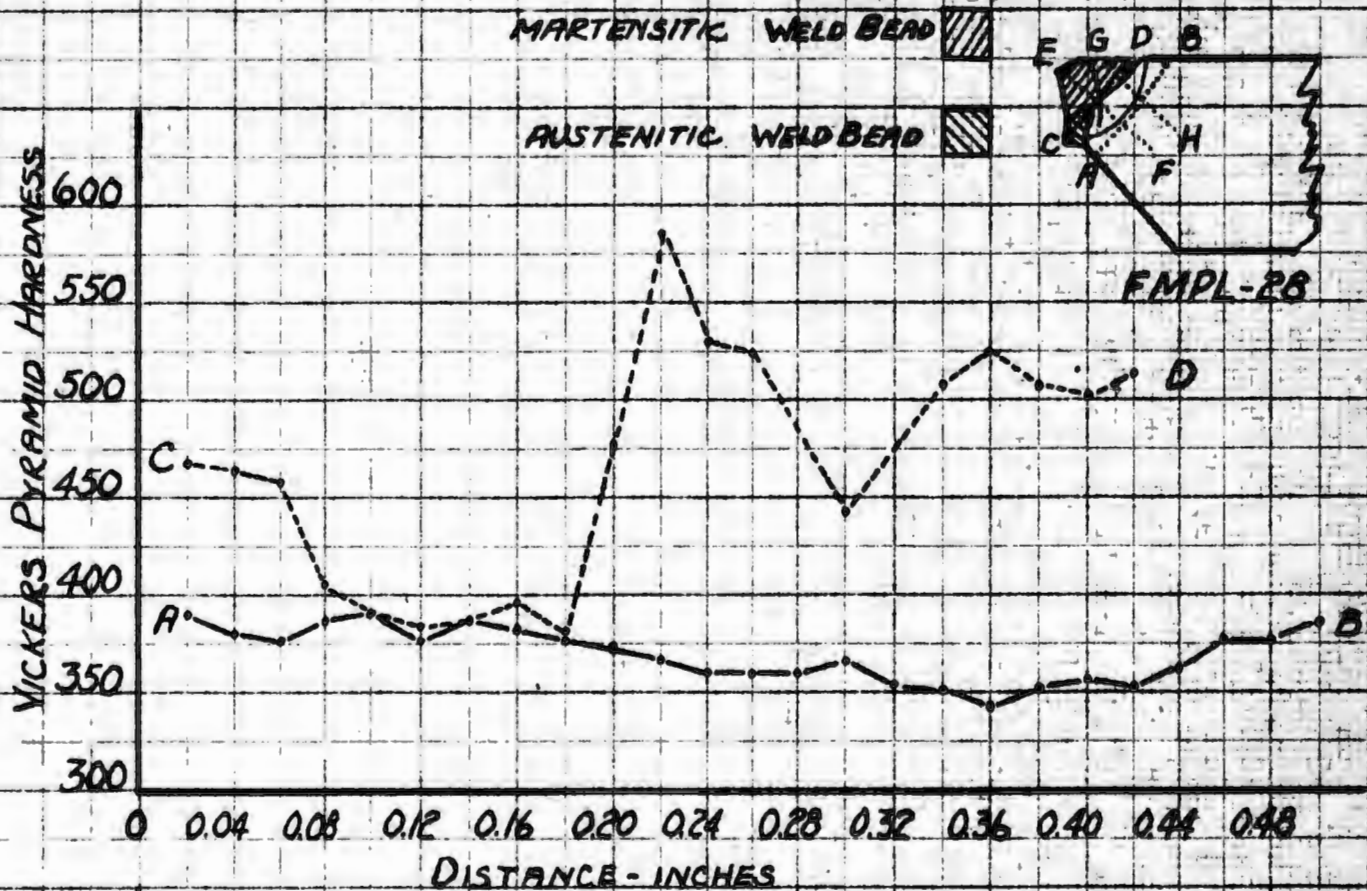


FIGURE 5



**FIGURE 6**

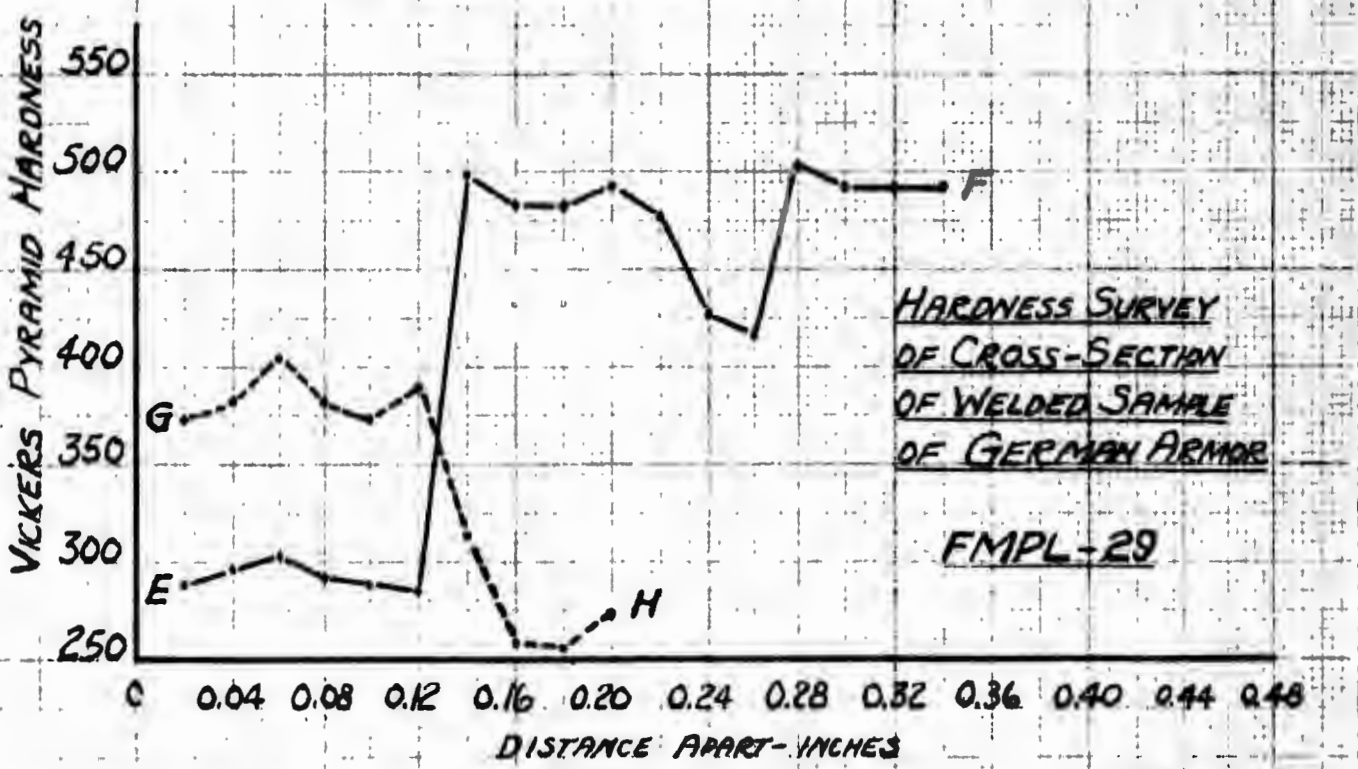
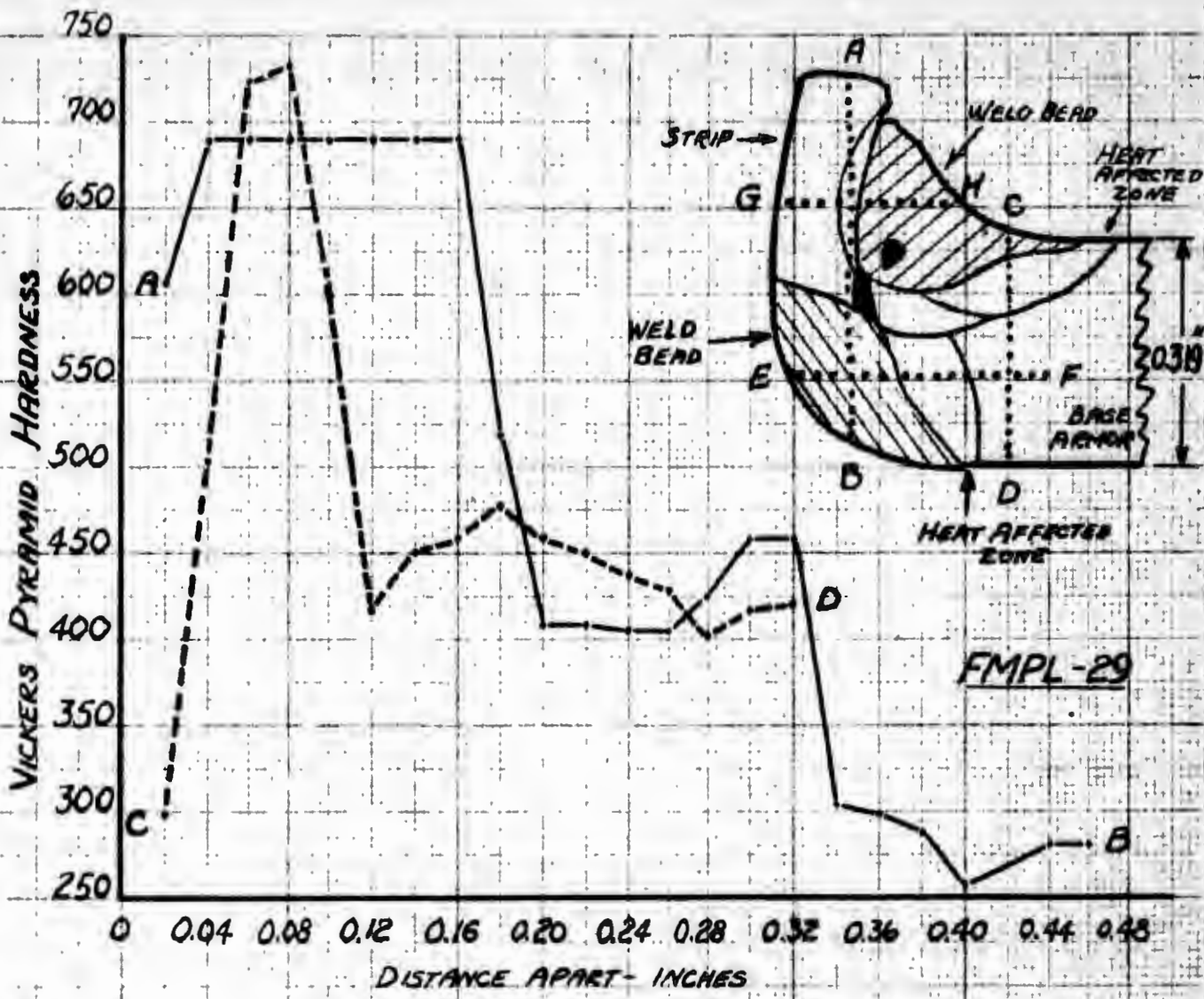
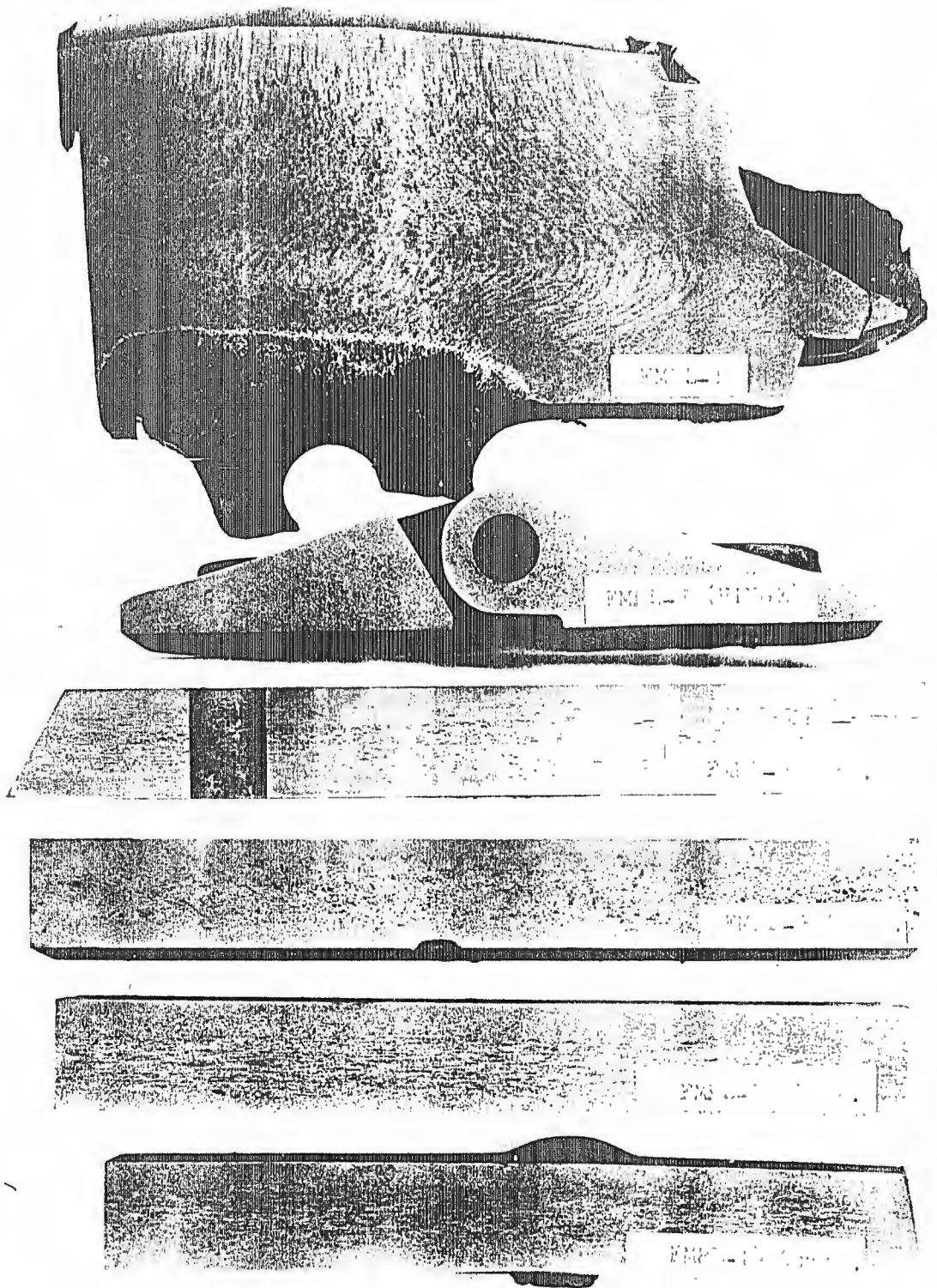
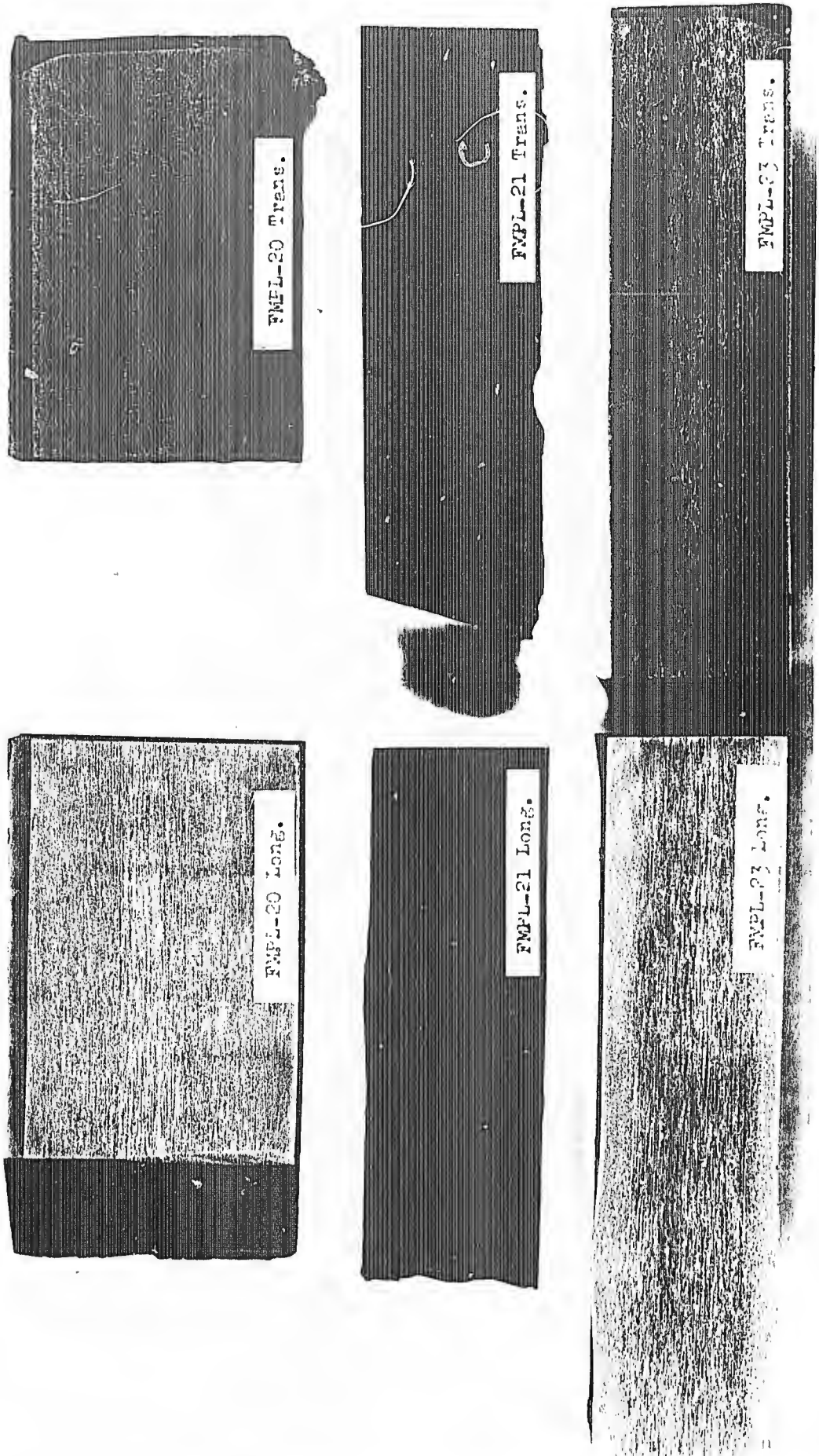


FIGURE 7



ORDNANCE DEPT U.S.A.  
WATERTOWN ARSENAL

MACROETCHED SECTIONS OF GERMAN ARMOR  
WTN.710-2134



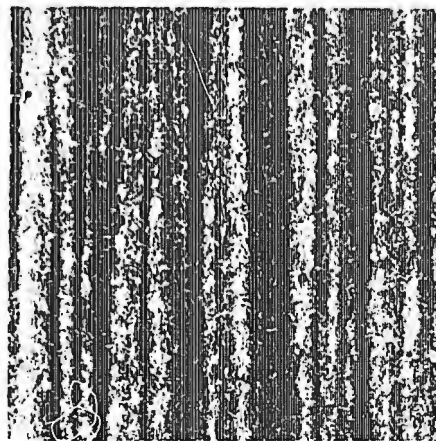
INCHES 3 2 1

ORDNANCE DEPT U.S.A.  
WATERTOWN ARSENAL  
MACROETCHED SECTIONS OF GERMAN ARMOR  
WTN.710-2135

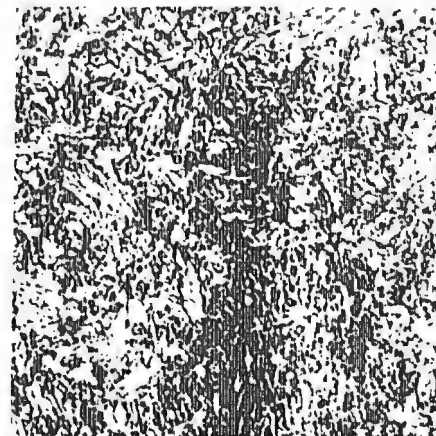
Microstructures of Enemy Armor Components



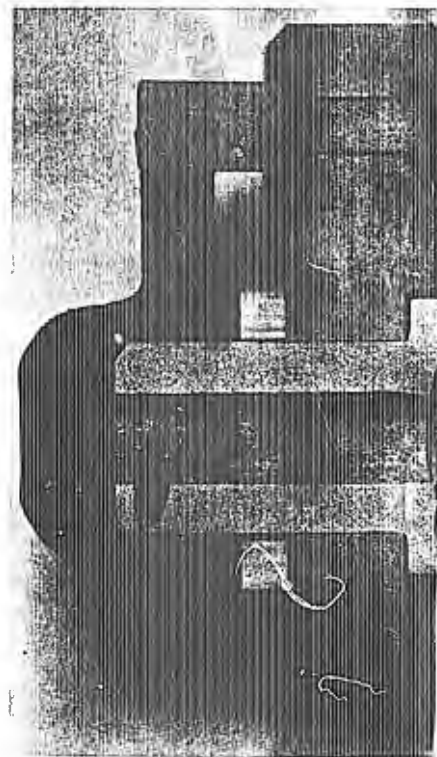
FMPL-1 -a- X1000  
Flame-hardened armor.  
Microstructure of core.  
Tempered martensite.



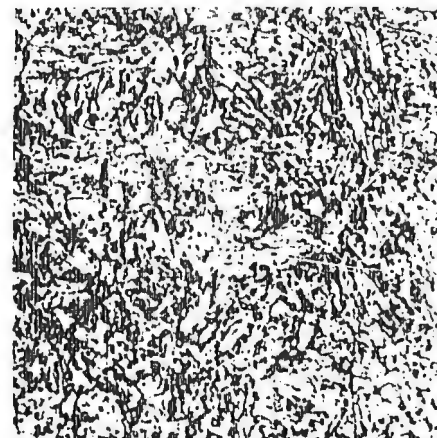
FMPL-3 -c- X100  
Severe banding.



FMPL-3 -d- X1000  
Homogeneous armor.  
Tempered martensite.



FMPL-3 -e- X1  
Cross-section of locking device in Top Engine  
Plate FMPL-3. Hot acid macroetch.



FMPL-3 -f- X1000  
Microstructure of threaded  
bolts attaching hinges to  
Top Engine Plate FMPL-3.  
Tempered martensite.

Microstructures of Enemy Armor Components

Etched in Nital-Picral



FMP-11 -a- X100  
Nonmetallic stringers and thermal crack extending to sheared end of plate. Unetched.



FMP-11 -b- X100  
Widmanstätten pattern of ferrite.



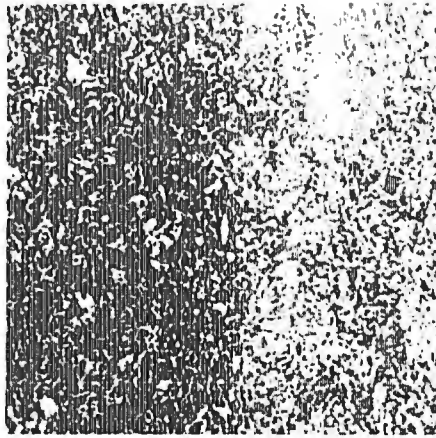
FMP-11 -c- X1000  
Ferrite and high temperature transformation products.



FMP-14 -d- X100  
Dirty steel. Many short inclusions. Unetched.



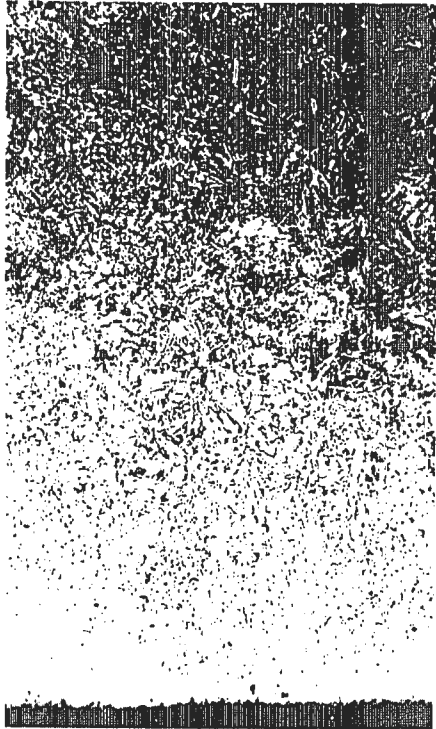
FMP-14 -e- X1000  
Homogeneous armor. Tempered martensite.



FMP-20 -f- X1000  
Flame-hardened armor. Core structure. Carbides and tempered martensite.

FMP-21 -g- X1000  
Flame-hardened armor. Core structure. Tempered martensite.

Microstructures of Enemy Armor Components

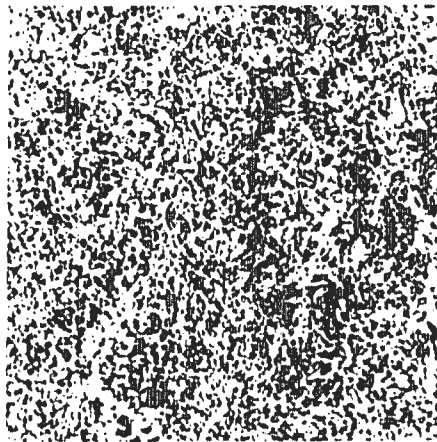


FML-23 -a- X100  
Homogeneous armor. Decarburized surface of plate. Total decarburization - 0.025".

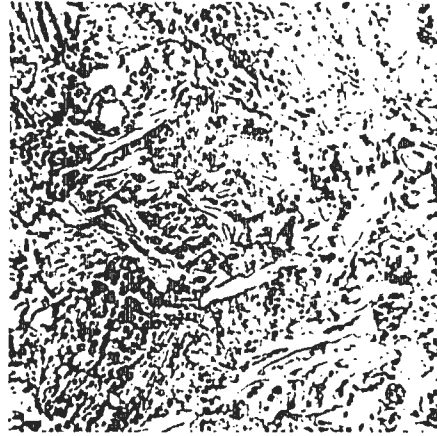
Etched in Nital-Picral



FML-23 -b- X1000  
Tempered martensite and high temperature transformation products.



FML-25 -c- X1000  
Carburized armor. 0.010" below surface. Carbides and tempered martensite.



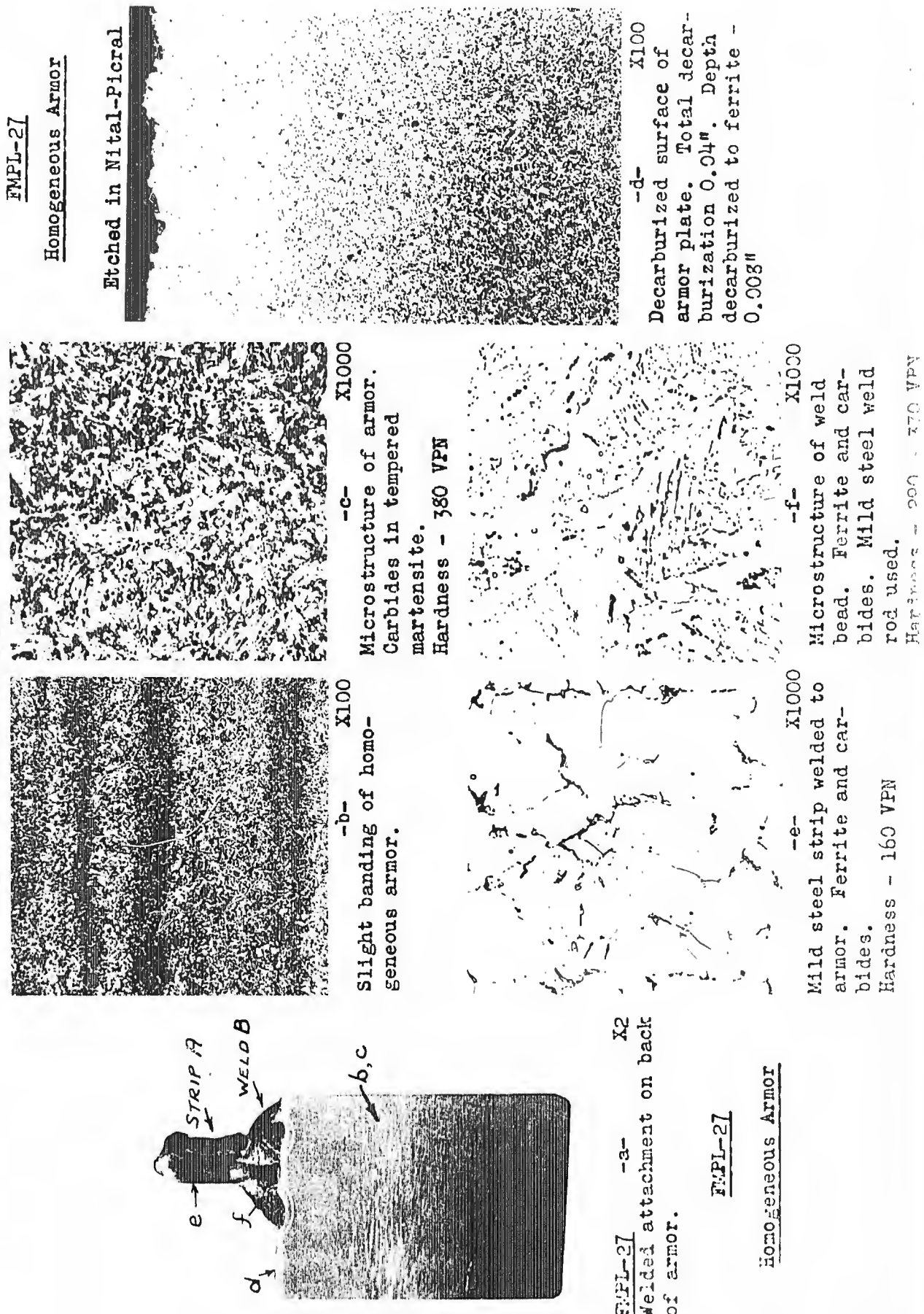
FML-25 -d- X1000  
Core structure of carburized armor. Tempered martensite, carbides, and ferrite.



FML-25 -e- X1000  
0.05" above back surface of plate. Decarburized region. Ferrite and carbides.

Figure 13

Microstructures of Enemy Armor Components



FMPL-27

Homogeneous Armor

Etched in Nital-Picral

FMPL-27 -a- X2  
Welded attachment on back of armor.

FMPL-27

Homogeneous Armor

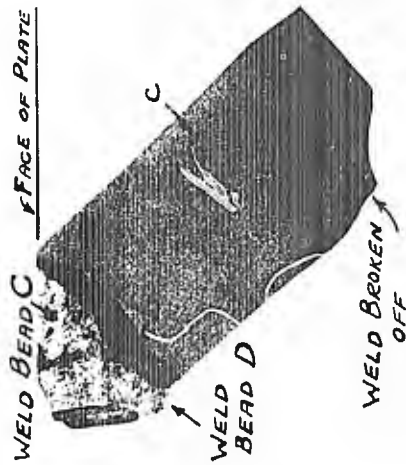
-b- X100  
Slight banding of homogeneous armor.

-c- X1000  
Microstructure of armor. Carbides in tempered martensite. Hardness - 380 VPN

-d- X100  
Decarburized surface of armor plate. Total decarburization 0.04". Depth decarburized to ferrite - 0.003"

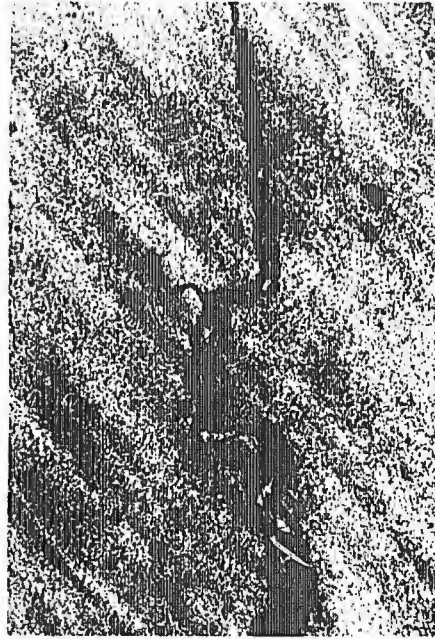
-e- X1000  
Mild steel strip welded to armor. Ferrite and carbides. Hardness - 160 VPN

-f- X1000  
Microstructure of weld bead. Ferrite and carbides. Mild steel weld rod used. Hardness - 200 - 370 VPN



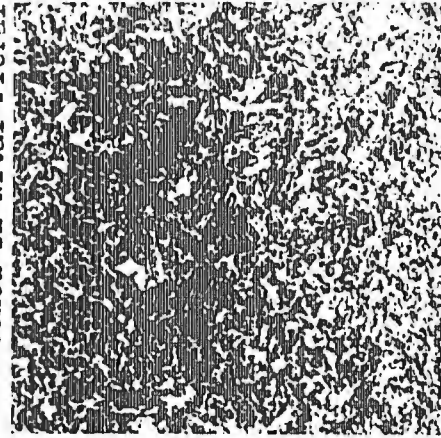
FMPL-28 -a- X2  
 Macrostructure of duplex weld  
 Weld bead C is martensitic  
 and is cracked, with crack  
 extending into heat-affected  
 zone of base metal. Weld  
 bead D is largely austenitic  
 and considerably softer than  
 weld bead C.

Microstructures of Enemy Armor Components



-b- X100  
 Crack in heat affected zone of base  
 armor.

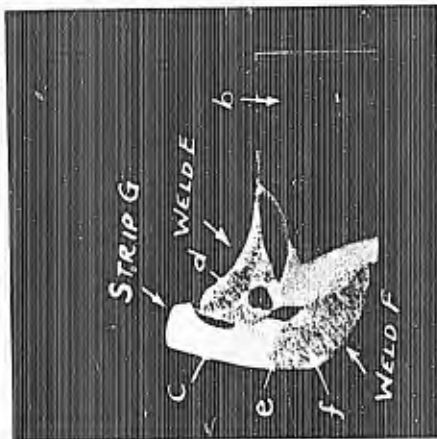
Etched in Nital-Picral



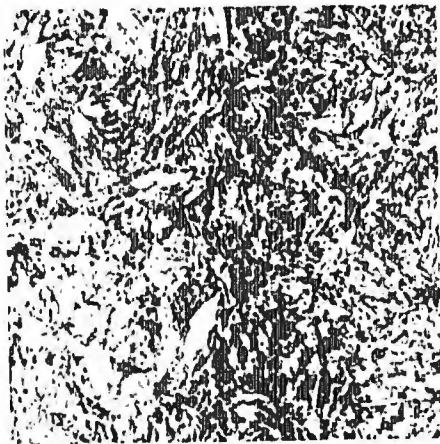
-c- X1000  
 Homogeneous armor. Tem-  
 pered martensite.

FMPL-28

Homogeneous Armor



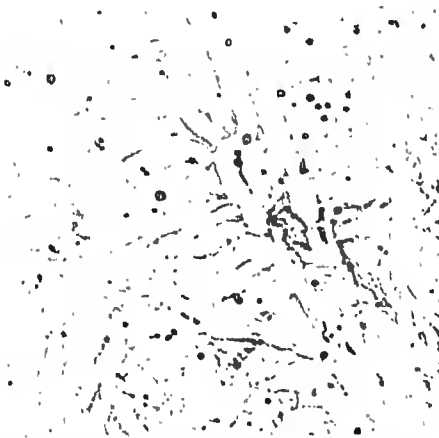
**F MPL-29 -a-**  
 X2  
 Macrostructure of welded section of armor.



**-b-**  
 X1000  
 Microstructure of base armor. Tempered martensite. Hardness - 450 VPN.



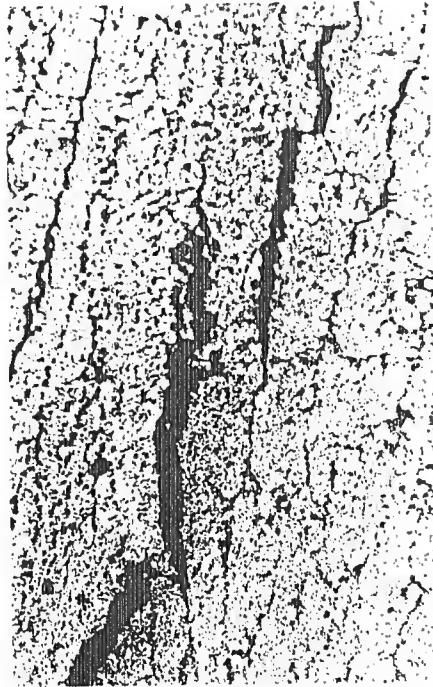
**-c-**  
 X1000  
 Microstructure of strip G. Martensite and ferrite. Hardness - 375 VPN.



**-d-**  
 X1000  
 Microstructure of weld E. Ferrite and carbides. Hardness - 250-300 VPN



**-e-**  
 X1000  
 Junction of weld F and strip G. Martensite, ferrite, and grain boundary segregate. Hardness - 450 VPN.



**-f-**  
 X100  
 Interdentritic cracks found in weld F. Cracks associated with intergranular segregate. Hardness - 250-300 VPN.

F MPL-29  
Homogeneous Armor

APPENDIX A

Data Abstracted from British and American Reports

Covering Metallurgical Examinations

of German Armor

DATA ABSTRACTED FROM W.A.L. REPORT NO. 710/527

Research Department, Woolwich

R.D. Met. Report 190/42

"Examination of Front Hull Inner Plate Assembly from a German  
PZ KW III Tank", March 1942  
(Interim Report)

Assembly consisted of three rolled plates, A, B, and C joined  
by welding.

Thickness - A - 26 mm  
B - 32.5 mm  
C - 32.5 mm

Plate A - Homogeneous - Average hardness 369 Vickers Pyramid Number

Plate B - Flame hardened - Face hardness - 650 VPN Core hardness - 366 VPN

Plate C - Flame hardened - Face hardness - 655 VPN Core hardness - 386 VPN

Average depth of flame hardened zones - 1/8"

Chemical Analysis

	<u>C</u>	<u>Mn</u>	<u>Si</u>	<u>S</u>	<u>P</u>	<u>Cr</u>	<u>Mo</u>	<u>Ti</u>
Plate A	.56	.44	.42	.015	.023	1.30	.47	.03
Plate B	.55	.63	.41	.012	.033	1.35	.48	.03
Plate C	.63	.66	.42	.011	.025	1.38	.29	.04

DATA ABSTRACTED FROM W.A.L. REPORT NO. 710/525

Research Department, Woolwich

R.D. Met. Report 232/42

"Examination of Front Hull Inner Plate Assembly from a German PZ KW III Tank", April 1942

This report covers a study of the welds joining plates A, B, and C which were examined and reported in R.D. Met. Report 190/42.

Vickers Pyramid Hardness Surveys of Cross-sections of the Welded Joints

Plate Joint	Max. VPN Hardness in Heat Affected Zone of Armor			Av. VPN Hardness of hard Face Weld	Av. VPN Hardness of inner Deposit of outer weld	Av. VPN Hardness of Inner Weld
	<u>A</u>	<u>B</u>	<u>C</u>			
A-B	642	642	-	558	421	287
B-C	-	650	698	556	360	251
Mild Steel-C	-	-	707	-	-	-

CHEMICAL ANALYSIS

	<u>C</u>	<u>Mn</u>	<u>Si</u>	<u>S</u>	<u>P</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>	<u>V</u>	<u>W</u>
Hard Face	.36	1.93	.16	.020	.028	3.33	2.42	.61	-	.62
{ Inner Deposit of outer weld	.30	5.0	-	-	-	1.00	12.9	.23	-	-
{ Internal Deposit	.18	6.5	.17	.02	.036	1.26	15.6	.10	.03	-

The welds and the heat affected zones of the base plates exhibited severe cracking believed capable of seriously weakening the structure.

DATA ABSTRACTED FROM W.A.L. REPORT NO. 710/526

Research Department, Woolwich. R.D. Met. Report 444/42

"An Examination of 50 mm. Frontal Armour from a German PZ  
KW III Tank", July 1942

This report covers a metallurgical examination of a flame hardened 50 mm armor section.

Chemical Analysis

<u>C</u>	<u>Mn</u>	<u>Si</u>	<u>S</u>	<u>P</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>	<u>V</u>	<u>Ti</u>
.50	.62	.32	.016	.012	.10	1.40	.66	.23	.01

Max. hardness of face - 690 Vickers Pyramid Number

Average hardness of core - 370 VPV

Depth of flame-hardened case - 0.125 - 0.175"

DATA ABSTRACTED FROM W.A.L. REPORT NO. 710/458

"Armor - Metallurgical Examination of Section of German Face-Hardened Armor from the Front of a PZ KW III Tank", October 1942

Section of armor consisted of a 13-1/2" x 31-1/2" x 32 mm piece.

Flame-hardened depth of case - 1/8"

Hardness of face - 643-681 Vickers Pyramid Number

Hardness of core - 354-397 VPN

CHEMICAL ANALYSIS

<u>C</u>	<u>Mn</u>	<u>Si</u>	<u>S</u>	<u>P</u>	<u>Cr</u>	<u>Mo</u>	<u>Cu</u>	<u>Al</u>	<u>Ti</u>
.55	.81	.51	.019	.028	1.63	.35	.06	.03	.065

DATA ABSTRACTED FROM W.A.L. REPORT 710/472

"Armor - Metallurgical Examination of Armored Vehicle Components (Armor Attachment Bolts and Welded Armor Sections) from a German PZ KW III Tank", January, 1943.

Sections consisted of a large and a small bolt, a weld with 2 base metal sections attached (A, B) which was knocked loose from an assembly upon ballistic impact, and a small triangular welded section of armor, having 4 weld deposits C, D, E, and F.

HARDNESS SURVEYS

Maximum Vickers Hardness

Item	Rockwell C	Heat Affected Zone		
		Low Alloy Weld	High Alloy Weld	of Base Metal
Large Bolt	41.5			
Small Bolt	41.5			
Weld Metal Section	-	446	-	{A-690 B-681
Weld C	-	455	-	376
Weld D	-	437	450	394
Weld E	-	464	421	370
Weld F	-	-	370	370

CHEMICAL ANALYSES

Item	C	Mn	Si	S	P	Ni	Cr	Mo	V	Cu	W	Al
Large Bolt	.44	.81	.28	.029	.021	.12	1.20	.34	.125	.155	-	-
Small Bolt	.38	.64	.28	.019	.020	.16	1.25	.28	.135	.155	-	-
Weld Metal Sect.	.12	.31	.17			2.46	1.1	.27	Trace	.15	.52	
Base Metal B	.44		.255			Trace	1.3	.50	.17	.18	nil	
Weld C	.36	1.93	.20			2.38	3.44	.57	Trace	.33	.20	
Weld D	.35	2.00	.19			2.44	3.54	.58	Trace	.31	.36	
Weld E	.37	1.67	.17			3.05	1.40	.64	Trace	.31	Present	
Weld F	.23	4.81				.81	10.36	Trace	.32	.3	nil	.03
Base Metal	.55	.54	.59	.018	.015	-	1.14	.27	Trace	.08	-	

All weld deposits and heat affected zones of the base armor were severely cracked.

DATA ABSTRACTED FROM W.A.L. REPORT NO. 710/485

"Armor - Metallurgical Examination of German Armor from a PZ KW III Tank", March, 1943

Armor consisted of five plates:

- A. Homogeneous plate from beneath the engine 14" x 31" x 16 mm
- B. Flame hardened plate 23" x 71" x 31 mm.
- C. Flame hardened plate 15" x 75" x 31 mm.
- D. Flame hardened plate 14" x 48" x 31 mm.
- E. Homogeneous armor escape door 31 mm. thick, from left side of tank.

HARDNESS SURVEYS

Section	Core Hardness		Face Hardness	Thickness of Hardened Layer - Inches
	BHN	Rockwell C	Rockwell C	
A	375	38-39	-	-
B	388	38-40	55-60	.210-.230
C	352-363	37-40	55-58	.090-.110
D	352-363	36-38	57-61	.140-.200
E	331-341	34-36	-	-
{ Carburized flange from Plate B	363	35-38	57-62	

CHEMICAL ANALYSES

Section	C	Mn	Si	S	P	Ni	Cr	Mo	V	Cu	Ti	Al
A	.52	.70	.58	.029	.018	Trace	1.39	.20	Trace	.03	.065	.03
B	.44	.97	.21	.026	.008	Trace	1.28	.38	.25	.19	nil	.02
C	.53	.71	.49	.025	.015	Trace	1.47	.18	Trace	.03	.07	.04
D	.48	1.03	.64	.031	.007	Trace	.83	.23	.23	.17	nil	.04
E	.54	.69	.49	.027	.016	Trace	1.25	.49	Trace	.09	.07	.02
{ Carburized Flange from B	.25	1.01	.63	.028	.007	.18	1.27	.26	Trace	.09	.07	.02
Stud from C	.35	.79	.29	.029	.007	Trace	.99	.15	.18	.25	nil	.02
{ Splash Shield from E	.07	.41	Trace	.077	.049	Trace	.09	nil	nil	.10	nil	.02
{ Weld deposit from E	-	5.19	-	-	-	.99	11.46	-				

APPENDIX B

CORRESPONDENCE

COPY

WAR DEPARTMENT  
OFFICE OF THE CHIEF OF ORDNANCE  
WASHINGTON, D. C.

Peterson/mks

O.O. 470.5/14377  
SPOTB-Intell.

April 20, 1943

Subject: Examination of Armor Plate

To: The Commanding Officer  
Watertown Arsenal  
Watertown, Mass.

1. Attention is invited to the attached copy of directive to the Proving Center requesting shipment of eleven (11) pieces of armor plate to Watertown Arsenal for complete chemical and metallurgical analysis.

2. It is requested that the Ordnance Intelligence Unit, Service Branch, Technical Division, be furnished with fifteen (15) copies of the reports covering the analysis of the items listed.

By order of the Chief of Ordnance:

S. B. Ritchie  
Colonel, Ord. Dept.  
Chief, Service Branch  
Technical Division

1 Incl.  
Copy of ltr. to Aberdeen Proving Center  
dated April 20, 1943

COPY

COPY

WAR DEPARTMENT  
OFFICE OF THE CHIEF OF ORDNANCE  
WASHINGTON, D.C.

Peterson/mks  
April 20, 1943

SPOTB-Intell.

Subject: Armor Plate to be Sent to Watertown Arsenal for  
Examination

To: The Director  
The Proving Center  
Aberdeen Proving Ground, Md.

Attn: Lt. Col. G. B. Jarrett  
Foreign Materiel Branch

1. It is requested that the following pieces of armor plate be shipped to Watertown Arsenal for complete chemical and metallurgical analysis:

FMPL-1 Cover, Pistol Port, PZ III Tank  
FMPL-3 Plate, Top Engine, PZ III Tank  
FMPL-11 Plate, Armor, Approx. 1" x 1" x 3", used on Landing boats  
FMPL-14 Plate, Armor, Homogeneous, 16.8 mm, 14" x 12"  
FMPL-20 Plate, Armor, Flame Hardened, 50 mm, 4 1/2" x 3"  
FMPL-21 Plate, Armor, Flame Hardened, 31.4 mm, 6 1/2" x 5"  
FMPL-23 Plate, Armor, Homogeneous, 31.7 mm, 19" x 15"  
FMPL-25 Plate, Armor, Carburized, 31.0 mm, 10 1/2" x 8 1/2"  
FMPL-27 Plate, Armor, Homogeneous, 30.0 mm, 11" x 6"  
FMPL-28 Plate, Armor, Homogeneous 26.1 mm, 12 1/2" x 4"  
FMPL-29 Plate, Armor, Homogeneous 8.1 mm, 9" x 6 1/2"

2. The above items have been requested by Col. Knable, armor plate specialist of the Service Branch.

By order of the Chief of Ordnance:

S. B. Ritchie  
Colonel, Ord. Dept.  
Chief, Service Branch  
Technical Division

CC: Watertown Arsenal  
Colonel Knable, Technical Division

COPY

COPY

O.O. 470.5/14377  
W.A. 470.5/7152

1st Ind.

Matthews/mpb

Watertown Arsenal, Watertown, Massachusetts, April 30, 1943.

To: Chief of Ordnance, U.S.A., Pentagon Building, Washington, D. C.  
Attn: SPOTB - Intelligence Unit

1. Reference request in basic letter, it is considered that a complete metallurgical examination on the numerous items involved would entail more time than can be devoted to this material at the present.

2. It is planned to incorporate an examination of these several items into one report and the advice of his office is requested as to whether or not the following work on each plate will be adequate for purposes of record:

- a. Complete chemical analysis.
- b. Macro-examination for steel quality in both transverse and longitudinal directions.
- c. Hardness and hardness distribution in face hardened plate.
- d. Microstructure.

For the Commanding Officer:

H. H. ZORNIG  
Colonel, Ordnance Dept.  
Director of Laboratory

1 Incl. n/c

O.O. 470.5/14377  
Attn: SPOTB-Intell.  
W.A. 470.5/7152

2nd Ind.

Peterson/mks

War Department, Ordnance Office, Washington, D. C., May 8, 1943

To: The Commanding Officer, Watertown Arsenal, Watertown, Massachusetts

1. The test program as outlined in paragraph two of first indorsement will be adequate for the examination of subject materiel and that one report be issued on the several items listed.

By order of the Chief of Ordnance:

S. B. RITCHIE  
Colonel, Ord. Dept.  
Chief, Service Branch  
Technical Division

1 Incl. n/c