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WATERTOWN ARSENAL LABORATORY

MEMORANDUM REPORT

NO. WAL 710/780

Metallurgical Examination of 4" and 5" Thick Rolled Homogeneous Armor Plates Submitted for Development by Jones & Laughlin Steel Corporation

BY

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DATE 26 September 1945

WATERTOWN ARSENAL
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WATERTOWN ARSENAL LABORATORY

MEMORANDUM REPORT NO. WAL 710/780

Final Report on Problem B-4.81

26 September 1945

Metallurgical Examination of 4" and 5" Thick Rolled Homogeneous Armor Plates Submitted for Development by Jones & Laughlin Steel Corporation

ABSTRACT

Two 4" and two 5" thick experimental rolled homogeneous plates were manufactured by Jones & Laughlin Steel Corporation, heat treated by Standard Steel Spring Company, and submitted to Aberdeen Proving Ground for ballistic testing. The 4" thick plates were tested in accordance with tests outlined in Specification AXS-488, Revision 1 and Tentative Specification AXS-488, Revision 3. The 5" thick plates were shock tested with 155 MM. AP M112 projectiles at 45° obliquity and tested for resistance to penetration with the 90 MM. AP T33 projectile at 0° obliquity in order to obtain development information. Metallurgical examination disclosed that the poor shock behavior of 4" thick plate No. 3B1 and the two 5" thick plates Nos. 3T1 and 3B1 was due to a combination of factors, namely, (1) temper embrittlement, caused by insufficiently fast cooling from the tempering temperature, and (2) inefficient quenching, resulting in incomplete quench hardening.

1. As requested by the Ordnance Research Center, Aberdeen[1], metallurgical examination has been completed on four sections of rolled homogeneous plates submitted for development by Jones & Laughlin Steel Corporation (heat treated by Standard Steel Spring Co.) designated as follows:

Thickness	Number
4"	3B1 and 3T1
5"	3B1 and 3T1

Ballistic tests were made at Aberdeen Proving Ground in order to determine the ballistic performance of the 4" thick plate under tests outlined in Specification AXS-488, Revision 1 and Tentative Specification AXS-488,

1. Wtn. 470.5/196 - APG. 470.5/1480 dated 24 April 1945.

Revision 3 and to obtain development information on the ballistic performance of the 5" thick plates; reference APG. Report No. Ar-16231, 3, 5, 6, 9 April 1945. The 4" thick plates passed the resistance to penetration tests according to Specification AXS-488, Revision 3. Plate No. 3B1 showed a 13" crack between two impacts as a result of the 155 MM. AP M112 shock test. Both 5" thick plates showed pronounced cracking under the 155 MM. AP M112 shock test. Ballistic data are summarized in Appendix A.

2. The metallurgical examination consisted of the following tests:

a. Chemical analyses of selected plates.

b. Fracture tests for steel soundness and fibre.

c. Brinell hardness surveys.

d. V-notch Charpy impact tests.

e. Microscopic examination.

f. Jominy hardenability tests.

3. The results of the metallurgical examinations are as follows:

a. Chemical Analyses. Chemical analyses of representative samples are given in Table I. These analyses are typical of those manufactured by Jones & Laughlin Steel Corporation.

b. Fracture Tests for Steel Soundness and Fibre. Fracture test blocks were properly notched, broken under the press, and rated for steel soundness and fibre. The results are given in Table II. Inspection of the fractures revealed that all plates had been well cross-rolled. Pronounced centerline laminations were present in all the plates except in the 4" thick plate No. 3B1. Since these laminations were contained within the central third of the section, the plates, although rated D1, are acceptable according to the fracture requirements of Specification AXS-488, Revision 3 and did not spall under the projectile-through-plate ballistic tests. It should be noted that the fracture ratings for steel soundness are different in the longitudinal than in the transverse sections of both 5" thick plates Nos. 3T1 and 3B1. Varying amounts of crystallinity were revealed in the fractures of all the four plates. Substantial amounts of crystallinity were detected in the fractures of the 4" thick plate No. 3T1 and the 5" thick plate No. 3T1. It has been proven on several occasions in the past that laminations tend to prevent a fracture specimen from breaking in a brittle manner. Further proof of this phenomenon is given by the results of the fracture tests of these plates. Correlation of the steel soundness of the fractures with the fibre fracture ratings reveals that the presence of laminations has greatly influenced the amount of crystallinity in the fractures. For example, in both fractures

of the 4" thick plate, No. 3T1, the material broke brittlely until deep center of section laminations were reached, at which point the fracture progressed in a more ductile manner, resulting in either partial crystallinity or complete fibre. To illustrate this further, in the cases of both 5" thick plates Nos. 3T1 and 3B1, the longitudinal fractures containing deep laminations were fibrous whereas transverse fractures which were free from laminations contained crystallinity.

c. Brinell Hardness Surveys. Brinell hardness readings were taken on the cross sections of the plates. All readings were equidistantly spaced throughout the sections tested. The results of these tests, which are tabulated in Table III, indicate that the hardness values determined across the sections of the 4" and 5" thick plates were fairly uniform. The two four-inch thick plates had an average Brinell hardness of 255-269 while the average Brinell hardness of the two five-inch thick plates was found to be 248-269.

d. V-Notch Charpy Impact Tests. V-notch impact specimens were machined from each plate at the regions just below the plate faces and adjacent to the center lines. The specimens were taken in the transverse direction (i.e., their long dimension was transverse to the major rolling direction) and notched parallel to the plate thickness. Specimens were also taken from the same locations of each plate after retempering 3/4" thick plate sections at 1200°F. (15 min. at temperature) followed by quenching in water. The results of these tests are given in Table IV. Impact tests show reduced impact values at -40°F. in almost every instance. In comparing the -40°F. values of the "as received" material with the -40°F. values of the material retempered and quenched from the temper in order to eliminate temper embrittlement, it has been found that the reduced impact values at -40°F. are due to a combination of factors, namely, incomplete quench hardening and temper embrittlement, caused by insufficiently rapid cooling from the tempering temperature. The factors for each plate are listed in Table IV. It is also revealed from the V-notch Charpy data that the 4" thick plate No. 3T1 had been quenched more efficiently at one face than at the other. The poor V-notch Charpy values at -40°F. obtained at the center of both 5" thick plates and the 4" thick plate No. 3B1 correlate with the poor behavior under ballistic shock. A similar correlation is not evident in the case of the 4" thick plate No. 3T1.

e. Microscopic Examination. Sulphide nonmetallic inclusions were segregated in the center of the cross sections of the 4" thick plates Nos. 3T1 and 3B1. This type of nonmetallic inclusion was scattered throughout the cross section of the 5" thick plates Nos. 3T1 and 3B1. Figure 1 illustrates the typical microstructure of the 4" and 5" thick plates. The area near the surface of the 4" thick plate No. 3T1 having the poor V-notch Charpy impact value (33.4 ft/lbs. at -40°F. after retempering to overcome temper embrittlement) has a microstructure consisting of ferrite and tempered bainite (Figure 1A). The opposite face of this plate which has higher V-notch Charpy impact properties (63.7 ft.lbs. at -40°F. after retempering) has a tempered martensitic structure. The microstructure of the central region of this plate consists of tempered bainite (Figure 1B). A similar microstructure to that shown in Figure 1B is present at the center of the 4" thick plate No. 3B1.

Microstructures at the centers of the 5" thick plates consist of tempered bainite (Figures 1C, 1D). The presence of more ferrite in the microstructure of plate No. 3T1 than exists in the microstructure of plate No. 3B1 explains why the -40°F. Charpy value of the retempered material of plate No. 3T1 is lower than the corresponding Charpy impact value of plate No. 3B1.

f. Jominy Hardenability. Standard Jominy hardenability tests were conducted on end-quenched bars machined from 4" thick plate No. 3T1 and the 5" thick plate No. 3T1. Company practice was used in austenitizing the bars prior to end quenching. This consisted of heating to 1625°F. for 1½ hours and holding at temperature for ½ hour. Hardness surveys were made on the end-quenched bars after removing .050" by careful grinding, after which the Jominy bars were polished, etched in picral, and examined microscopically. The results of the hardness surveys are shown in Figure 2. From the Jominy curves, only a slight drop in hardness is noted at 40/16" from the quenched end of the 4" plate Jominy bar and none at this location in the 5" plate Jominy bar. Microscopic examination, however, revealed the presence of 20% of bainite at the 40/16" location in the Jominy bar of the 4" plate No. 3T1. At this location in the Jominy bar of the 5" plate No. 3T1 the microstructure was entirely martensite. From correlations[1] made at Battelle between the cooling rates at various locations on Jominy bars with the cooling rates within the cross sections of plates, microscopic examination of the Jones & Laughlin Jominy bars indicates that the analyses are suitable for nearly complete quench hardening of the plate thicknesses for which they were employed. It is, therefore, evident from the re-drawn -40°C. impact values shown in Table IV that with the exception of the 4" plate, No. 3B1, all plates had not been quenched efficiently.

4. The results of this investigation can be summarized as follows:

a. Poor shock behavior of the 4" thick plate No. 3B1 and the two 5" thick plates Nos. 3T1 and 3B1 was due to a combination of factors, namely, (1) temper embrittlement, caused by insufficiently fast cooling from the tempering temperature, and (2) inefficient quenching, resulting in incomplete quench hardening.

b. Laminations in the material interfered with the accurate determination of fibre characteristics but by means of the V-notch Charpy impact tests (whose fractures were free from lamination) a correlation could be made between the impact toughness and the ballistic shock performance of the plates.

c. The steel soundness ratings of the plates varies from B to D1. No spalling occurred from the PTP impacts of both 75 MM. and 90 MM. AP projectiles against the 4" thick plate No. 3T1, the only plate of poor soundness that was given a projectile-through-plate test. It should be noted that

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

the laminations in this plate were contained wholly within the central third of the cross section.

M. Bolotsky

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APPROVED:

E. L. Reed.

E. L. REED
Research Metallurgist
Chief, Armor Section

TABLE I

Chemical Analyses

Plate No. As Marked	Thick-ness	C	Mn	Si	S	P	Ni	Cr	Mo	V	Cu	Al	B	Ti	Zr
3-T1	*4"	.29	1.80	.20	.019	.020	nil	.03	.49	nil	.055	.035	.0009	.04	nil
3-T1	*5"	.29	1.71	.19	.018	.018	nil	.03	.51	nil	.06	.03	.0007	.04	nil

*Note: The two 4" thick plates Nos. 3-T1 and 3B1 were rolled from heat No. J2243-3 while the two 5" thick plates Nos. 3-T1 and 3B1 were rolled from heat No. J2295-3.

TABLE II

Fracture Tests for Steel Soundness and Fibre

Plate No. As Marked		Thick-ness	Fracture Test for Steel Soundness	Fibre Fracture Test
3T1	Long.	4"	D1- one deep centerline lamination 1.8" from Face A.	Largely crystalline for 1" in from Face A. Partially crystalline in other half of fractured surface.
3T1	Trans.	4"	D1- Two deep center laminations each 1½" from a face.	Largely crystalline 1.2" from Face A, balance of fracture fibrous.
3B1	Long.	4"	B	Fibrous, except for small amount of crystallinity adjacent to center line in Face A half of the section.
3B1	Trans.	4"	C - one centerline lamination .8" long.	Completely fibrous.
3T1	Long.	5"	D1- three fairly deep laminations in middle 3/4" of section.	Fibrous except for trace of crystal-linity at center of section.
3T1	Trans.	5"	B - one 3/4" lamination at 1.3" from Face A.	Mostly crystalline in central third of section.
3B1	Long.	5"	D1- shallow laminations in center 1" of section.	Entirely fibrous.
3B1	Trans.	5"	B quality - two laminations about .4" long at center line.	Small amount of crystallinity in Face A half of section.

Note: Fibre characteristics were determined on fractured samples broken by the press. Plate surfaces were designated Face A and Face B for identification of test specimens machined from the plates.

TABLE III

Results of Brinell Hardness Surveys

Plate No. As Marked	Thickness	Cross Section Hardness	
		Range	Average
3T1	4"	255-269	262
3B1	4"	255-269	263
3T1	5"	248-269	263
3B1	5"	262-267	269

TABLE IV

Summary of the Results of V-Notch Charpy Impac

Plate No. As Marked	Thick-ness	Location	Ave. BHN	[1] V-Notch Charpy Impact Tests — As Received +70°F. Ft.Lbs.	+70°F. Fibre Rating	-40°F. Ft.Lbs.	-40°F. Fibre Rating	After a (15 m & Quenc Ft.Lb
3T1	4"	1/8" below Surface A		58.2	2,3F	23.6	2,3Cbf 3/4	33.1
3T1	4"	1/8" below Surface B	262	63.7	F	41.5	Cdf 1/8	63.
3T1	4"	Adjacent to center line		52.8	Fc trace	27.3	Cbf 2/3	35.
3T1	4"	Adjacent to center line		53.2	Fc trace	28.0	Cbf 2/3	31.
3B1	4"	1/8" below Surface A		59.1	F	35.8	Cbf 2/5	60.
3B1	4"	1/8" below Surface B	263	60.5	F	47.5	Cbf 1/3	66.
3B1	4"	Adjacent to center line		63.7	F	30.3	Cbf 2/3	56.
3B1	4"	Adjacent to center line		65.1	F	39.1	Cbf 2/5	51.
3T1	5"	3/4" below Surface A		66.6	F	56.4	Cbf trace	71.
3T1	5"	3/4" below Surface B	263	67.5	F	60.9	Cbf trace	71.
3T1	5"	Adjacent to center line		43.2	Cbf 3/5	11.8	Cbf 4/5	25.
3T1	5"	Adjacent to center line		57.7	Cbf 1/5	10.6	Cbf 4/5	25.
3B1	5"	3/4" below Surface A		76.2	F	70.3	F	81.
3B1	5"	3/4" below Surface B	269	68.4	F	52.8	Cdf 1/4	77.
3B1	5"	Adjacent to center line		66.1	F	29.5	Cbf 3/4	48.
3B1	5"	Adjacent to center line		65.6	F	29.9	Cbf 3/4	44.

Notes: 1. The notch in V-notch Charpy bar was parallel to final rolling direction of the plate
2. No laminations were evident in the fractures of the entire series of V-notch Charpy
3. F = fibrous, Cdf = dull crystalline patch surrounded by fibrous border, Cbf = bright
The fraction following the fracture symbol refers to estimated surface area which is

TABLE IV

...lts of V-Notch Charpy Impact Tests

...otch Charpy Impact Tests

...ceived -40°F. Ft.Lbs.	Fibre Rating	After Retempering at 1200°F. (15 min. at temp.) & Quenching in Water -40°F. Ft.Lbs.	Fibre Rating	Causes of Reduced Impact Values at -40°F.
23.6	2,3 Cbf 3/4	33.4	2,3 Cbf 2/3	Mostly incomplete quench hardening; some temper embrittlement.
41.5	Cdf ½	63.7	F	Temper embrittlement.
27.3	Cbf 2/3	35.8	Cbf 2/3	Mostly incomplete quench hardening; some temper embrittlement.
28.0	Cbf 2/3	31.8	Cbf 2/3	Same as above.
35.8	Cbf 2/5	60.9	F	Temper embrittlement.
47.5	Cbf 1/3	66.6	F	Same as above.
30.3	Cbf 2/3	56.4	F	Mostly temper embrittlement.
39.1	Cbf 2/5	51.0	Cbf 1/5	Same as above.
56.4	Cbf trace	71.3	F	Temper embrittlement.
60.9	Cbf trace	71.3	F	Same as above.
11.8	Cbf 4/5	25.4	Cbf 3/4	Mostly incomplete quench hardening; some temper embrittlement.
10.6	Cbf 4/5	25.0	Cbf 3/4	Same as above.
70.3	F	81.1	F	Temper embrittlement.
52.8	Cdf 1/4	77.6	F	Same as above.
29.5	Cbf 3/4	48.8	Cbf 3/5	Incomplete quench hardening plus temper embrittlement.
29.9	Cbf 3/4	44.1	Cbf 3/5	Same as above.

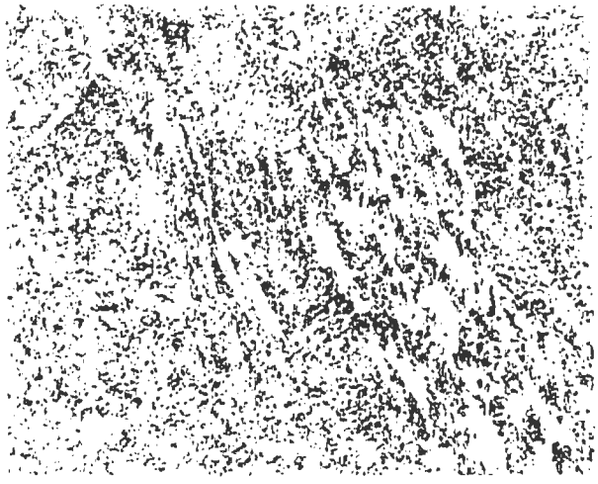
...ling direction of the plates.
... series of V-notch Charpy bars.
...ibrous border, Cbf = bright crystalline patch surrounded by fibrous border.
...ated surface area which is crystalline.

(2)

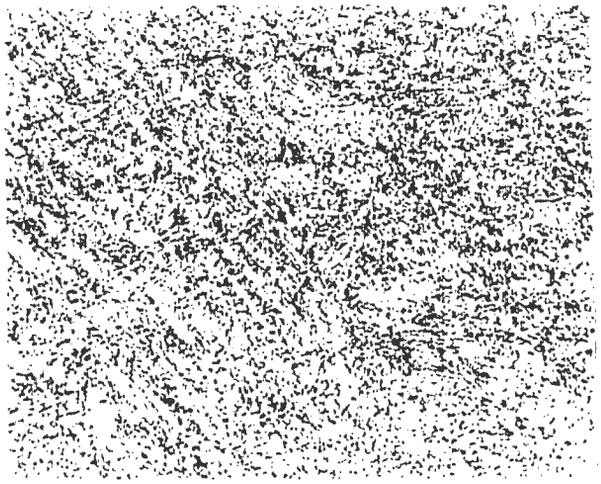
Microstructure of [illegible] Plates

All Photomicrographs Taken at X1000, After Etching with Nital

½" Plates

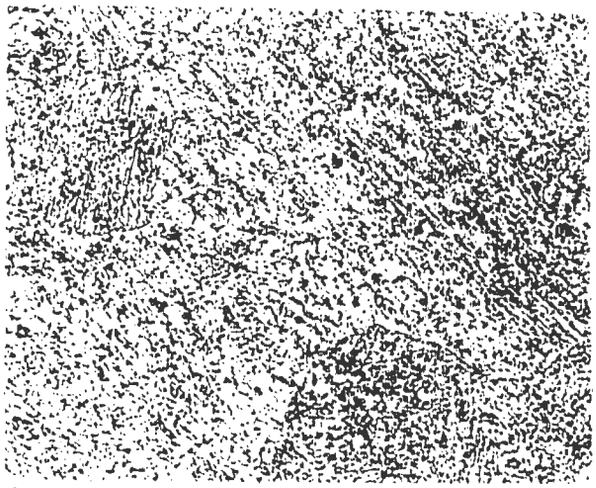


A [illegible]" Below Face A Plate 3T1
Tempered bainite containing much free ferrite.

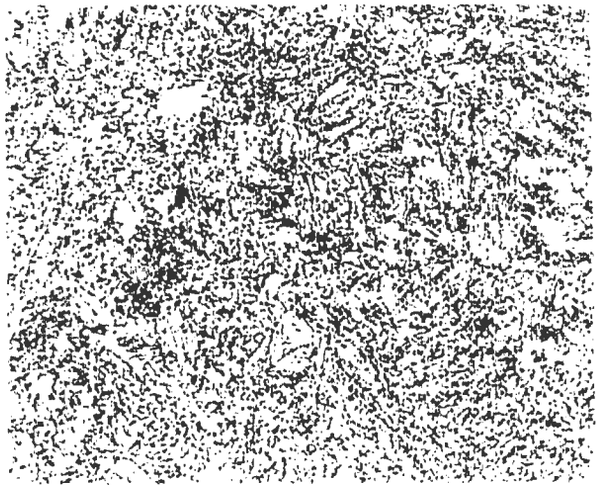


B Center of Section Plate 3B1
Tempered bainite. Center of section of 3T1 (½" plate) has a similar appearance.

5" Plates



C Center of Section Plate 3T1
Tempered bainite - more ferrite than in 3B1 (5" plate).



D Center of Section Plate 3B1
Tempered bainite.

FIGURE 1.

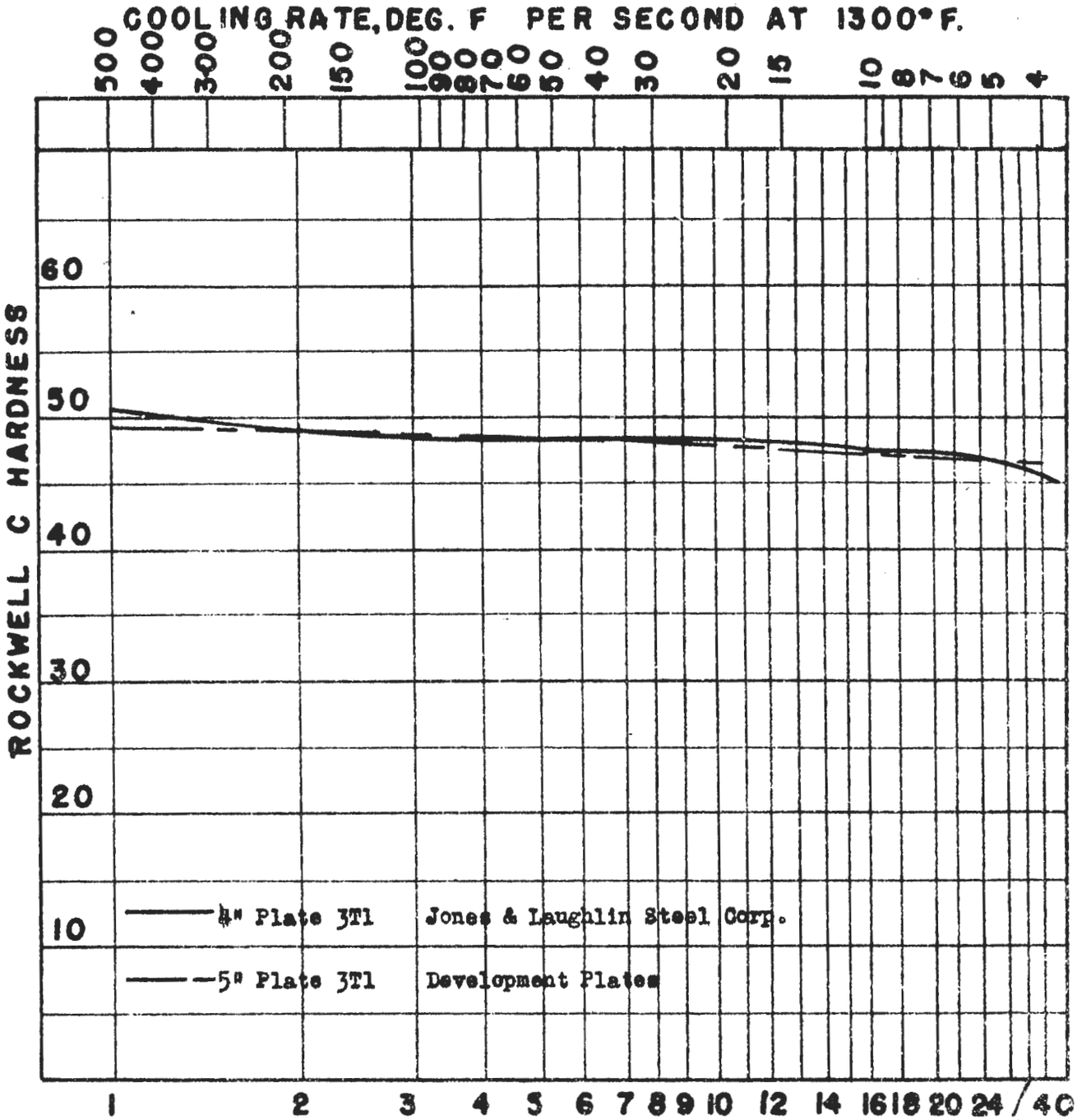


PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	B	Al	Ti	QUENCH TEMP	TIME	G.S.
														Rise	Hold
4" - 3T1	———	.29	1.80	.20	.019	.020	nil	.03	.49	.0009	.035	.04	1625° F	1½ hrs.	½ hr.
5" - 3T1	———	.29	1.71	.19	.018	.018	nil	.03	.51	.0007	.03	.04	"	"	"

FIGURE 2.

APPENDIX A

Ballistic Data

BALLISTIC DATA

(Data abstracted from APG Report No. AR-16231.)

4" Armor

Ballistic Limits and PTP Tests

Plate No.	155 MM. AP M112 30°	75 MM. AP M72 0°	75 MM. AP M72 0° PTP* 2000 f/s	90 MM. AP M77 0°	90 MM. AP T33 0°	90 MM. AP T33 0° PTP* 2000 f/s
3B1	1518, CP(M). Thru hole 6"x6"; exit dia. 8"x12" w/bs. 1442, CP(A), PP(P). 2-1/4"x1" opening on back. Plate cracked 13" between impacts, also from Rd. 1 to plate edge. 1480, CP(A), PP(P). 3½"x1-1/4" opening on back. Cracked from Rd. 2 toward edge of plate. BL(P,M) 1999 f/s.	1696(A)	4½"x5"	1705(M)		6" x 6"
3T1	1542, CP(P), CP(A). Projectile in plate 8"x8½" back opening. Petals off; no spalling. 1515, CP(A), PP(P). 1"x3" back opening. BL(P) 1529 f/s.	1694(A)	4"x4½"		1756(M)	5½"x6"

*Dimensions under PTP denote the exit diameter.
Note: 3B1 appeared to be crystalline.

5" Armor

Ballistic Limits

Plate No.	155 MM. AP M112 45°	90 MM. AP T33 0°
3B1	PP(A) at 2410 f/s. 17½" crack on back.	1902(A) 2036(M)
3T1	CP(P) at 2517 f/s. 33" crack on back. Opening on back; 11½x17½".	1841(A) 1994(M)

NOTE: Both plates appeared to be crystalline.