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WATERTOWN ARSENAL LABORATORY

TECHNICAL REPORT

ARMOR

[illegible] Test to Indicate the [illegible] of Armor Steels Upon Quenching

BY

A. HURLICH
Asst. Metallurgist

DATE 1 AUGUST [illegible]

WATERTOWN ARSENAL

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1st Indorsement

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eral, Philadelphia, Pa., 15 October 1943

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ransmittal of Watertown Arsenal Report No. 710/532

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r the Commanding Officer:

C. H. GREENALL
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Assistant

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27 August 1943

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To: The Commanding Officer
Frankford Arsenal
Philadelphia, Pa.

Attn: Laboratory

1. There is attached one (1) copy of Watertown Arsenal Laboratory Report No. 710/532 entitled "Armor - Development of a Fracture Test to Indicate the Degree of Hardening of Armor Steels Upon Quenching" for his information and file.

2. The subject report covers the work performed at this Arsenal over a period of the last few months on the correlation between the fibre fracture test, microstructure, impact properties and ballistic properties. It has been shown that the fibre fracture test is a valid indication of whether or not a tempered martensitic structure, essential for optimum ballistic properties has been produced. The test is simple in nature and may be readily applied to the production inspection of armor.

For the Commanding Officer:

/s/ C. L. Cox
Lt. Col., Ord. Dept.
for H. H. Zornig,
Colonel, Ord. Dept.
Assistant

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W.A. Report #710/532

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Report No. [illegible]
Watertown Arsenal
Problem No. B-3

1 August 1943

ARMOR

Development of a Fracture Test to Indicate the Degree of Hardening of Armor Steels Upon Quenching

OBJECT

To develop a test capable of determining the extent of quench hardening of armor steels for application as an inspection control.

SUMMARY

As the result of the study of a fracture test developed at the Union Steel Casting Division of the Blaw-Knox Company for the purpose of selecting tempering temperatures which would produce optimum ballistic properties in armor, further experiments were performed at this Arsenal to devise a more useful fracture test to indicate the extent of quench hardening of armor.

It was found that the appearance of the fractured surface of the low alloy steels used for armor can be correlated with the degree of quench hardening, the microstructure, and the relative impact strength of the material.

Incompletely quenched steels (those containing high temperature transformation products) fracture in a brittle manner. The fractured surface has a bright silvery sheen caused by reflections from facets. The impact strength of incompletely quenched steels is usually low at room temperature and always very low at reduced temperatures.

Steels which have been completely quench hardened and tempered fracture in a ductile manner. The fractured surface is rough and jagged in appearance, and of a dark, nonreflecting color. Steels having a tempered martensitic microstructure completely free from high temperature transformation products such as ferrite, grain boundary carbides, pearlite, and bainite have the best combination of hardness and impact strength.

The fracture of completely quench hardened and tempered steel can be readily differentiated from that of incompletely quenched steels. A fracture

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test has been devised that is applicable to production procedures and which is capable of being used to control the quality of heat treatment of armor components.

A. Hurlich

A. HURLICH,
Asst. Metallurgist.

APPROVED:

H. E. ZORNIG,
Colonel, Ord. Dept.,
Director of Laboratory.

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INTRODUCTION

A non-ballistic test of armor capable of predicting its ballistic behavior with a fair degree of accuracy has been the goal of considerable endeavor. No physical or metallurgical test has yet been devised which can be considered wholly adequate. Possibly the best criterion of armor performance to date has been microstructive, but many inconsistencies have been observed.

It is generally agreed that best ballistic properties result when armor steels are quenched and tempered to a uniform sorbitic[1] microstructure completely free of high temperature transformation products. When the steel is incompletely quenched or has insufficient hardenability to quench harden through the section, high temperature transformation products such as ferrite, pearlite, and bainites are formed. The steel then has poor shock properties and frequently fails during ballistic testing. The appearance of the microstructure is not, however, a completely reliable indication of ballistic properties; many slack quenched plates have been found to have satisfactory ballistic properties and apparently well heat treated plates to have poor ballistic properties.

As a result of the study of the Union Steel Casting Division's fracture test,[2] a series of experiments were performed at this Arsenal to devise, if possible, a fracture test that would be practicable as a means of selecting satisfactory armor and which could be applied as an inspection tool to control the uniformity of the product.

It was necessary to correlate the appearance of the fracture with quenching rates, microstructure, impact strength, temperature of fracture, and rate of load application in order to determine and evaluate the factors affecting the fracture.

If properly heat treated armor steel has a distinctive fracture easily differentiated from that of improperly heat treated material, the use of a fracture test as an inspection tool is clearly indicated.

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[1] "Sorbite", as used throughout this report, is a decomposition product of martensite resulting from relatively high temperature tempering. See the definition of sorbite given on page 9 of Metals Handbook, 1939 Edition.

[2] W.A. Report No. 710/530 "Armor - Metallurgical Investigation of the Fiber Fracture Test Used by the Union Steel Casting Division of Blaw-Knox Company".

MATERIALS AND TEST PROCEDURE

Armor Steels

Eight 6"x12" pieces cut from production plate of various chemical compositions were selected, including five cast and three rolled armor plates. The steels were selected as representing the majority of the more common analyses used for armor. Seven of the plates were 2" and one 1½" in thickness.

Chemical Analysis and Hardenability

The chemical analyses of the eight plates were determined at this Arsenal. Standard 3" long, 1" diameter Jominy bars were machined from each plate. The bars were austenitized at 1600°F for 2 hours immersed in an upright position to a depth of two inches in a pot of "neutra-pack" to prevent excessive oxidation, and then end-quenched according to the standard procedure.

Heat Treatments

Three pieces, 2"x6"xthickness, were cut from each of the eight plates. The pieces were heat treated as follows:

a. One section from each plate heated to 1600°F for 2 hours, quenched in agitated water, tempered 2 hours at either 1125°F or 1200°F.

b. One section from each plate heated to 1600°F for 2 hours, quenched in oil, tempered 2 hours at either 1125°F or 1200°F.

c. One section from each plate heated to 1600°F for 2 hours, air cooled, tempered 2 hours at either 1125°F or 1200°F.

The Brinell hardness of all pieces was obtained both after quenching and after tempering.

Fracture Test

After heat treatment, the pieces were notched to a depth of approximately ¼" with an abrasive cut-off wheel and broken under the impact of a 1000-pound forge hammer. The fractures were examined and rated.

Microexamination

Specimens for microexamination were cut from each of the three sections of the eight steels to correlate the appearance of the fractures with the microstructures resulting from the various heat treatments.

Effect of Microstructure and Temperature upon Impact Strength and the Appearance of the Fracture.

Eight standard V-notch Charpy impact bars were machined from each of the 24 fractured sections representing various heat treatments and chemical analyses. Two bars were broken at each of four different temperatures from room temperatures down to -70°C to determine both the influence of microstructure and temperature upon the impact strength and the appearance of the fracture.

Additional studies of the effect of microstructure upon impact strength and the appearance of fractures were conducted upon sections of 4-6" thick cast armor.[3] Some of this material had insufficient hardenability to completely harden through the thickness and consequently developed pearlitic structures upon heat treatment. Standard V-notch Charpy impact bars were machined from the sections in the as-received condition and also after 1" thick sections were reheat treated to fully quenched and tempered structures.

Effect of Hardness upon the Appearance of the Fracture

Sections from two sets of 1" thick cast armor plates manufactured by the Lebanon Steel Foundry,[4] and the Kelsey-Hayes Wheel Co.[5] ranging in hardness from 260 to approximately 360 Brinell were fractured both at room temperature and at -70°C to determine the effect of both hardness and temperature upon the appearance of the fracture.

Effect of Rate of Straining upon the Appearance of the Fracture

Two 2" wide strips were cut from several armor plates of various chemical analyses and thicknesses, notched and fractured. One piece of each steel was fractured under the impact blow of a steam forge hammer, and the other was broken under the head of a tensile machine at a rate of application of load of 9000 pounds per minute. Fractures resulting from the two different strain rates were compared.

---

3. W.A. Report 710/500. "Armor - Metallurgical Examination of Cast Gun Shield Armor Four to Six Inches in Thickness".

4. W.A. 470.5/5749 1st Ind. A.P.G. 470.5/4881.

5. W.A. Report 710/499. "Armor - Metallurgical and Ballistic Properties of 1" Cast Armor Test Plates Manufactured by the Kelsey-Hayes Wheel Co.".

DATA AND DISCUSSION

1. Chemical Analyses

The chemical analyses of the eight steels selected are listed in Table I.

TABLE I

Chemical Analyses

Manufacturers Analyses -

N.A. No.	Manufacturer, Heat and Plate No.	Type and Thickness	C	Mn	Si	S	P	Ni	Cr	Mo	
1	Continental Roll and Steel Foundry 1983-1	2" cast					Unavailable				
2	Pittsburgh Steel Foundry [illegible]	2" cast	.34	1.05	.39	.025	.014	.52	.56	.47	
3	Ordnance Steel Foundry [illegible]	2" cast	.29	1.55	[illegible]	.027	.016	–	–	[illegible]	[illegible]
4	National Traffic Guard 1203-2	2" cast	.26	1.47	.39	.024	.013	–	[illegible]	.47	
5	Stockham Pipe Fitting Co. [illegible]	2" cast					Unavailable				
6	Republic Steel Corp. [illegible]	2" rolled	.26	[illegible]	.25	.019	.023	.37	.67	[illegible]	
7	Ford Motor Co. [illegible]	2" rolled	.26	1.47	.25	.016	.014	[illegible]	.03	[illegible]	
8	Henry Disston & Sons 21218-1	1½" rolled	.22	.93	.99	.016	.017	.10	.19	.17	

Watertown Arsenal Analyses -

W.A. No.	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	Al	B
1	.37	.92	.31	.029	.041	.63	.54	.37	.055	.008	-
2	.36	1.13	.32	.016	.009	.53	.48	.48	.115	.01	-
3	.29	1.64	.34	.020	.019	-	.03	.38	.15	.02	-
4	.27	1.62	.19	.014	.027	-	.36	.42	.135	.03	-
5	.26	1.60	.32	.017	.023	-	.48	.44	.125	.04	-
6	.27	.92	.20	.022	.022	.91	.71	.46	.13	.02	-
7	.27	1.57	.20	.027	.012	-	.04	.47	.12	.02	.003
8	.21	.94	1.03	.010	.010	.10	.16	.18	.12	.01	-

2. **Hardenability**

The Jominy hardenability curves of the eight steels are shown in Figures 1, 2, and 3, and the data are summarized in Table II.

TABLE II

End-Quench Hardenability of Armor Steels

	Jominy Hardenability Data					
		No. of 1/16ths. of an Inch for a Drop in Hardness				
Steel No.	Hardness 1/16" from Quenched End Rc	of 5 Rc	of 10 Rc	to 42 Rc (400 BHN)	Hardness at 2½" from Quenched End Rc	Thickness of Plate Quenchable to 400 BHN in Center
1	57.5	12	16	28	40.5	3.5
2	54.5	14	20	28	41	3.5
3	51.5	7	9	8	31	1.4
4	49.5	12	18	14	32	2.1
5	52	14	24	24	40	3.4
6	50	11	16	14	35.5	2.1
7	50	7	10	9.5	29	1.6
8	45.5	3	3.5	2.5	17	0.6

The thickness of plate quenchable to 400 Brinell hardness in the center was calculated according to recent investigations performed by Battelle Memorial Institute[6] and the Great Lakes Steel Corporation.[7]

Both steel No. 3 (Mn-Mo) and steel No. 7 (Mn-Mo with boron) have insufficient hardenability to quench out in a 2" thick section. The boron addition to steel No. 7 did not produce an appreciable increase in hardenability over that of steel No. 3. Previous work at this Arsenal has indicated that the Mn-Mo composition has insufficient hardenability for application in section sizes greater than approximately 1½" in thickness.

3. Heat Treatments and Brinell Hardness

The heat treatments of the 2" x 6" x plate thickness sections and the surface Brinell hardnesses developed upon quenching and tempering are included in Table III.

TABLE III

Heat Treatments and Brinell Hardnesses of Armor Steels

Steel No.	Specimen Size	Heat Treatment	Brinell Hardnesses of Water Quenched Specimen	Brinell Hardnesses of Oil Quenched Specimen	Brinell Hardnesses of Air Cooled Specimen
1	2x2x6"	1600°F - 2 hrs. - quenched	555	415	285
		1200°F - 2 hrs. - air	269	269	229
2	2x2x6"	1600°F - 2 hrs. - quenched	477	444	277
		1125°F - 2 hrs. - air	285	285	241
3	2x2x6"	1600°F - 2 hrs. - quenched	415	285	248
		1200°F - 2 hrs. - air	255	212	207
4	2x2x6"	1600°F - 2 hrs. - quenched	429	352	241
		1200°F - 2 hrs. - air	248	255	207
5	2x2x6"	1600°F - 2 hrs. - quenched	444	375	277
		1200°F - 2 hrs. - air	241	241	212
6	2x2x6"	1600°F - 2 hrs. - quenched	477	341	248
		1200°F - 2 hrs. - air	277	248	217
7	2x2x6"	1600°F - 2 hrs. - quenched	444	311	241
		1125°F - 2 hrs. - air	277	241	201
8	2x1½x6"	1600°F - 2 hrs. - quenched	388	217	179
		1125°F - 2 hrs. - air	255	207	174

---

6. "Correlation of Cooling Velocity of the Standard Jominy Hardenability Test with the Cooling Velocity within the Cross Section of Plates". John G. Kura, C. H. Lorig. Battelle Memorial Institute, Aug. 24, 1942.

7. "Hardenability Comparisons" - Chart published by Great Lakes Steel Corporation, 1942.

The as-quenched hardnesses produced by the cooling rates resulting from water, oil, and air quenching are in substantial agreement with the hardenability characteristics of the eight steels.

4. Fracture Test

After heat treatment, the specimens were notched and fractured as previously described. The fractures were examined and rated.[8]

Photographs of the fractures of cast steels No. 1 through 5 are shown in Figure 4. The water quenched specimens are arranged at the extreme left of the photograph and are all fibrous in nature. The oil quenched specimens occupy the middle row of the photograph and have either fibrous or mixed fractures. The air cooled specimens are at the right of the photograph and are all completely crystalline in appearance. The photograph illustrates the brightness of the crystalline fractures as compared to the dark and rough appearance of the fibrous fractures.

The fracture ratings of the 24 heat treated specimens are listed in Table IV with the steels arranged in order of decreasing as-quenched hardness.

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[8] The definitions of the fracture ratings used at this Arsenal are as follows:

Fibrous Fracture

The fibrous fracture is characterized by a non-reflecting dark grey, rough and pitted surface. The sides of the fracture show the necking-in associated with ductile behavior.

Crystalline Fracture

The crystalline fracture is characterized by a bright silvery sheen caused by reflections from facets. The surface of the fracture tends to be flat and the sides undeformed. The fracture appears brittle in nature.

Mixed Fracture

The mixed fracture contains elements of both the fibrous and crystalline types of fracture. The crystalline regions usually consist of patches or streaks in a fibrous matrix.

TABLE IV

Fracture Ratings of Heat Treated Armor Steels

Steel No.	Quenching Medium	As-Quenched Brinell Hardness	Fracture Rating	Microstructure
1	Water	555	Fibrous	Sorbite
2	Water	477	Fibrous	Sorbite
6	Water	477	Fibrous	Sorbite
5	Water	444	Fibrous	Sorbite
7	Water	444	Fibrous	Sorbite
2	Oil	444	Fibrous	Sorbite and very small amount of ferrite.
4	Water	429	Fibrous	Sorbite
3	Water	415	Mixed - Almost completely fibrous.	Sorbite, ferrite and pearlite.
1	Oil	415	Fibrous	Sorbite and very small amount of ferrite.
8	Water	388	Mixed - Mainly crystalline.	Ferrite and carbides.
5	Oil	375	Mixed - Mainly fibrous.	Sorbite, ferrite and pearlite.
4	Oil	352	Mixed - Mainly fibrous.	Sorbite, ferrite and pearlite.
6	Oil	341	Mixed - Mainly fibrous.	Sorbite and very small amount of ferrite.
7	Oil	311	Mixed - Mainly fibrous.	Sorbite, ferrite and pearlite.
3	Oil	285	Mixed - Large crystalline patches.	Ferrite and carbides.
1	Air	285	Crystalline	Ferrite and carbides.
2	Air	277	Crystalline	Ferrite and carbides.
5	Air	277	Crystalline	Ferrite and carbides.
3	Air	248	Crystalline	Ferrite and carbides.
6	Air	248	Crystalline	Ferrite and carbides.
4	Air	241	Crystalline	Ferrite and carbides.
7	Air	241	Crystalline	Ferrite and carbides.
8	Oil	217	Crystalline	Ferrite and carbides.
8	Air	179	Crystalline	Ferrite and carbides.

From the foregoing data, the minimum as-quenched hardness capable of producing a completely fibrous fracture after tempering appears to be approximately 400 Brinell when the carbon content is in the range of 0.25-0.35%.

For some time now manufacturers and heat treaters of armor have been using the core hardness test whereby armor must develop an as-quenched core hardness of at least 400 BHN to be considered acceptable. The results of the fracture experiments indicate the validity of the core hardness test, assuming that the core hardness has been accurately determined.

5. Microexamination

Specimens for microscopic examination were cut from the 24 heat treated sections. Photomicrographs of the structures developed by the various heat treatments are shown in Figures 5 through 8.

Except in the cases of steels Nos. 3 and 8, the heat treatment consisting of water quenching and tempering produced sorbitic microstructures resulting from the tempering of completely martensitic structures. Steels Nos. 3 and 8 have insufficient hardenability to quench out in 2" square sections and consequently some high temperature transformation products were formed upon water quenching, see Figures 6G and 8V.

Steels Nos. 1 and 2 almost completely quench hardened upon oil quenching; only very few small isolated patches of ferrite can be found in the microstructures, see Figures 5B and E. Greater or lesser amounts of high temperature transformation products resulted from the oil quenching of the other six steels. These high temperature transformation products consist of ferrite, as in Figure 6H, imperfectly formed pearlite, as in Figure 6K and 8T, and precipitates of grain boundary carbides, as in Figures 6K and 8T.

In all cases, air cooling resulted in the precipitation of ferrite and carbides at grain boundaries and along cleavage planes.

By comparing the microstructures with the data in Table IV it is seen that the fibrous fracture is associated with tempered martensitic microstructures essentially free from the presence of high temperature transformation products. The crystalline fracture is associated with microstructures consisting almost entirely of high temperature transformation products, while mixed fractures occur when the microstructures are such as result when the steel is slack quenched to a degree intermediate between water quenching and air cooling.

6. Effect of Microstructure and Temperature upon Impact Strength and the Appearance of the Fracture

Eight standard V-notch Charpy impact bars were machined from each heat treated section. The bars were taken from regions equidistant from the centers and the surfaces of the sections, as illustrated in Figure 9.

To reduce the scattering of results, the bottoms of the V notches were polished to remove all irregularities and scratches. The polishing was accomplished by holding the specimens against a short piece of revolving piano wire charged with alumina abrasive.

Two bars from each section were tested at +20°C, -10°C, -40°C, and -70°C. The low temperatures were attained by immersing the impact bars in a mixture of dry ice and acetone and keeping them at temperature for 15 minutes prior to testing.

The results of the tests are shown graphically in Figures 10 through 17 and the individual values and fracture ratings are contained in Appendix A.

The fractured surfaces of the Charpy bars of steels Nos. 3 and 6 are shown in Figure 18 to illustrate the effect of temperature and quenching rate upon impact strength and upon the appearance of the fracture.

The following observations and conclusions result from the series of impact tests performed:

a. In spite of the fact that the air cooled steels average approximately 40 points Brinell softer than the water and oil quenched steels, the impact strength of the air cooled steels is uniformly poor at room temperature and decreases to very low values at reduced temperatures, having mixed to crystalline fractures at room temperature and completely crystalline fractures at reduced temperatures.

b. The water quenched steels which became fully martensitic upon quenching have good impact strength. Some of these steels retain their room temperature impact strength down to -70°C, while others show a reduction in impact strength with a lowering of temperature, but the impact strength does not decrease to the same extent as that of the air cooled steels within the temperature range investigated.

c. Except in the steels which almost completely quench hardened in oil, the impact strength of the oil quenched steels is intermediate between that of the water quenched and the air cooled steels. In some cases the room temperature impact strength of the oil quenched steel is equal to or slightly greater than that of the water quenched steel. The reason for this may be the fact that the oil quenched steels under consideration average approximately 30 points Brinell softer that the water quenched steels, and, in addition, had quench hardened to a considerable extent so that the microstructure did not contain very large amounts of high temperature transformation products.

d. A decrease in temperature increases the tendency for the incompletely quench hardened steels to have brittle fractures and low impact strengths.

e. In general it was observed that the fractures of the Charpy impact bars broken at room temperature tended to be less brittle in nature than those of the same steels fractured in 2"x2"x6" section sizes. This phenomenon has been noted by many investigators who believe that the constraint exerted upon the deformation of the sidewalls; i.e., prevention of necking down of the specimen at the region of fracture in large sections, is responsible for the more brittle behavior of the large sections. Another cause of the more brittle behavior of large sections is traced to the size effect whereby the notch of the progressing crack is effectively sharper because the crack is longer, in the large section than in the small section. The sharper notch results in more brittle behavior during fracturing.

f. The low impact strength at reduced temperatures of incompletely quench hardened steel explains to a great extent the generally poor performance of 1½" and 2" thick cast armor sections which were proof fired at Camp Shilo in January and February of 1943 at temperatures of -15 to -35°F (-26 to -37°C).[9] Metallurgical examination of the failing plates revealed that most of them had either been slack quenched or possessed insufficient hardenability to completely quench harden.

Additional data upon the effect of microstructure upon impact strength and the appearance of the fracture was obtained during a recent study of the metallurgical characteristics of 4-6" thick cast gun shield armor.[3] Four of the armor sections had the following analyses:

Heat No.	C	Mn	Si	S	P	Ni	Cr	Mo
3245	.34	.87	.28	.035	.042	1.00	.07	.45
3372	.32	.90	.35	.027	.044	.98	.11	.45
6405	.33	1.61	.48	.019	.013	.17	.10	.31
6848	.30	.68	.38	.031	.007	--	2.39	.46

Heats 3245 and 3372 (Ni-Mo) have insufficient hardenability to quench harden to a core hardness of 400 Brinell in sections greater than 2" in thickness, and since the shields were 6" in thickness, they were incapable of quench hardening. The microstructure of these two heats consisted of ferrite and other high temperature transformation products, see Figure 19A.

Heat 6405 (Mn-Mo) possesses hardenability sufficient to quench out a 2-3/4" thick plate but was cast into a 4" thick section. The microstructure of heat 6405 was more satisfactory than those of heats 3245 and 3372, but also contained some ferrite and grain boundary carbides in addition to spheroidized sorbite, see Figure 19B.

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9. Cast Armor Subcommittee Report No. 38. "Results of Low Temperature Ballistic Tests on Cast Armor Test Plates" Watertown Arsenal, March 16, 1943.

3. See footnote No. 3 on page 5.

Heat 6848 (Cr-Mo) is capable of being completely quench hardened in a section 6" in thickness. The microstructure of this steel in the as-received condition consisted entirely of spheroidized sorbite with no high temperature transformation products anywhere in the section, see Figure 19C.

The hardnesses of the four steels as-received were in the range of 207-229 Brinell. One inch thick sections were cut from heats 3245, 3372, and 6405 and reheat treated by quenching in agitated water from 1600°F and tempering back to the same hardness they originally possessed. The 1" thick sections were completely quenched to martensite and tempered back to a spheroidized sorbite very much like the microstructure of heat 6848.

Three standard V-notch Charpy impact bars were machined from the four plates in the as-received condition and from the three reheat treated 1" thick sections. The impact bars were tested at room temperature with the following results representing the average of the three tests:

TABLE V

V-Notch Charpy Impact Properties of Gun Shield Armor

Heat No.	Type Analysis	As-Received Charpy Ft.Lbs.	Fracture	After Reheat-Treatment Charpy Ft.Lbs.	Fracture
6848	Cr-Mo	82.8	Fibrous	-	-
3245	Ni-Mo	12.3	Crystalline	82.7	Fibrous
3372	Ni-Mo	9.5	Crystalline	69.4	Fibrous
6405	Mn-Mo	54.1	Mixed	69.1	Fibrous

Photographs of the fractured surfaces of typical Charpy bars are shown in Figure 20. These photographs illustrate the relative ductility of tempered martensite and the brittleness of slack quenched structures.

This evidence emphasizes the influence of microstructure upon the impact properties of steel. Since armor is subjected to tremendous impact forces in service the steel must have the maximum impact strength consistent with its hardness level. A homogeneous microstructure of tempered martensite will provide the best combination of impact strength and hardness.

The microstructural details of the various types of fractured surfaces were studied. Several fractured Charpy bars were electroplated with nickel, sectioned perpendicularly to the fractured surfaces and mounted in bakelite. The nickel plate prevented rounding of the edge of the specimen during polishing. A considerable difference was observed in the appearance of the fractured edges of slack quenched and fully quenched steels.

The fracture of slack quenched steels progresses along an angular zig-zag transgranular path, see Figures 21A and 22A. The path of the fracture is not influenced by the crystallographic orientation of the microconstituents. There is no deformation whatsoever at the surface of the fracture, the microconstituents being completely undisturbed. On the other hand, the fracture of tempered martensite is rough and jagged with considerable deformation of the grains in the vicinity of the fracture, see Figures 21B and 22B. The severe distortion accompanying the fracture of tempered martensite nicely accounts for the comparatively high impact strength of the material in this condition.

The appearance of the fractured surfaces is explained by their microstructures. The bright crystalline sheen of the brittle fracture is due to reflections from the flat crystalline facets such as are illustrated in Figure 21A. The dark, pitted, nonreflecting appearance of the fibrous fracture results from the jagged character of the fractured surface.

7. Effect of Hardness upon the Appearance of the Fracture

Sections from two series of one inch thick cast armor plates manufactured by the Lebanon Steel Foundry[4] and the Kelsey-Hayes Wheel Co.[5] ranging in hardness from 260 to approximately 360 Brinell were fractured under the steam hammer both at +70°F and -70°F to determine the effect of both hardness and temperature upon the appearance of the fracture.

Data covering the one inch thick cast plates are contained in Table VI.

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[4], [5]. See footnotes on page 5.

TABLE VI

1" Thick Cast Armor

Lebanon Steel Foundry:

Plate No.	Brinell Hardness	Chemical Analysis C	Mn	Ni	Cr	Mo
Q111	245	.34	.80	.50	.57	.37
Q90	260	.25	.76	.47	.49	.37
Q91	260	.27	.69	.59	.67	.46
Q112	285	.34	.80	.51	.60	.37
Q110	320	.35	.80	.54	.60	.39
Q109	355	.35	.85	.54	.60	.40

Kelsey-Hayes Wheel Co:

Plate No.	Brinell Hardness	Chemical Analysis C	Mn	Ni	Cr	Mo
[illegible]5	255	[illegible]	[illegible]	.27	.48	.50
[illegible]12	269					
[illegible]10	285					
[illegible]7	293	.26	1.16	.24	.52	.47
[illegible]9	311					
[illegible]11	321					
[illegible]8	341					
[illegible]6	363	.26	1.16	.24	.52	.47

The Kelsey-Hayes Wheel Company's plates are all from the same heat of steel and the Lebanon Steel Foundry plates are from three different heats, Q90 and Q91 being from two different low carbon heats and the rest from a high carbon heat. With the exception of plate Q90, all plates had been heat treated to a fully tempered martensitic structure, while plate Q90 had been slack quenched to the extent that some ferrite had been precipitated at elevated temperatures.

The following results were obtained upon fracturing the samples at +70 and -70°F:

a. At +70°F, the fractures of all the steels are distinctly fibrous; those at 360 Brinell not being distinguishable from those at 260 Brinell, compare Figure 23B to 23A.

b. At -70°F, Lebanon Steel Foundry plate Q90 has a crystalline fracture, see Figure 27A. This steel had been slack quenched and is consequently brittle at low temperatures.

c. The fractures of all the other steels are recognizably fibrous at -70°F. The appearance of the fracture is, however, changed from that at +70°F, particularly at the higher hardness levels. The fracture at -70°F tends to become flatter and more granular in appearance as the hardness increases, see Figures 23B and 6. The fracture still retains the dark nonreflecting qualities of the truly fibrous fracture and does not assume any of the sheen of the crystalline fracture.

This same phenomenon was noted on the Union Steel Casting Division's fracture test bar. At the end of the bar tempered at the lower temperatures, the fracture was much smoother than in the fibrous zone which had been tempered at higher temperatures.

6. Effect of Rate of Loading upon the Appearance of the Fracture

Two 2x2x6" sections were cut from each of several armor plates of various chemical analyses and microstructures. The sections were notched with an abrasive cut-off wheel. One piece of each steel was fractured under the impact blow of a steam forge hammer and the other under the head of a tensile machine at rate of load application of 9000 pounds per minute, with the following results:

a. When the fracture resulting from the impact break was completely crystalline, the fracture under the head of the tensile machine was also completely crystalline.

b. In some cases, when the fracture from the impact break was mixed, the fracture under the head of the tensile machine was also mixed to the same extent.

c. Generally, however, when the fracture from the impact blow was mixed, the fracture under the head of the tensile machine was more fibrous in nature. In some cases, the slow rate of straining produced completely fibrous fractures in the same material which broke with a mixed fracture under the steam hammer.

In view of the above results, the fracture obtained upon an impact blow is much more useful as a criterion for judging the characteristics of armor than that obtained by a slow rate of load application.

9. General Considerations

The series of experiments performed upon steels of various chemical analyses and heat treatments indicate that the appearance of the fracture is an excellent gauge of the degree of quench hardening of armor steels. The fibrous fracture has been associated with tempered martensitic microstructure, high impact strength, and the optimum combination of hardness and toughness. When the fracture is crystalline or mixed, the microstructure is heterogeneous, the room temperature impact strength is generally poor, and the impact strength at reduced temperatures is always low.

The fracture test, to be of real value, must incorporate the following features:

a. The test sample should be poured from the same heat as the armor components it represents.

b. The test sample should be equal in thickness to the heaviest section of the armor components it represents and of a size sufficient to have approximately the same cooling rate as the armor components upon quenching so that both would respond identically to heat treatment.

c. The test sample should be heat treated with the armor components it represents to eliminate the variables encountered in normal heat treating practice.

d. The test sample should be notched in such a fashion that the area of the fractured surface should be at least equal to T x T where T is the thickness of the test sample.

e. The test sample should be broken by an impact blow, either under a forge hammer, or by any other falling weight mechanism.

The fracture test as outlined above can be easily performed by the steel producers and Ordnance inspectors can be readily trained to interpret the fractures. The application of the fracture test will greatly expedite the production of satisfactory armor through the control it will exert over heat treatment.

During the time that the experimental work was being performed, fracture test samples were taken from many plates which had been subjected to firing tests at Aberdeen Proving Ground. It was found that no plate having a fibrous fracture failed the ballistic test. Every plate that failed the ballistic test showed either a crystalline or a mixed fracture, while several of the plates that did meet the ballistic requirements also had crystalline or mixed fractures. These results indicate that the fracture test is more critical than the present ballistic tests in differentiating between well and poorly heat treated armor

Because the fracture test is more critical than the ballistic test, it is conceivable that the successful application of the fracture test may very well lead to reduced ballistic testing; a factor which would greatly expedite production of armor components.

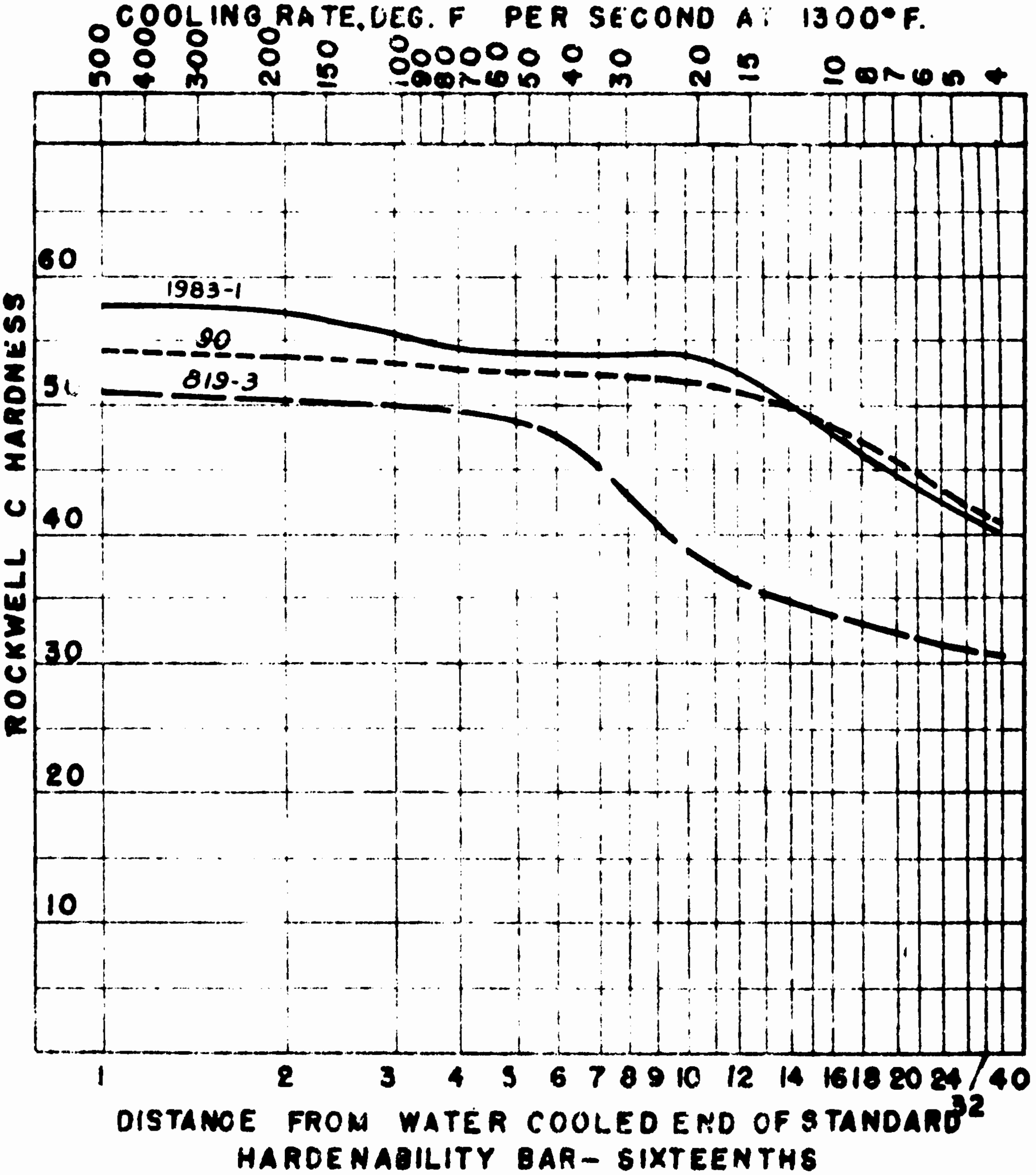


PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	CU	AL	QUENCH TEMP	TIME	G.S.
CONTINENTAL ROLL		.37	.92	.31	.029	.041	.63	.54	.37	.055	.008	1600	2	
& STEEL FRDY. #1983-1														
PITTSBURGH		.36	1.13	.32	.016	.009	.53	.48	.48	.115	.01	1600	2	
STEEL FRDY. #90														
ORDNANCE STEEL		.29	1.64	.34	.020	.019	–	.03	.38	.15	.02	1600	2	
FRDY.	#819-3													

FIGURE 1

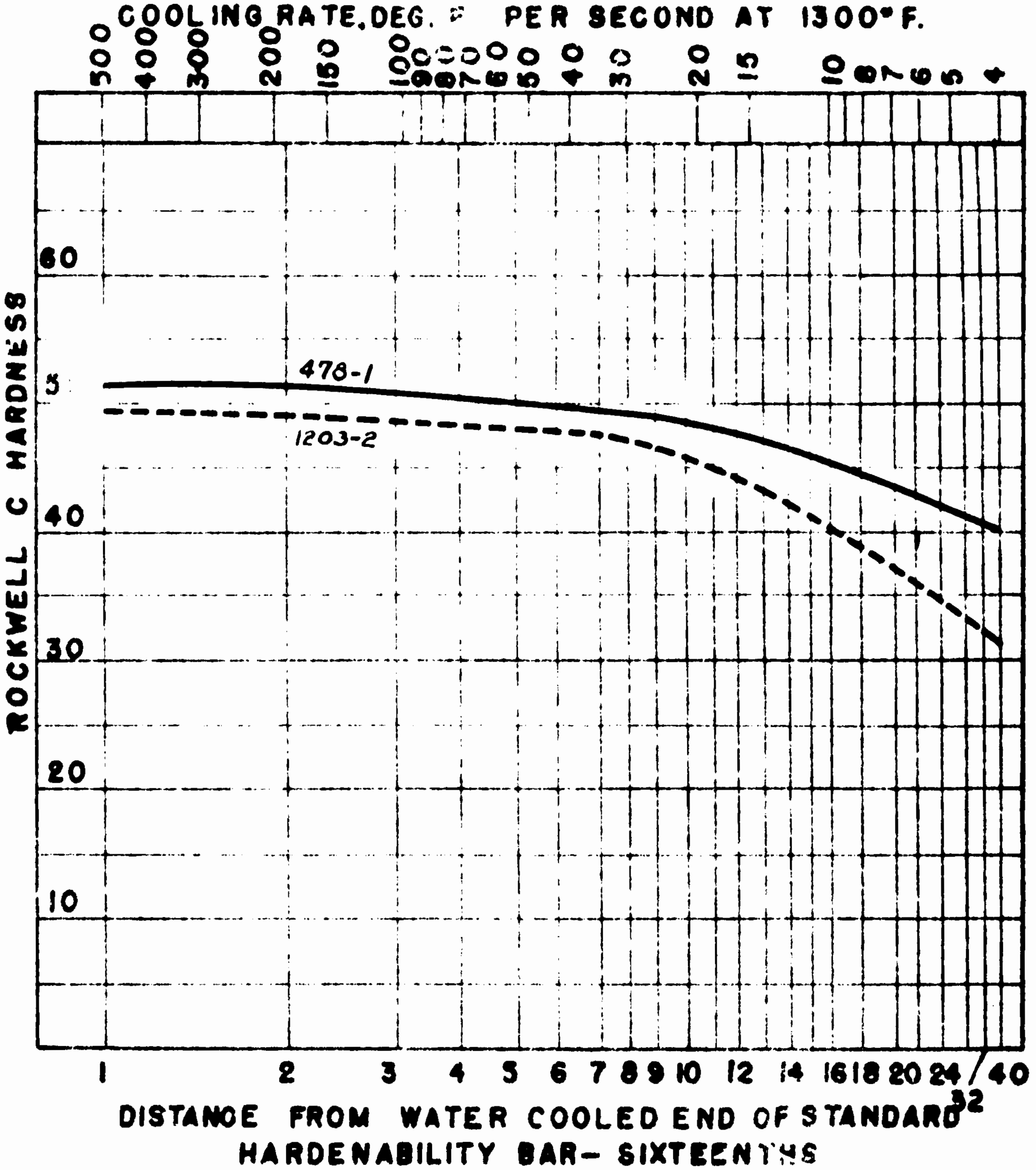


PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	CU	AL	QUENCH TEMP °F.	TIME HRS.	G.S.
NATIONAL	*TRAFFIC*	.27	1.62	.19	.014	.027	—	.36	.42	.135	03	1600	2	
GUARD	*#1203-2*													
STOCKHAM	*PIPE*	.26	1.60	.32	.017	.023	—	.48	.44	.125	.04	1600	2	
FITTINGS	*#478-1*													

FIGURE 2

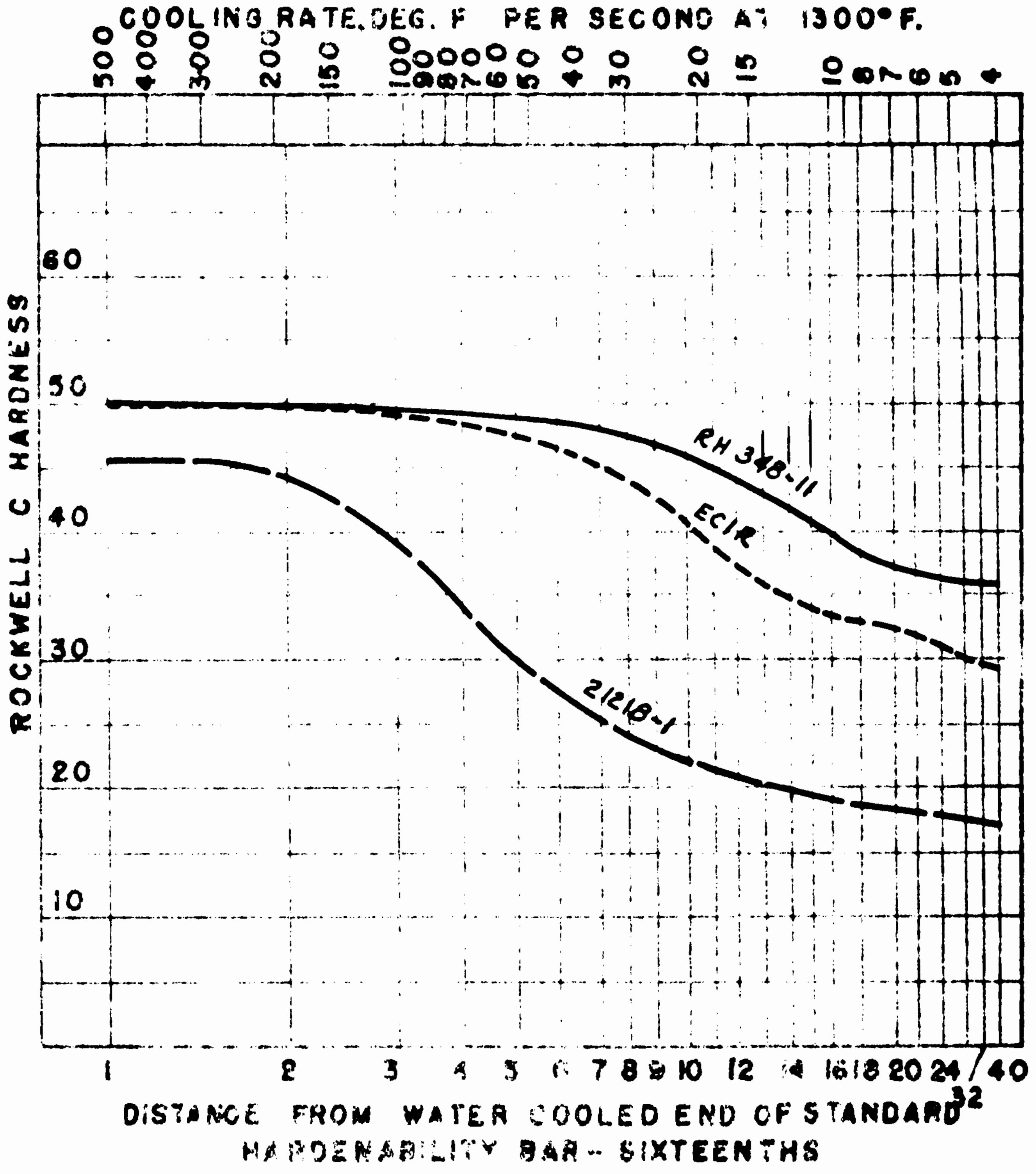
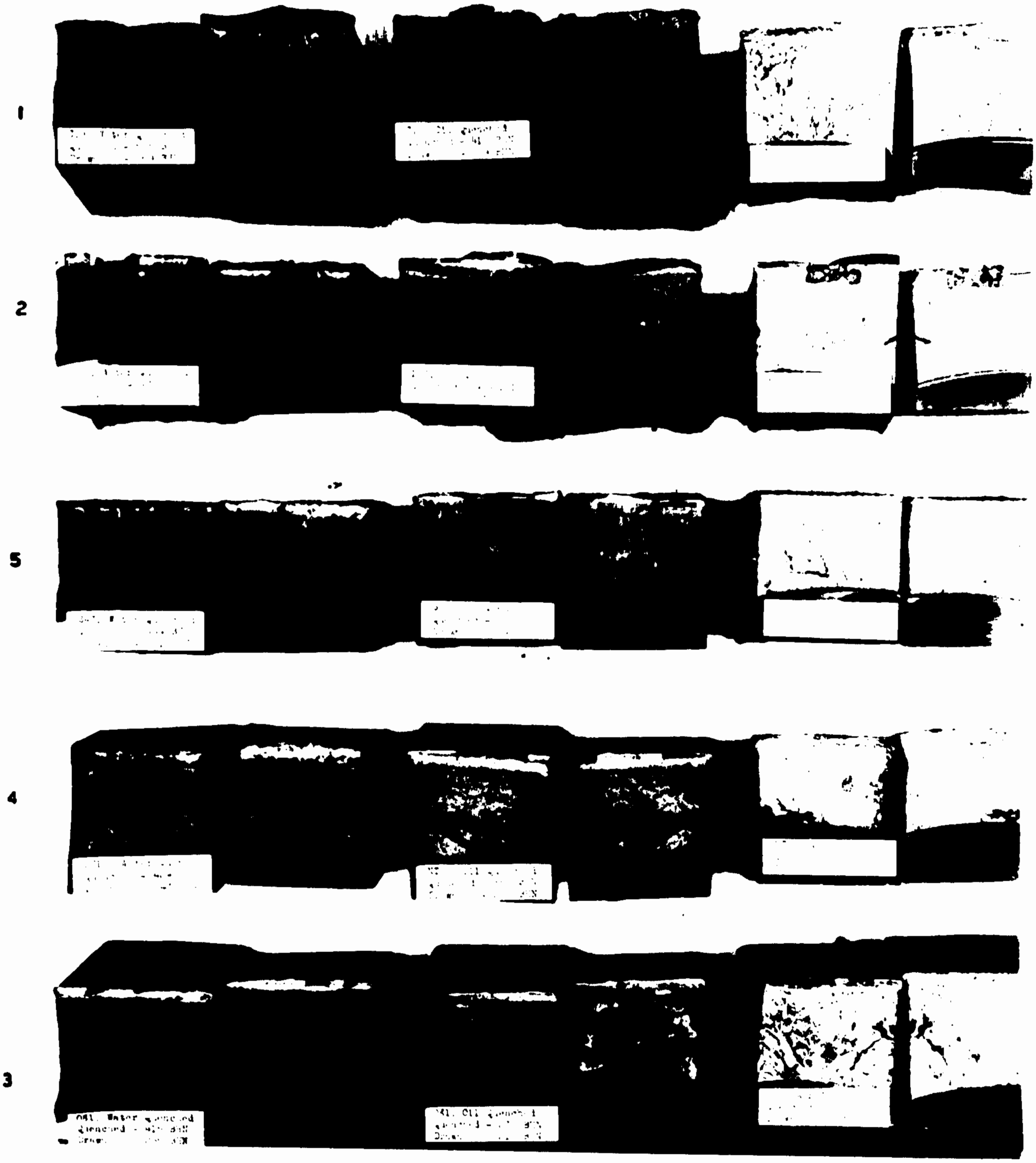


PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	CU	AL	B	QUENCH TEMP.	QUENCH TIME	G.S.
Republic	Steel	.27	.92	.20	.022	.022	.91	.71	.46	.13	.02	–	1600	2	
Corp	#RH348-11														
Ford	Motor	.27	1.57	.20	.027	.012	–	.04	.47	.12	.02	.003	1600	2	
Co.	#ECIR														
Henry	Disston	.21	.94	1.03	.010	.010	.10	.16	.18	.12	.01	–	1600	2	
& Sons	#21218-1														

FIGURE 3



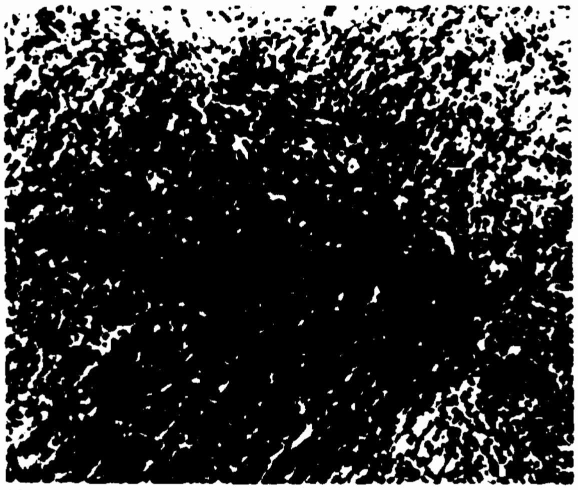
WATERTOWN ARSENAL

FRACTURED SECTIONS OF 2" CAST ARMOR. QUENCHED AS INDICATED FROM 1600°F. P90 DRAWN AT 1125°F. C19, S47, NT12, AND 081 DRAWN AT 1200°F. MARCH 22 1943 WTN.710-2048

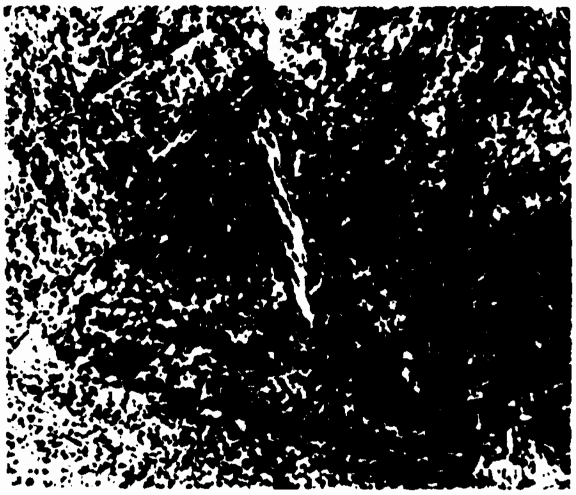
FIGURE 4

Steel No. 1.

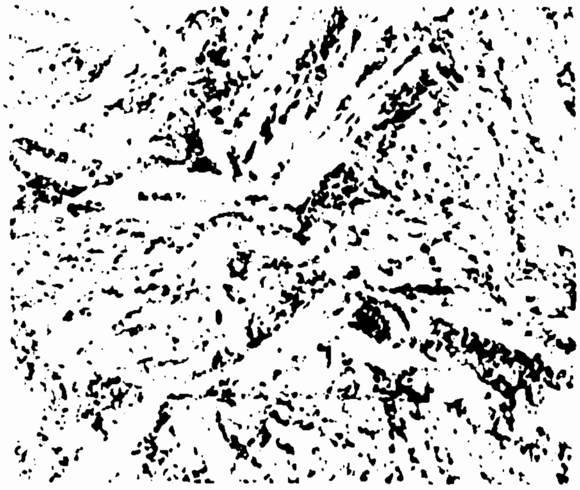
Continental Roll & Steel Foundry Co.
Magnification X1000 #1983-1



Water quenched and tempered. -A-
Tempered martensite. (Sorbite)



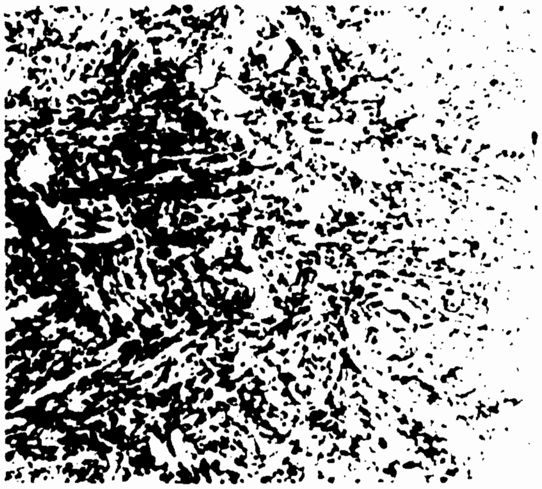
Oil quenched and tempered. -B-
Tempered martensite and very small amount of rejected ferrite.



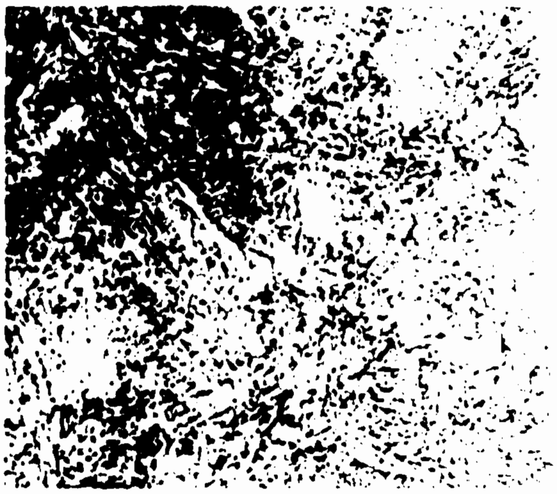
Air cooled and tempered. -C-
Ferrite and carbides. High temperature transformation products.

[illegible]

Pittsburgh Steel F[illegible]
[illegible]



Water quenched and tempered.
Tempered martensite. (Sorbite)



Oil quenched and tempered.
Tempered martensite and very small amount of rejected ferrite.

Air cooled and tem[illegible].
Ferrite and carbides.

[illegible]

[illegible] Steel Foundry #F1[illegible] [illegible]

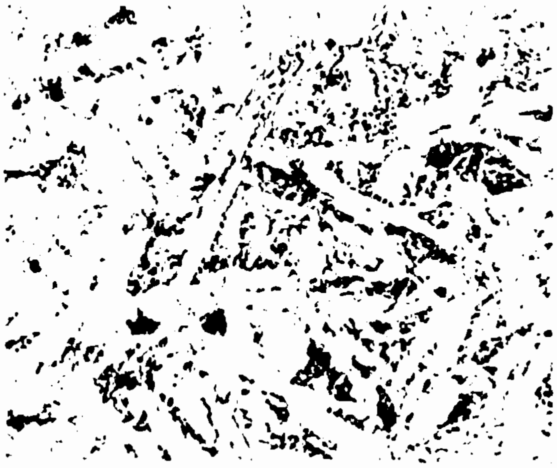
[illegible]nification X1000

Water quenched and tempered. -G-
Tempered martensite and ferrite and pearlite formed at high temperatures

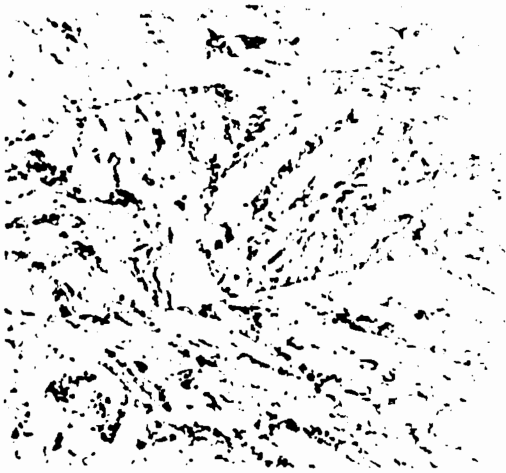
Water quenched and tem[illegible].
Tempered martensite.

Oil quenched and tempered. -H-
High temperature transformation products.

Oil quenched and tempered.
Tempered martensite with f[illegible]
and pearlite formed at hi[illegible]
temperatures.



Air cooled and tempered. -I-
High temperature transformation products.

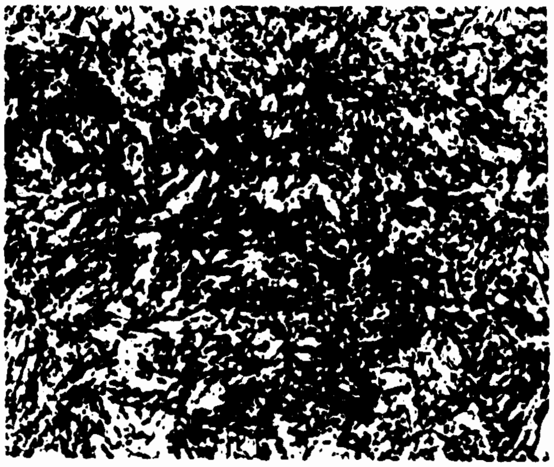


Air cooled and tempered.
High temperature trans[illegible]
products.

Steel No. 5.

Stockham Pipe Fitting Co. #-[illegible] Republic Steel [illegible]

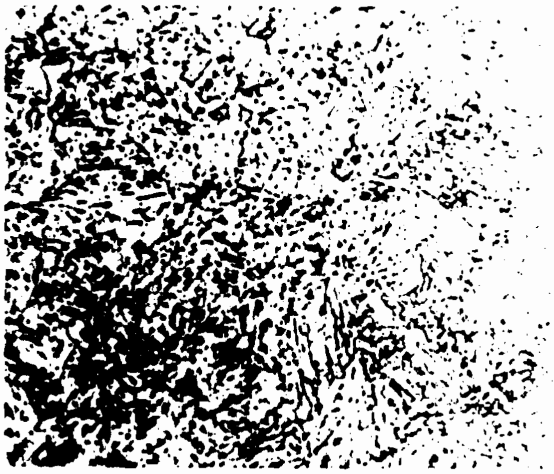
Magnification X1000



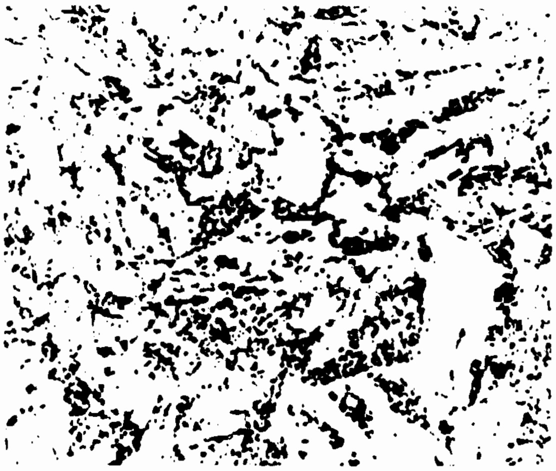
Water quenched and tempered. -M-
Tempered martensite.

Water quenched and tempered.
Tempered martensite.

Oil quenched and tempered. -N-
High temperature transformation products.



Oil quenched and tempered.
Tempered martensite with very [illegible] amount of ferrite rejected.



Air cooled and tempered. -O-
Ferrite and carbides.

Air cooled and tempered.
Ferrite and carbides.

WTN.635-5374

Steel No. 7.

Ford Motor Co.

Magnification X1000

Water quenched and tempered. -S-
Tempered martensite.

Oil quenched and tempered. -T-
Tempered martensite and high temperature transformation products.

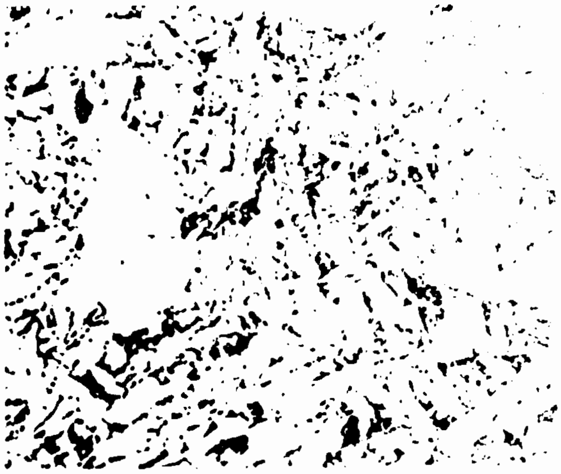
Air cooled and tempered. -U-
Ferrite and carbides.

Steel [illegible]

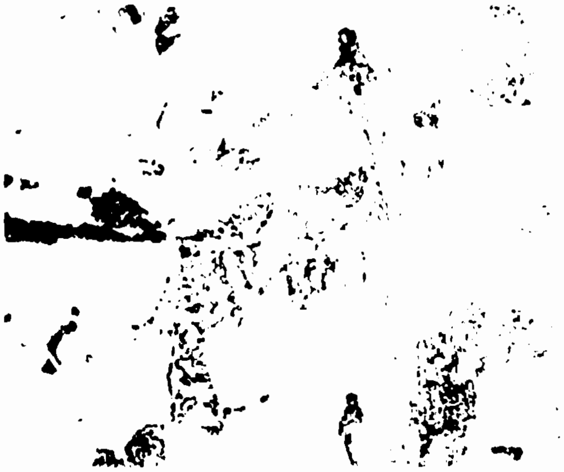
#ECIR Henry Disston & Sons, Inc.

[illegible]

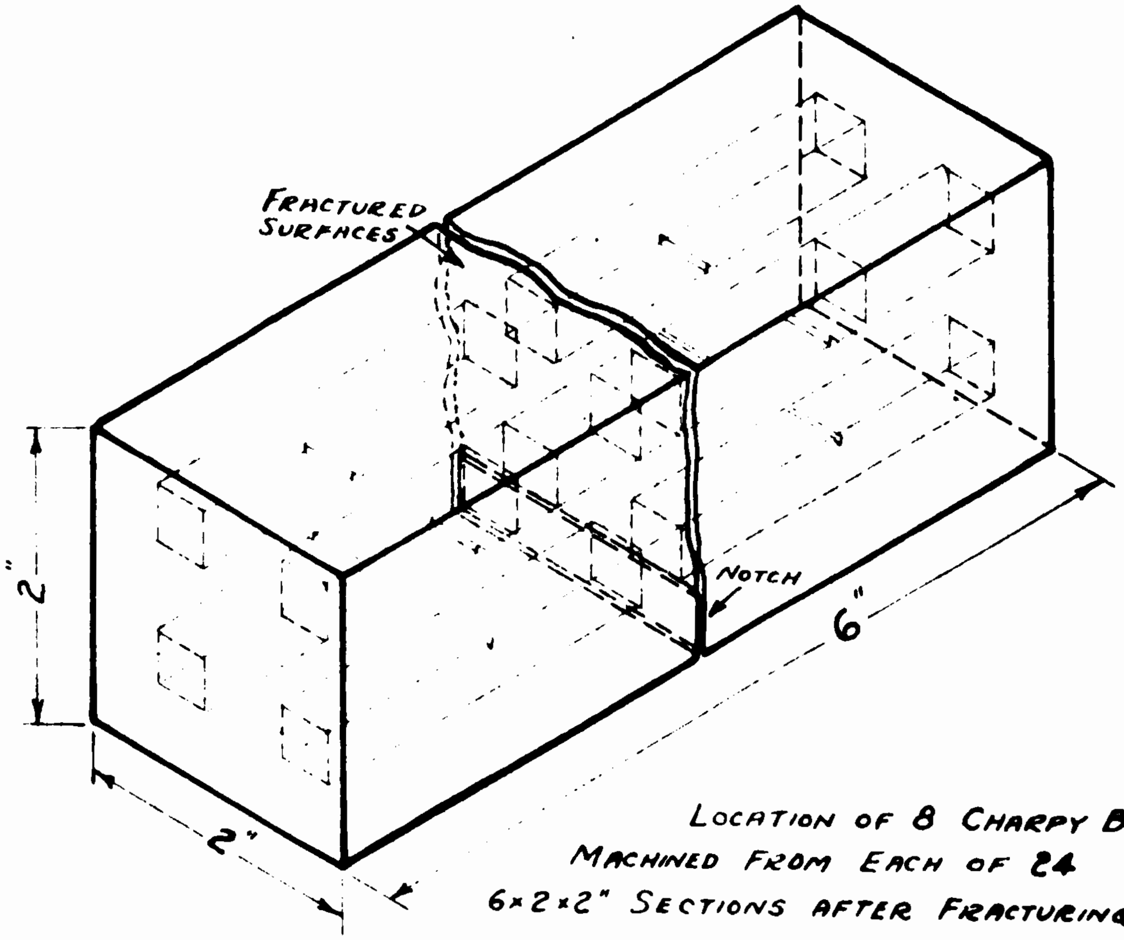
Water quenched and tempered.
Ferrite and carbides.



Oil quenched and tempered.
Ferrite and carbides.



Air cooled and tempered.
Ferrite and carbides.



LOCATION OF 8 CHARPY BARS
MACHINED FROM EACH OF 24
6×2×2" SECTIONS AFTER FRACTURING.

STANDARD V-NOTCH CHARPY BAR

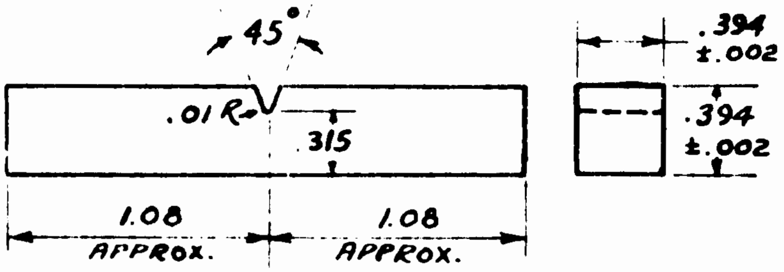
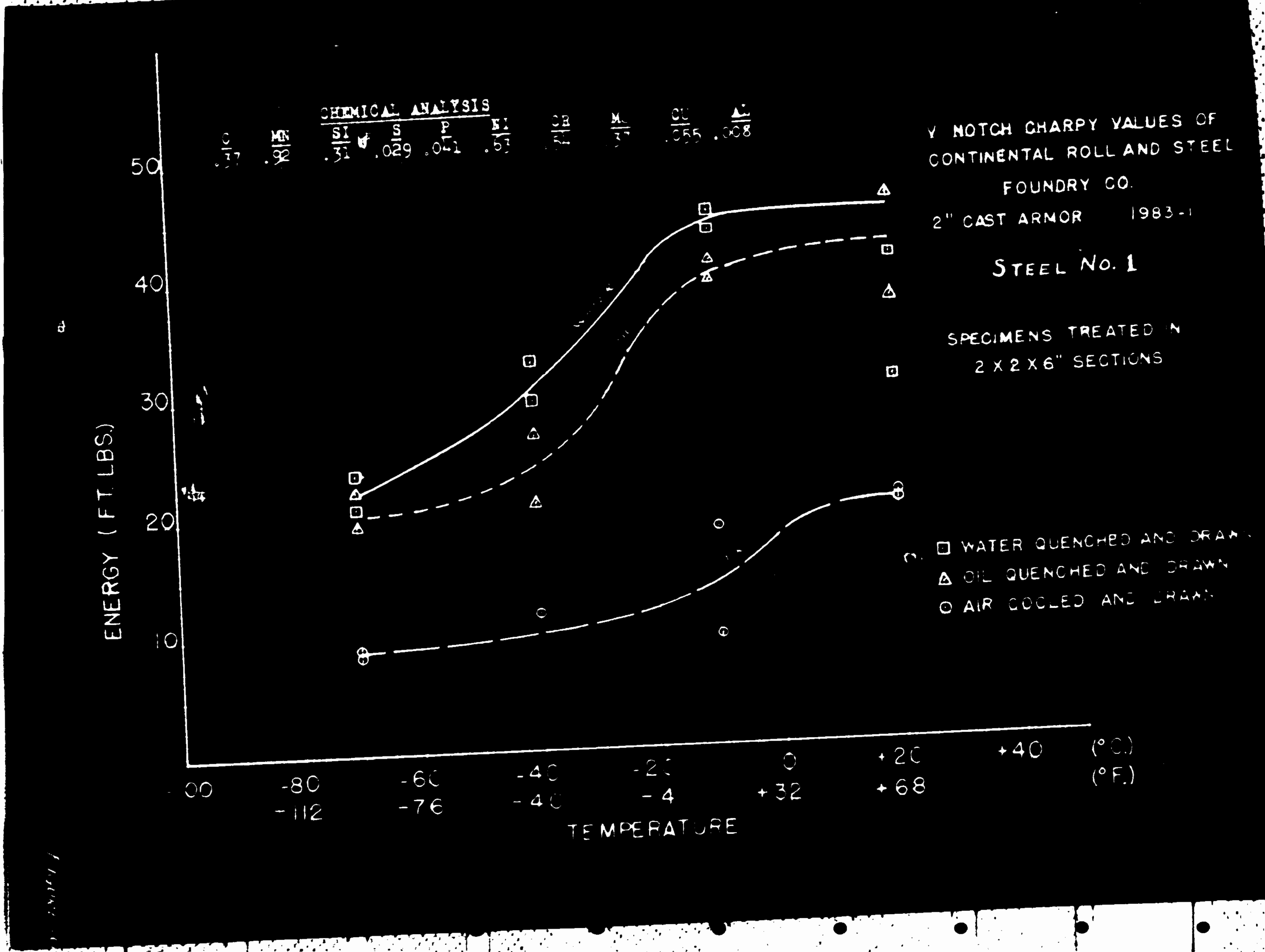


FIGURE 9


V NOTCH CHARPY VALUES OF
CONTINENTAL ROLL AND STEEL
FOUNDRY CO.
2" CAST ARMOR 1983-1
STEEL No. 1
SPECIMENS TREATED IN
2 X 2 X 6" SECTIONS
CHEMICAL ANALYSIS
C .37
MN .92
SI .31
S .029
P .041
NI .53
CR
MO .37
CU .055
AL .008
□ WATER QUENCHED AND DRAWN
Δ OIL QUENCHED AND DRAWN
○ AIR COOLED AND DRAWN
ENERGY (FT. LBS.)
50
40
30
20
10
-100
-80
-60
-40
-20
0
+20
+40
(°C.)
-112
-76
-40
-4
+32
+68
(°F.)
TEMPERATURE

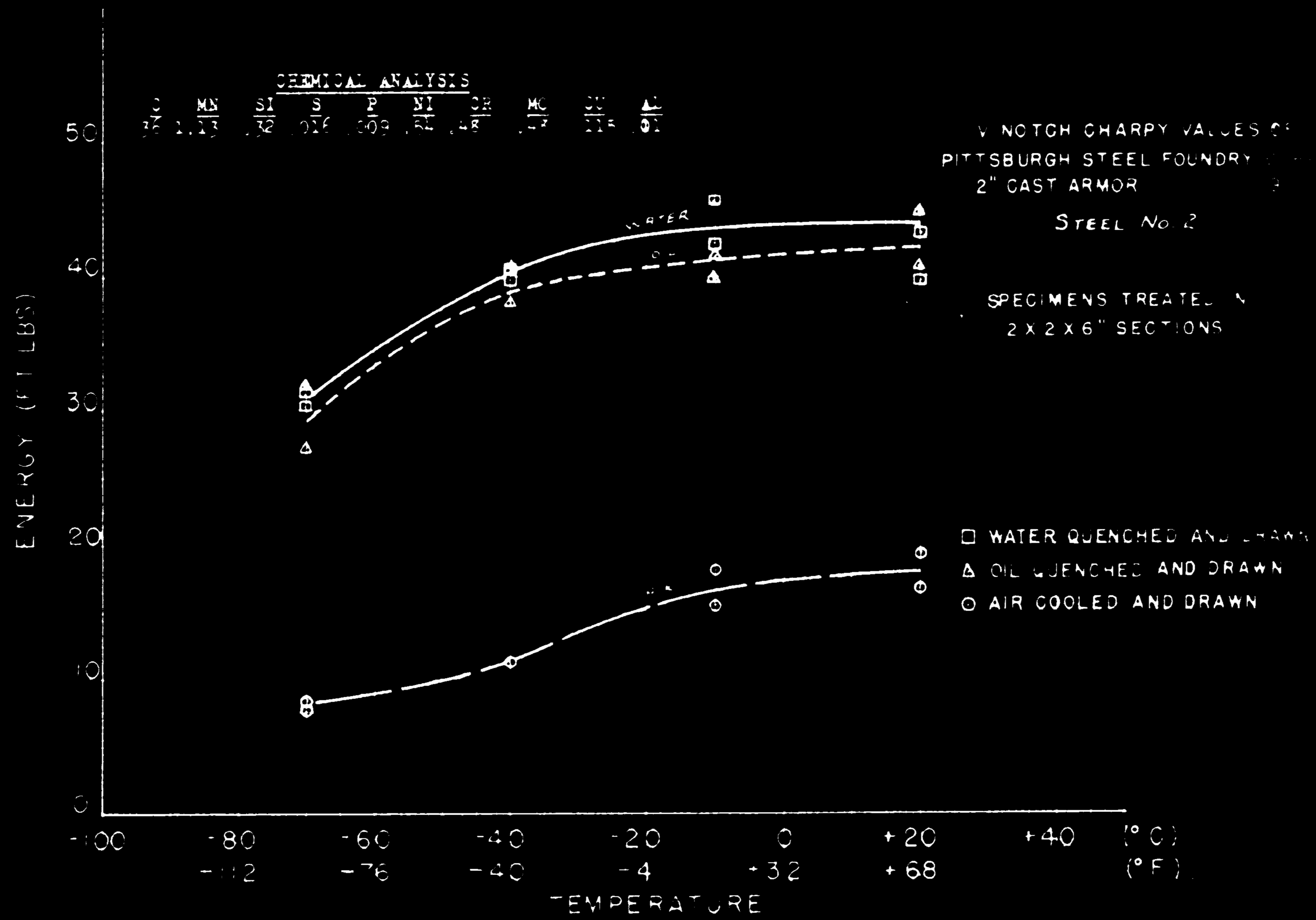
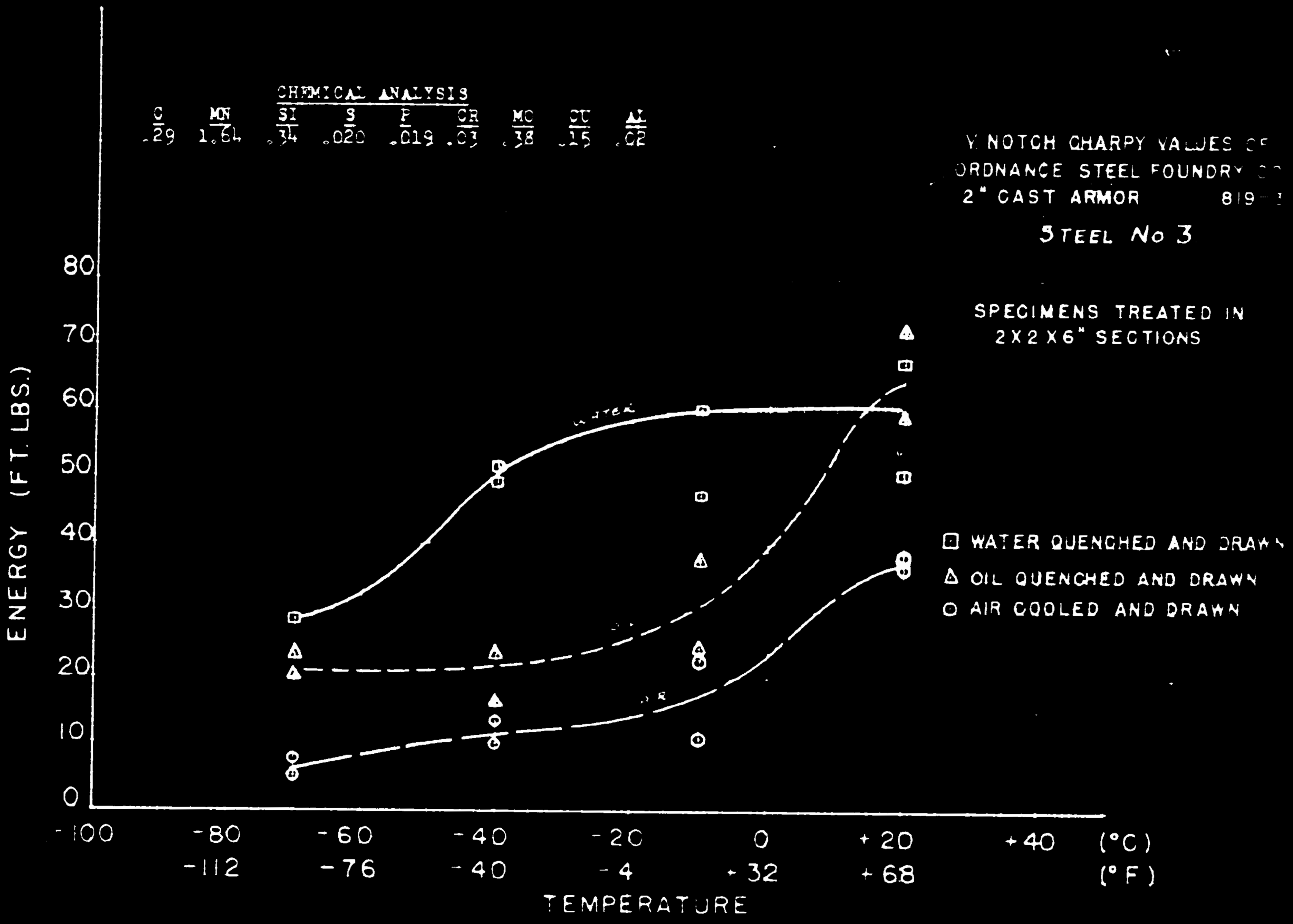

V NOTCH CHARPY VALUES OF
PITTSBURGH STEEL FOUNDRY
2" CAST ARMOR
STEEL No. 2
SPECIMENS TREATED IN
2 X 2 X 6" SECTIONS
CHEMICAL ANALYSIS
C MN SI S P NI CR MO CU AL
1.13 .32 .016 .009 .48 .01
□ WATER QUENCHED AND DRAWN
Δ OIL QUENCHED AND DRAWN
⊙ AIR COOLED AND DRAWN
WATER
OIL
ENERGY (FT LBS)
0
10
20
30
40
50
-100
-80
-60
-40
-20
0
+20
+40
(°C)
-112
-76
-40
-4
+32
+68
(°F)
TEMPERATURE

FIGURE 11



V NOTCH CHARPY VALUES OF
ORDNANCE STEEL FOUNDRY CO
2" CAST ARMOR 819-

STEEL No 3

SPECIMENS TREATED IN
2 X 2 X 6" SECTIONS

CHEMICAL ANALYSIS

C	MN	SI	S	P	CR	MO	CU	AL
.29	1.64	.34	.020	.019	.03	.38	.15	.02

FIGURE 12

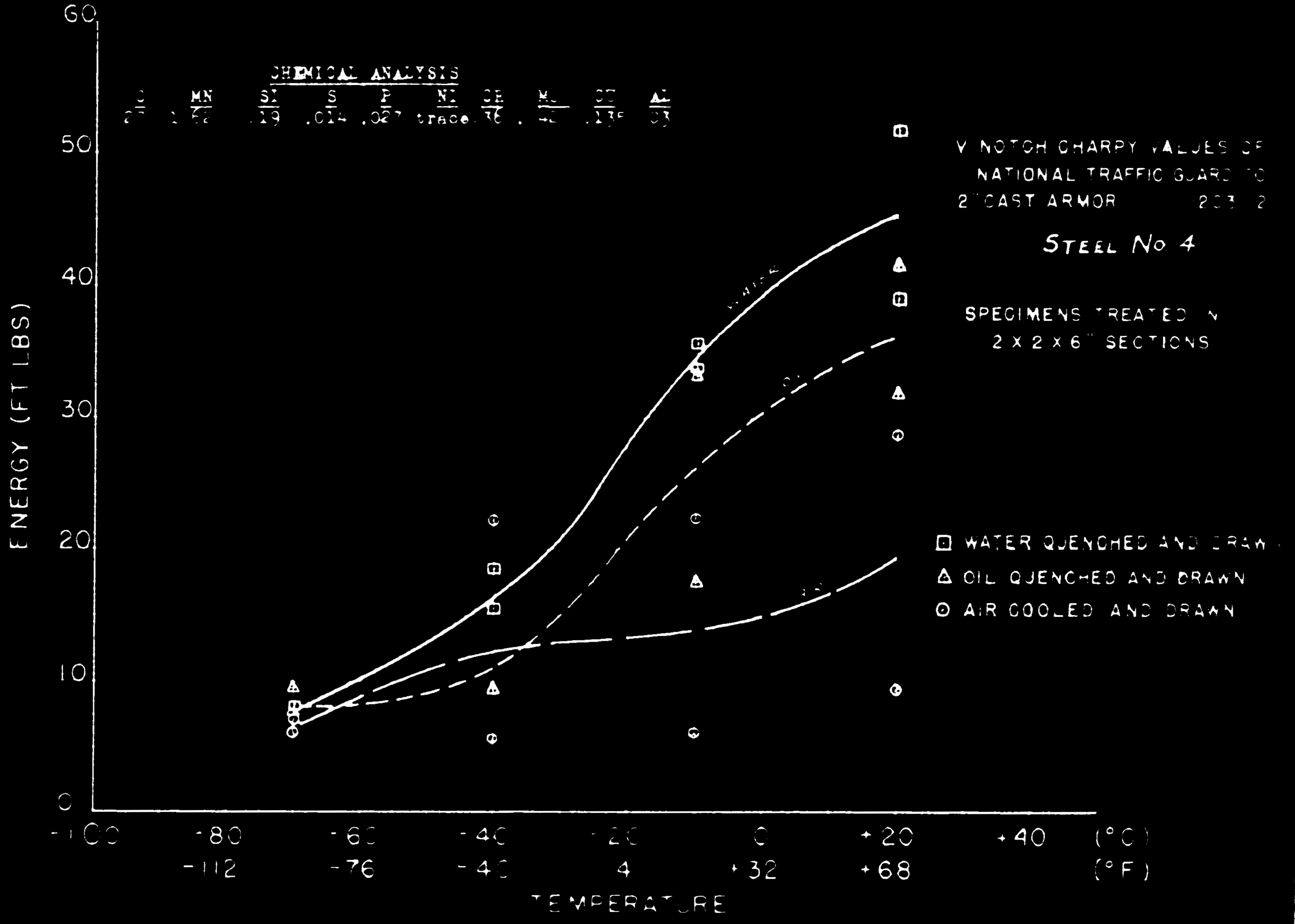
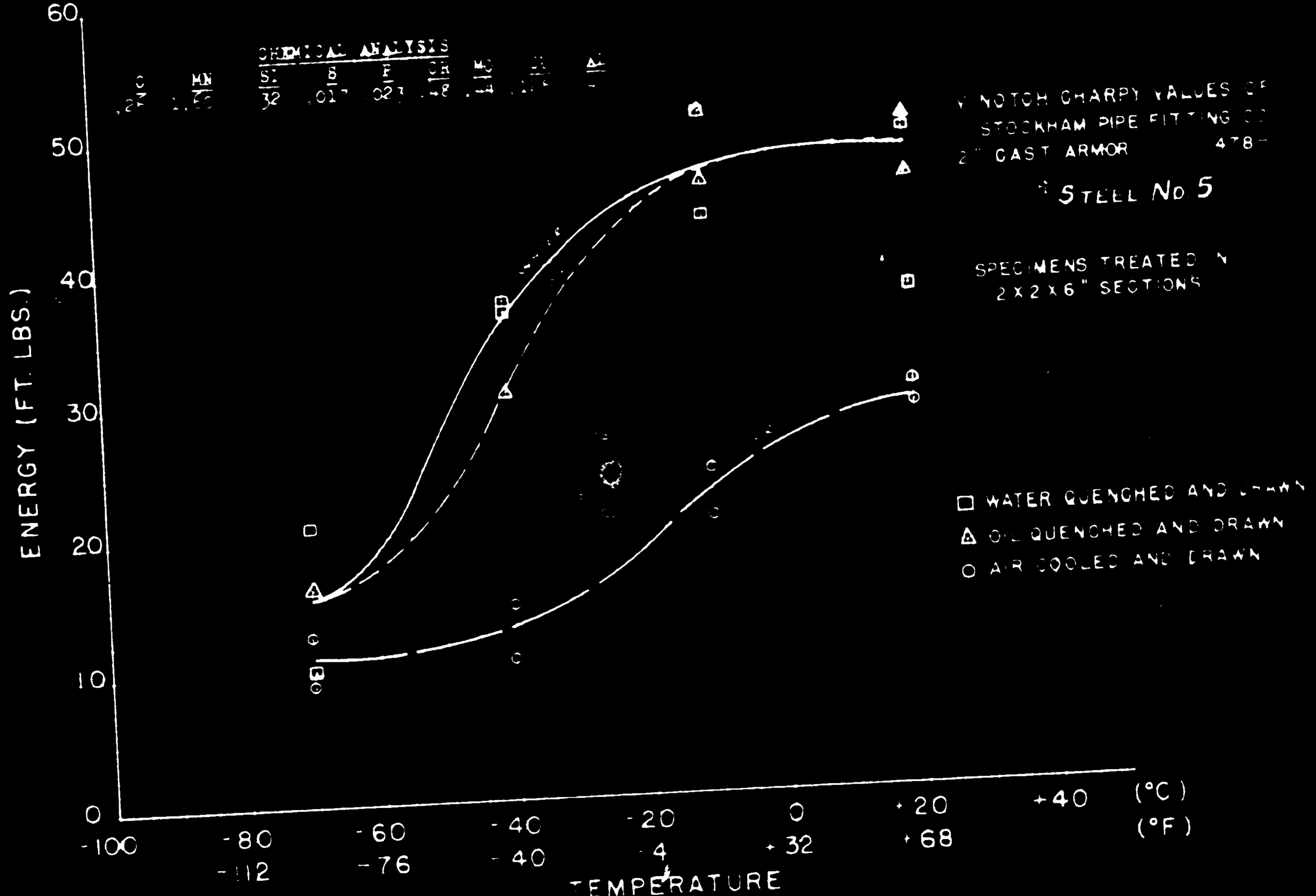
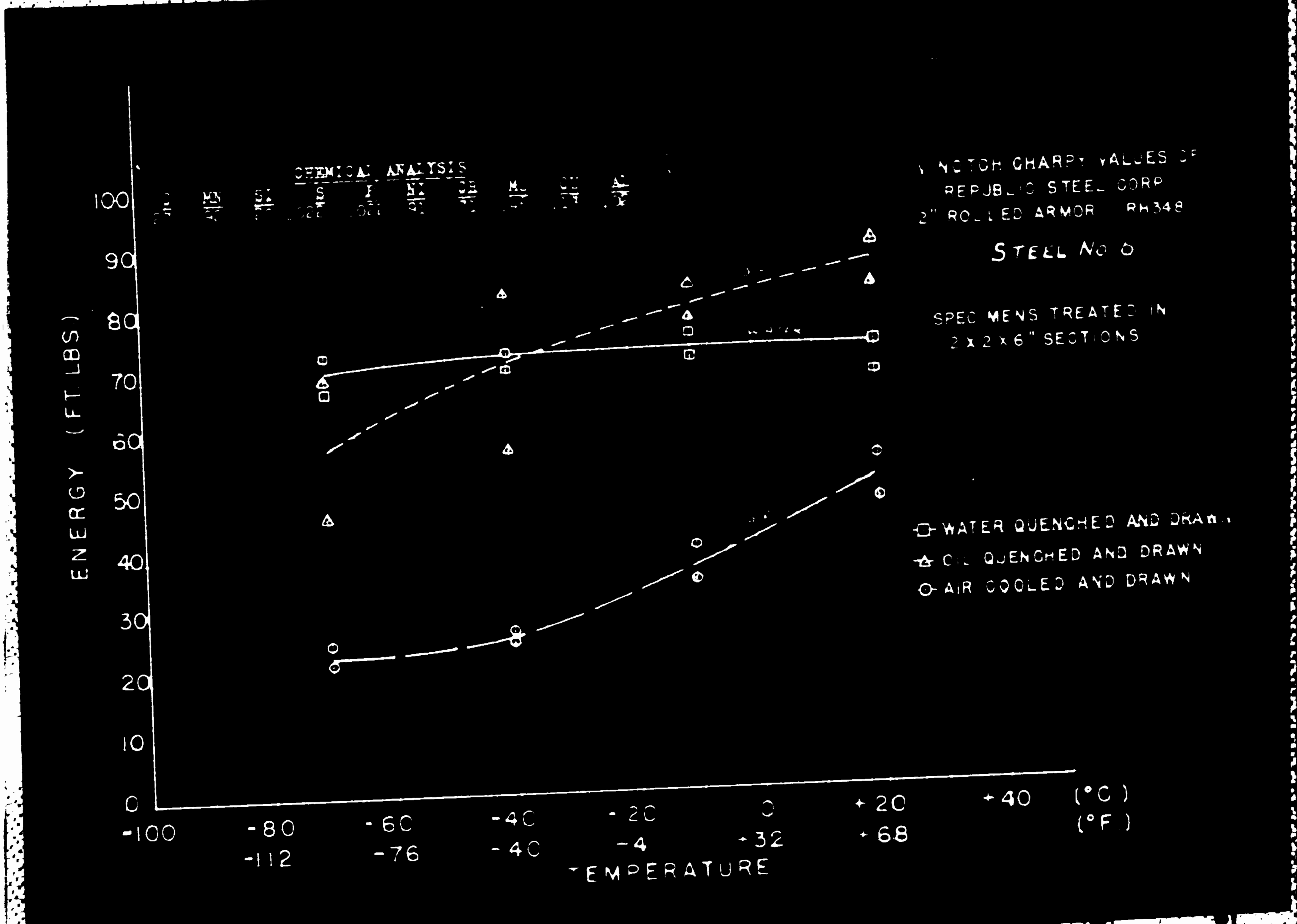

CHEMICAL ANALYSIS
C MN SI S P NI CR MO CU AL
[illegible] 1.62 .19 .014 .027 trace .76 .42 .135 .03
V NOTCH CHARPY VALUES OF
NATIONAL TRAFFIC GUARD CO
2" CAST ARMOR 203-2
STEEL No 4
SPECIMENS TREATED IN
2 X 2 X 6" SECTIONS
□ WATER QUENCHED AND DRAWN
△ OIL QUENCHED AND DRAWN
⊙ AIR COOLED AND DRAWN
WATER
OIL
AIR
ENERGY (FT LBS)
0
10
20
30
40
50
60
-100
-80
-60
-40
-20
0
+20
+40
(°C)
-112
-76
-40
4
+32
+68
(°F)
TEMPERATURE

FIGURE 13



V NOTCH CHARPY VALUES OF
STOCKHAM PIPE FITTING CO
2" CAST ARMOR 478-
STEEL No 5
SPECIMENS TREATED IN
2 X 2 X 6" SECTIONS
CHEMICAL ANALYSIS
C .27
MN 1.50
SI .32
S .017
P .023
CR .48
MO
NI
AL
□ WATER QUENCHED AND DRAWN
△ OIL QUENCHED AND DRAWN
○ AIR COOLED AND DRAWN
ENERGY (FT. LBS.)
60
50
40
30
20
10
0
-100
-80
-60
-40
-20
0
+20
+40
(°C)
-112
-76
-40
-4
+32
+68
(°F)
TEMPERATURE

FIGURE


V NOTCH CHARPY VALUES OF
REPUBLIC STEEL CORP
2" ROLLED ARMOR RH348
STEEL No 6
SPECIMENS TREATED IN
2 x 2 x 6" SECTIONS
WATER QUENCHED AND DRAWN
OIL QUENCHED AND DRAWN
AIR COOLED AND DRAWN
CHEMICAL ANALYSIS
MN
SI
S
P
NI
CR
MO
.022
ENERGY (FT LBS)
100
90
80
70
60
50
40
30
20
10
0
-100
-80
-112
-60
-76
-40
-40
-20
-4
0
+32
+20
+68
+40
(°C)
(°F)
TEMPERATURE

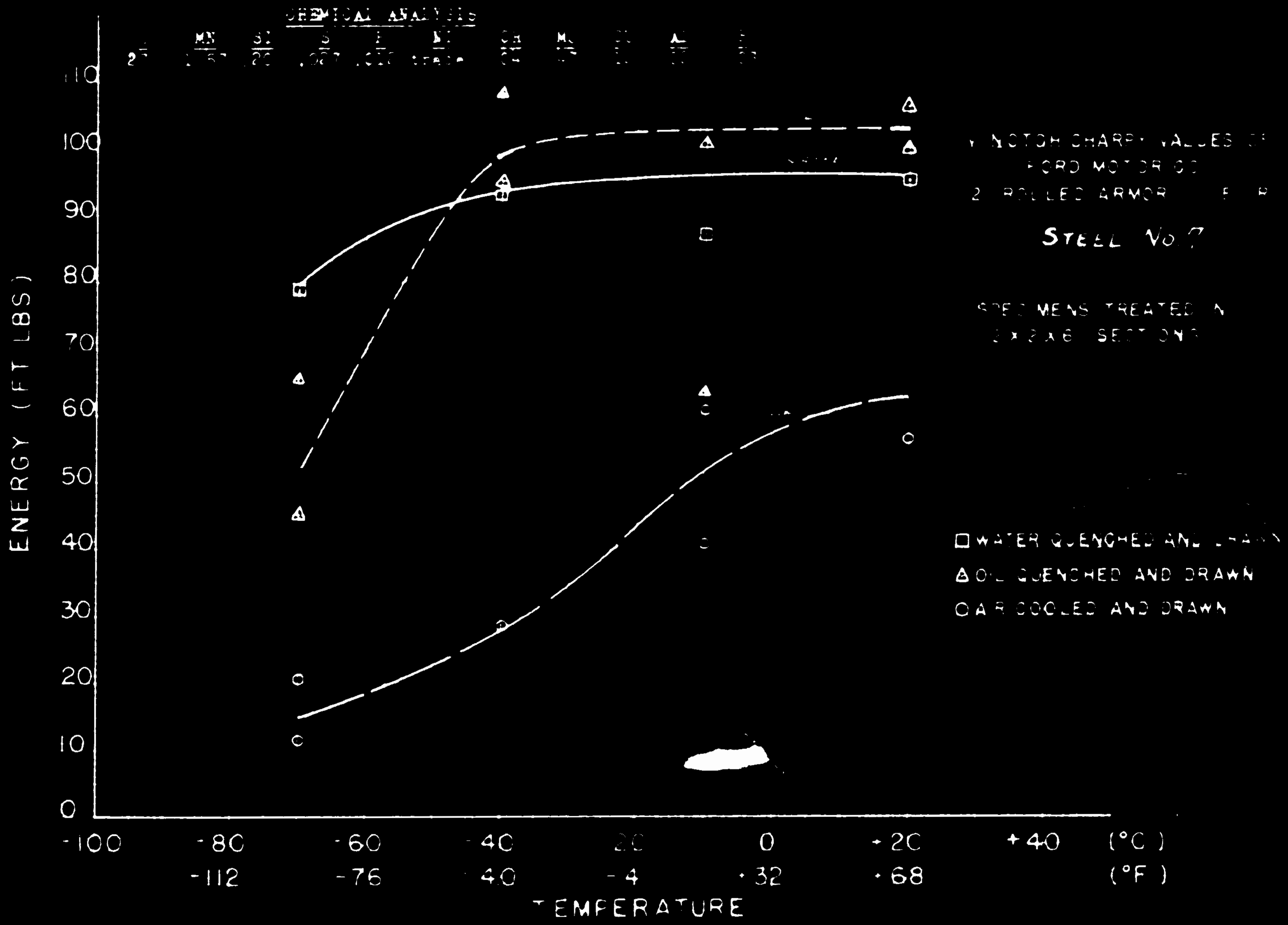

CHEMICAL ANALYSIS
MN
SI
S
P
NI
CR
MO
AL
.20
.027
.010
trace
V NOTCH CHARPY VALUES OF
FORD MOTOR CO
2" ROLLED ARMOR
STEEL No 7
SPECIMENS TREATED IN
2 x 2 x 6 SECTIONS
□ WATER QUENCHED AND DRAWN
△ OIL QUENCHED AND DRAWN
○ AIR COOLED AND DRAWN
ENERGY (FT LBS)
0
10
20
30
40
50
60
70
80
90
100
110
-100
-80
-60
-40
-20
0
+20
+40
(°C)
-112
-76
-40
-4
+32
+68
(°F)
TEMPERATURE

FIGURE 16

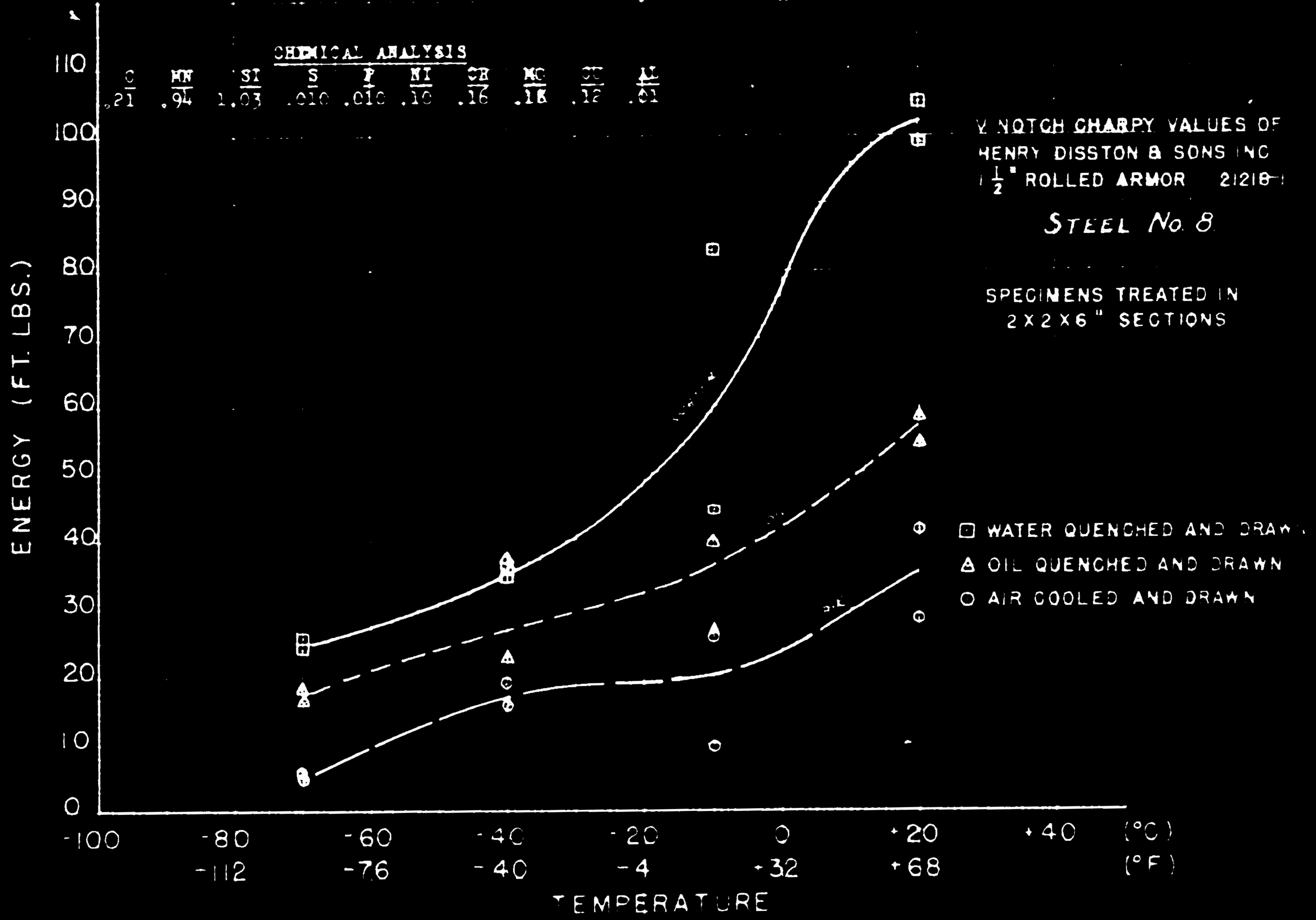
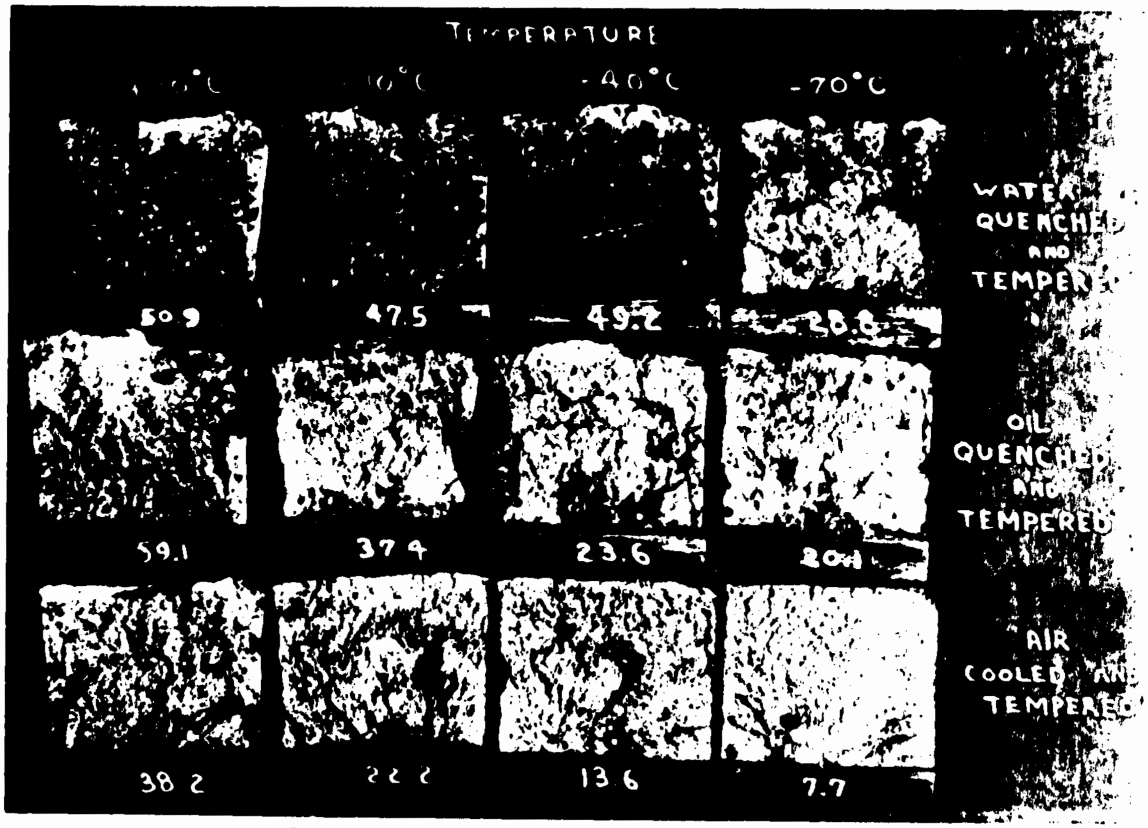
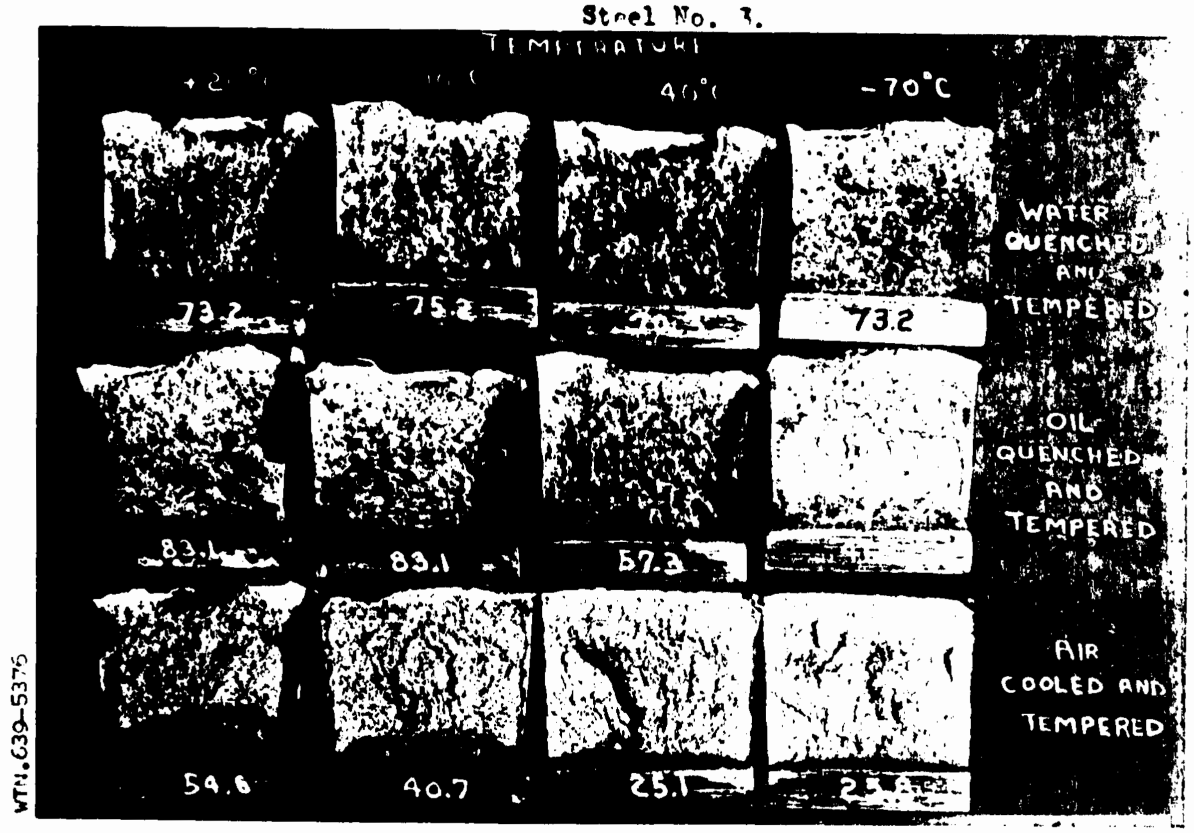

CHEMICAL ANALYSIS
C .21
MN .94
SI 1.03
S .010
P .010
NI .10
CR .16
MO .18
CU .12
AL .01
V NOTCH CHARPY VALUES OF
HENRY DISSTON & SONS INC
1 1/2" ROLLED ARMOR 21218-1
STEEL No. 8
SPECIMENS TREATED IN
2 X 2 X 6" SECTIONS
□ WATER QUENCHED AND DRAWN
△ OIL QUENCHED AND DRAWN
○ AIR COOLED AND DRAWN
ENERGY (FT. LBS.)
0
10
20
30
40
50
60
70
80
90
100
110
-100
-80
-60
-40
-20
0
+20
+40
(°C)
-112
-76
-40
-4
+32
+68
(°F)
TEMPERATURE

FIGURE 1[illegible]

Fractures of V-Notch Charpy Impact [illegible]



Ordnance Steel Foundry - 2" Cast Armor #81[illegible]
Steel No. 3.

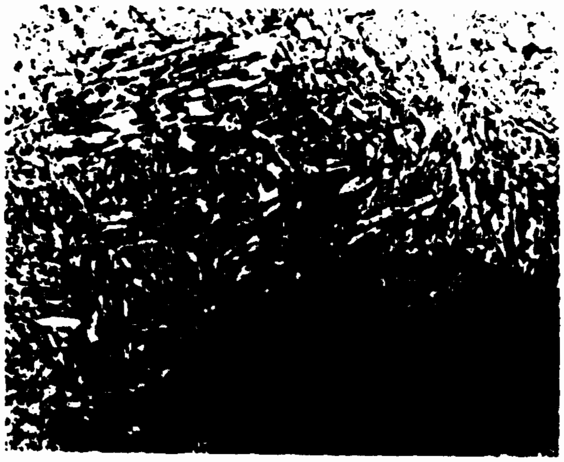


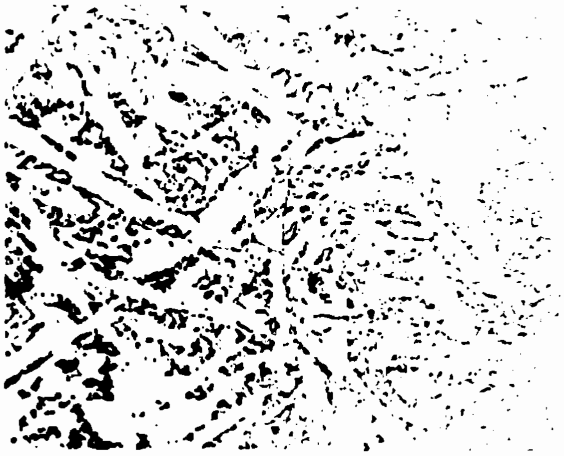
Republic Steel Corp. - 2" Rolled Armor #RH[illegible]-11
Steel No. 6.

Microstructures of Gun Shield Castings
1-6" in Thickness

Etchant - Nital and Picral

Microstructures of cent [illegible] section.

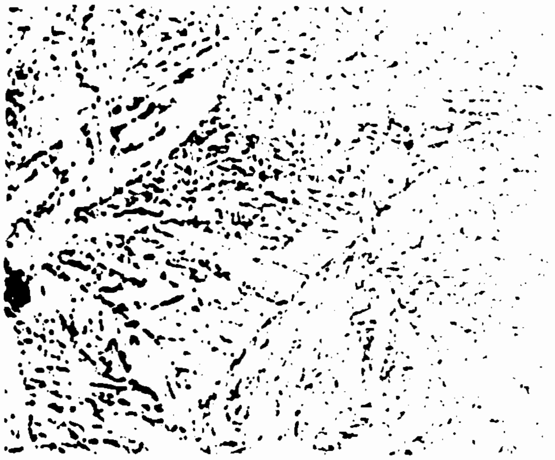




X200 **Plate 1-13-3372 Heat 3372** -A- X1000

Large amount of ferrite rejected upon quenching.

Large amount of ferrite and boundary carbides rejected upon quenching.



X200 **Plate 1 Heat 6405** -B- X1000

Dendritic segregation and rejected ferrite.

Ferrite and grain boundary carbides rejected upon quenching.

X200 **Plate GSC-26** Heat 6848 -C- X1000

Relatively uniform microstructure, no free ferrite.

Spheroidized sorbite with [illegible] ferrite present.

WTN.639-5377

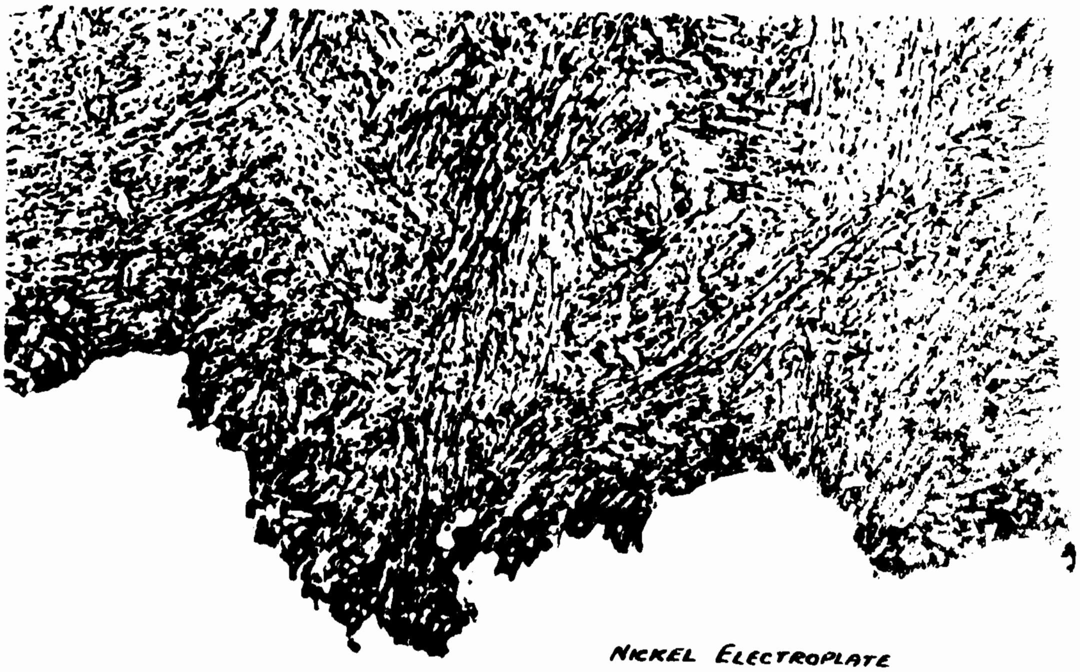
Fractures of V-[illegible]

Cast Armor

Picral Etch

-A-

Heat 3[illegible]45. As received. Average Charpy impact - 12.3 ft. lbs. 220 Brinell. Section perpendicular to fractured surface of [illegible] Crystalline fracture.



WTN.632-5378

Picral Etch

-B-

Heat 3[illegible]45. Reheat-treated. Average Charpy impact - [illegible] ft. lbs. 229 Brinell. Fibrous fracture.

Fractures of V-Notch Charpy Bars
Rolled Armor - Steel No. 7.

Nickel Electroplate

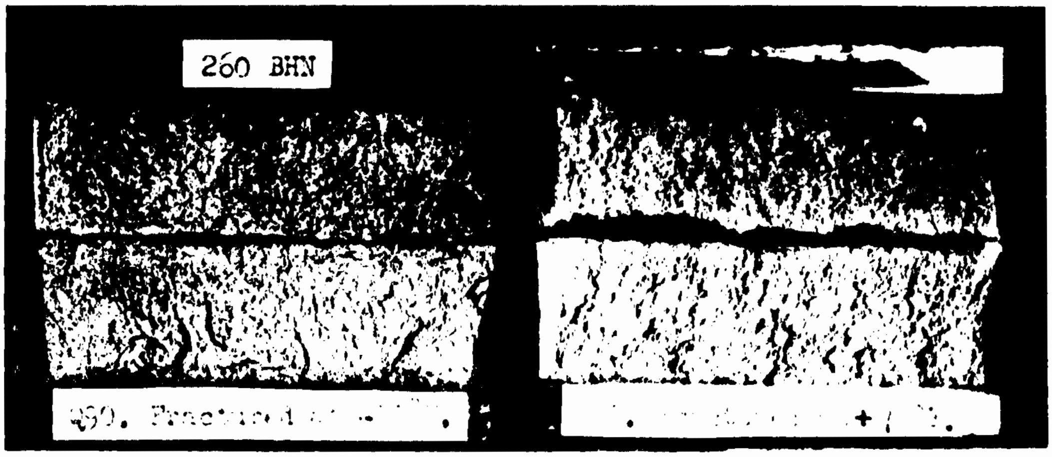
Picral Etch -A- [illegible]
Steel No. 7. Air cooled and tempered. Brinell hardness - [illegible]
Charpy - 28.8 ft. lbs. at -40°C. Crystalline fracture.

WTN.639-5379

Nickel Electroplate

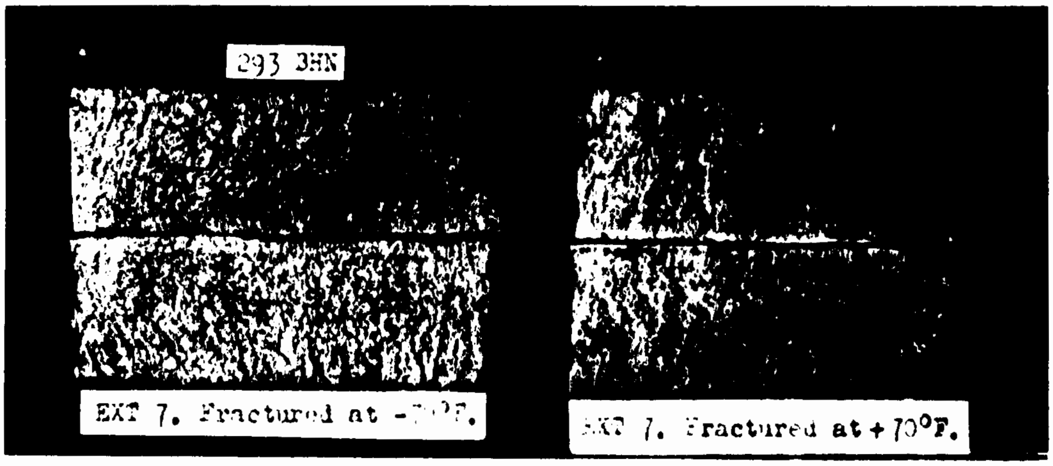
Picral Etch -B- [illegible]
Steel No. 7. Water quenched and tempered. Brinell Hardness - [illegible]
Charpy - 93.0 ft. lbs. at - 40°C. Fibrous fracture.

[illegible]



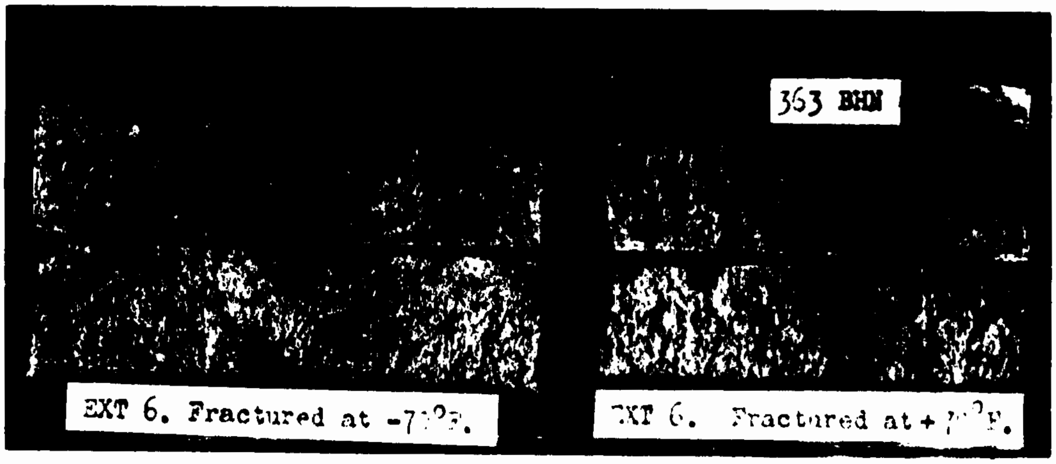
Lebanon Steel Foundry Q[illegible].

C	Mn	Si	S	P	Ni	Cr	Mo
.25	.76	.44	.027	.026	.47	.49	.37



Kelsey - Hayes EXT 7.

C	Mn	Si	S	P	Ni	Cr	Mo
.26	1.18	.44	.021	.024	.24	.52	.47



Kelsey - Hayes EXT 6.

C	Mn	Si	S	P	Ni	Cr	Mo
.26	1.18	.44	.022	.024	.23	.49	.47

Figure 23

APPENDIX A

V-NOTCH CHARPY IMPACT DATA

Steel	Temp. °F.	Impact Ft.-Lbs.	Fracture*	Steel	Temp. °F.	Impact Ft.-Lbs.	Fracture*
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Water Quenched	[illegible]	[illegible]	[illegible]	Water Quenched	[illegible]	[illegible]	[illegible]
Tempered	-10	[illegible]	[illegible]	Tempered	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]
	-50	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]
	-50	[illegible]	[illegible]		-70	[illegible]	[illegible]
	-70	20.8	[illegible]		-70	[illegible]	[illegible]
	-70	[illegible]	[illegible]		-70	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Oil Quenched	[illegible]	[illegible]	[illegible]	Oil Quenched	[illegible]	[illegible]	[illegible]
Tempered	-30	[illegible]	[illegible]	Tempered	[illegible]	[illegible]	[illegible]
	-30	39.1	[illegible]		[illegible]	[illegible]	[illegible]
	-50	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]
	-50	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]
	-70	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]
	-70	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Air Cooled	[illegible]	[illegible]	[illegible]	Air Cooled	[illegible]	[illegible]	[illegible]
Tempered	[illegible]	11.7	[illegible]	Tempered	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]
	[illegible]	11.6	[illegible]		[illegible]	[illegible]	[illegible]
	[illegible]	6.3	[illegible]		[illegible]	[illegible]	[illegible]
	-70	8.1	[illegible]		[illegible]	[illegible]	[illegible]

*F - Fibrous [illegible]

Cr. - Crystalline [illegible]

[illegible]

Steel	Temp. °C	Impact Ft.Lbs.	Fracture	Steel	Temp. °C	Impact Ft.Lbs.	Fracture
3	+20	67.5	Fc	4	+20	39.1	Fc
Water Quenched	+20	50.9	Fc	Water Quenched	+20	51.9	Fc
Tempered	-10	60.1	Fc	Tempered	-10	35.8	FC
	-10	47.5	Fc		-10	33.4	FC
	-40	51.9	Fc		-40	15.5	Cfc
	-40	49.2	Fc		-40	18.1	Cfc
	-70	28.8	Cfc		-70	7.7	C
	-70	28.8	Cfc		-70	-	C
3	+20	59.1	Fc	4	+20	31.8	FC
Oil Quenched	+20	72.3	Fc	Oil Quenched	+20	41.5	FC
Tempered	-10	37.4	Cfc	Tempered	-10	33.4	Cf
	-10	24.3	Cfc		-10	17.4	Cfc
	-40	16.1	C		-40	9.4	C
	-40	23.6	Cfc		-40	9.4	C
	-70	20.1	C		-70	9.4	C
	-70	23.6	C		-70	7.2	C
3	+20	36.6	Cfc	4	+20	28.7	C
Air Cooled	+20	38.2	Cf	Air Cooled	+20	9.5	C
Tempered	-10	22.2	Cfc	Tempered	-10	22.2	C
	-10	10.6	C		-10	6.1	C
	-40	10.1	C		-40	22.2	C
	-40	13.6	C		-40	5.6	C
	-70	5.1	C		-70	7.2	C
	-70	7.7	C		-70	6.1	C

Steel	Temp. °C	Impact Ft.Lbs.	Fracture	Steel	Temp. °C	Impact Ft.Lbs.	Fracture
5	+20	37.4	Fo	6	+20	62.4	F
Water Quenched	+20	49.2	Fo	Water Quenched	+20	73.8	F
Tempered	-10	50.9	Fo	Tempered	-10	71.3	F
	-10	43.8	Fo		[illegible]	75.8	F
	-40	37.4	Fo		-40	73.8	F
	-40	36.6	Fo		-40	70.3	F
	-70	10.0	Cfo		-70	73.8	F
	-70	20.8	Cfo		-70	67.8	F
5	+20	50.1	Fo	6	+20	[illegible]	F
Oil Quenched	+20	45.8	Fo	Oil Quenched	+20	[illegible]	F
Tempered	-10	50.9	Fo	Tempered	-10	76.3	F
	-10	45.8	Fo		[illegible]	[illegible]	F
	-40	30.3	Fc		[illegible]	70.8	F
	-40	-			[illegible]	37.8	F
	-70	16.1	Cf		-70	[illegible]	[illegible]
	-70	-			-70	[illegible]	[illegible]
5	+20	25.6	Cfo	6	+20	54.6	[illegible]
Air Cooled	+20	30.3	Cfo	Air Cooled	+20	47.3	[illegible]
Tempered	-10	20.8	C	Tempered	-10	[illegible]	[illegible]
	-10	24.3	C		[illegible]	[illegible]	[illegible]
	-40	10.6	C		[illegible]	27.5	C
	-40	14.8	C		[illegible]	[illegible]	C
	-70	9.4	C		-70	[illegible]	C
	-70	12.9	C		[illegible]	[illegible]	C

Steel	Temp. °C	Impact Ft.Lbs.	Fracture	Steel	Temp. °C	Impact Ft.Lbs.	Fracture
7	+20	95.0	F	8	+20	99.0	F
Water Quenched	+20	–		Water Quenched	+20	105.0	F
Tempered	-10	87.0	F	Tempered	-10	83.1	Cfe
	-10	–			-10	44.1	Cfe
	-40	93.0	F		-40	35.8	C
	-40	–			-40	35.0	C
	-70	79.1	F		-70	24.3	C
	-70		F		-70	25.8	C
7	+20	106.0	F	8	+20	54.6	Cfe
Oil Quenched	+20	100.0	F	Oil Quenched	+20	58.2	Cfe
Tempered	-10	101.0	Fc	Tempered	-10	26.5	C
	-10	63.7	FC		-10	39.9	C
	-40	95.0	FC		-40	22.9	C
	-40	108.0	FC		-40	37.4	C
	-70	44.9	Cfe		-70	18.6	C
	-70	65.6	Cfe		-70	16.8	C
7	+20	56.4	Fc	8	+20	28.8	C
Air Cooled	+20	–		Air Cooled	+20	41.5	C
Tempered	-10	40.7	Cfe	Tempered	-10	25.8	C
	-10	60.9	Cfe		-10	9.4	C
	-40	28.8	C		-40	16.1	C
	-40	–			-40	19.4	C
	-70	11.8	C		-70	6.7	C
	-70	20.8	C		-70	6.1	C

~~RESTRICTED~~

TITLE: Armor, Development of a Fracture Test to Indicate the Degree of Hardening of Armor Steels Upon Quenching
AUTHOR(S): Hurlich, A.
ORIGINATING AGENCY: Watertown Arsenal, Watertown, Mass.
PUBLISHED BY: (Same)

ATI- 38795

DIVISION
(None)

ORIG. AGENCY NO.
R-710/532

PUBLISHING AGENCY NO.
(Same)

DATE	DOC. CLASS.	COUNTRY	LANGUAGE	PAGES	ILLUSTRATIONS
Aug '43	~~Restr.~~	U.S.	Eng.	47	photos, tables, graphs, drwg

ABSTRACT:

Experiments were conducted to devise a more useful fracture test to indicate the extent of quench hardneing of armor. It was found that the appearance of the fractured surface of the low alloy steels used for armor can be correlated with the degree of quench hardening, the microstructure, and the relative impact strength of the material. A fracture test has been devised that is applicable to production procedures and which is capable of being used to control the quality of heat treatment of armor components. Because the fracture test is more critical than the ballistic test, it is conceivable that the successful application of the fracture test may very well lead to reduced ballistic testing; a factor which would greatly expedite production of armor compounds.

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SECTION: Armor (5)

SUBJECT HEADINGS: Armor plate - Effect of heat treatment (11453.7); Steel - Heat treatment (90396.3)

ATI SHEET NO.: R-22-5-22

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DECEMBER 1948