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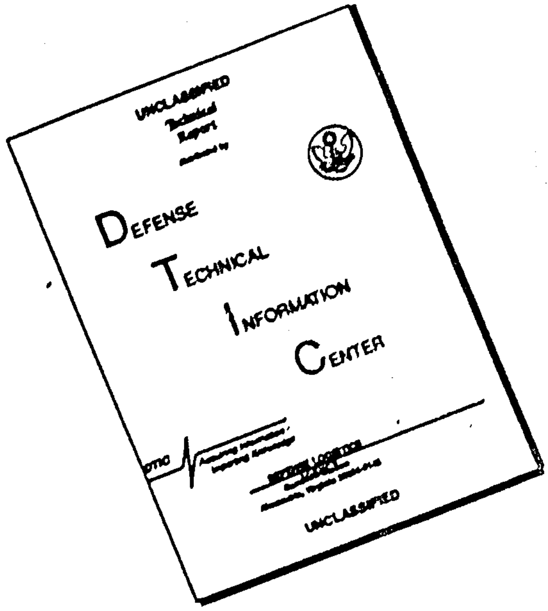

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ARMOR PLATE COMPOSITIONS

PROGRESS REPORT I

INDEXED

By

E. L. Reed

[redacted]

January [illegible], 1936

WATERTOWN ARSENAL

WATERTOWN, MASS.

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Report No. 710/46
Watertown Arsenal

January 21, 1936

Armor Plate Compositions

Progress Report I

Purpose

The purpose of this investigation was to select promising experimental armor plate compositions primarily for future ballistic study.

Conclusions

1. The following compositions have been selected for ballistic study on the basis of distinctive physical characteristics, that is, high yield strength/0.00% set, tensile strength and impact resistance in combination with good ductility.

A. Chemical Analysis

Ingot No.	C %	Mn %	Si %	Ni %	Cr %	Mo %	Va %
2 Standard	.47	.92	.39	-	1.19	.67	.22
2X	.38	.80	.35	-	1.21	.65	.21
3	.36	.69	.29	-	1.77	.52	.24
7X	.41	.67	.20	2.38	1.20	.60	.20
9X	.44	.60	.14	1.26	-	.68	.20
24	.40	.85	2.20	3.20	-	-	-
25	.42	.67	.28	-	-	1.04	.10
34	.40	.44	.15	3.88	-	.60	-

B. PHYSICAL PROPERTIES

No.	Y. S. 0.00% Set #/sq.in.	Tensile Strength #/sq.in.	True Breaking Strength #/sq.in.	Elongation in 2 inches		Reduction Of Area		Charpy Tension Impact Ft./lbs.	Brinell Hardness		Fracture Tensile Test Bars
				Static	Dynamic	Static	Dynamic		On Tensile Bars	On Charpy Bars	
2	206,000	227,500	307,000	12.9	11.5	43.6	43.0	315.4	418	460	90° break, smooth Star fracture
2X	201,000	218,500	316,000	14.3	14.0	50.6	49.2	326.9	418	430	Coarse Star fracture, internal cracks
3	204,000	225,500	308,000	12.1	13.5	47.0	49.0	324.3	444	460	Star fracture, internal cracks
7X	197,000	212,000	294,000	13.6	14.0	49.0	48.6	319.2	418	418	Coarse Star fracture, internal cracks
9X	195,000	215,000	288,000	14.3	14.1	51.0	52.5	311.7	387	418	Star fracture
24	188,000	207,000	286,000	13.6	15.0	46.5	46.3	342.1	402	418	Full shallow cup, pitted, nonmetallics at center of fracture
25	188,000	204,000	290,000	14.3	13.8	51.0	52.5	315.4	418	444	Star Fracture
34	193,000	239,500	320,000	12.1	11.6	44.6	44.1	307.9	444	444	Cup pitted.

2. Chemical analyses were made on samples taken from physical test bars and compared with ingot analyses. Segregation of 0.28% Nickel was found in Ingot No. 6; 0.18% Nickel, 0.16% Chromium in Ingot No. 8; 0.16% Molybdenum in Ingot No. 26; and 0.20% Molybdenum in Ingot No.27. The balance of check analyses were in close agreement with the ingot analyses - Table 4.

3. Brinell hardness determinations made on the tensile test and charpy tensile impact bars showed a hardness range of 364 - 460. In the original program, it was intended to work within a hardness range of 418 - 430 Brinell.

In some cases, the Brinell hardness of the tensile test and charpy tensile impact bars varied between 23 to 42 points.

4. When making a study of the effect of one or more additional elements on the physical properties of the basic composition, consideration of the following factors is necessary.

(a) Tensile tests based on one tensile test bar.

(b) The presence of non-metallics and internal cracks in the fractures of some tensile test bars.

(c) Variable drawing temperatures in the same series.

(d) Variation in hardness of tensile test and charpy tension impact test bars.

5. There was close agreement between static and dynamic percentage elongation and also, between the static and dynamic reduction of area values. Figures 1, 2.

6. A survey of the plot of physical properties of the series of steels indicates, in most cases, a close relationship between Yield Strength/0.00% set, Tensile Strength, Impact Values and Brinell Hardness. Some irregularities were evident in the percentage elongation and reduction curves.

7. Sand added to heat #30, and manganese sulphide inclusions resulting from the screw stock base in heat #31, did not promote increased ballistic resistance in samples of plate rolled therefrom.

No sand inclusions were found in the microstructure of heat #31.

8. The standard composition, with .38% Carbon, has the best combination of strength, ductility and toughness.

Introduction

A program was initiated by Capt. D. J. Martin, in 1934, covering development work on armor plate compositions. A study was made on the casting of small ingots of about 60 pounds, theirforging, heat treatment and testing for tensile and impact properties, and hardness. It is proposed that a few promising compositions will be rolled and treated to determine the ballistic properties.

Procedure

Casting

Sixty pound induction furnace heats of the following chemical specifications given in Table I, were cast in the form of 4" x 4" Ingots.

In view of the fact that the chemical analyses of Ingots Nos. 2, 4, 5, 6, 7, 9, 10, 13, 17, 18, 28, and 29 failed to meet the specifications in Table I, new heats were made which were designated 2X, 4X, 5X, 6X, 7X, 9X, 10X, 13X, 17X, 18X, 28X, and 29X.

Sand was intentionally added to Heat #30 in order to determine the effect of sand inclusions on ballistic properties.

Screw stock was used as a base in Heat #31 in order to determine the effect of manganese sulphide inclusions on ballistic properties.

Forging Ingots

A lot of ingots consisting of twelve or thirteen ingots were placed in a furnace and heated to forging heat, 1150 - 1185°C, in about three hours and held within this range for nearly 3 1/2 hours and forged to bars, 2 3/8 inches in diameter or to a 3:1 reduction. All forged bars were buried in cinders from forging temperature. Four lots of ingots were likewise heated and forged separately.

In all cases, as shown in Table II, difficulty was experienced in maintaining a uniform ingot temperature in the heating furnace.

TABLE I

CHEMICAL SPECIFICATIONS

No.	C	Mn	P	S	Si	Ni	Cr	Mo	Va	W
1 Std.	.45/.55	.40/.70	< .02	< .02	.15/.25	0	1.10/1.30	.60/.80	.20/.30	0
2 Std. low C	.35/.45	"	"	"	"	"	"	"	"	"
3	"	"	"	"	"	"	1.90/2.10	"	"	"
4	"	"	"	"	"	"	2.90/3.10	"	"	"
5	"	"	"	"	"	"	5.90/6.10	"	"	"
6	"	"	"	"	"	1.10/1.40	1.10/1.30	"	"	"
7	"	"	"	"	"	2.40/2.60	"	"	"	"
8	"	"	"	"	"	4.90/5.10	"	"	"	"
9	"	"	"	"	"	1.10/1.40	0	"	"	"
10	"	"	"	"	"	2.40/2.60	"	"	"	"
11	"	"	"	"	"	4.90/5.10	"	"	"	"
12	"	"	"	"	"	3.90/4.10	"	.25/.35	"	"
13	"	"	"	"	"	"	"	.45/.55	"	"
14	"	"	"	"	"	"	"	.55/.65	"	"
15	"	"	"	"	"	"	"	.85/.95	"	"

TABLE I (Cont'd)

CHEMICAL SPECIFICATIONS

No.		C	Mn	P	S	Si	Ni	Cr	Mo	Va	W
16		.35/.45	.40/.70	<.02	<.02	.15/.25	3.90/4.10	1.10/1.30	.25/.35	.20/.30	0
17		"	"	"	"	"	"	"	.45/.55	"	"
18		"	"	"	"	"	"	"	.55/.65	"	"
19		"	"	"	"	"	"	"	.85/.95	"	"
20		"	"	"	"	"	"	"	.55/.65	.08/.12	"
21		.48/.53	.30/.60	"	"	"	1.50/2.00	.90/1.25	0	0	"
22	Hadfield	.30/.40	.50/.80	"	"	"	3.20/3.30	.90/1.15	.55/.65	"	"
23	"	"	1.10/1.40	"	"	1.90/2.10	0	0	"	"	"
24		"	.60/.80	"	"	2.40/2.60	2.90/3.10	"	"	"	"
25		.35/.45	.50/.80	"	"	.15/.25	0	"	.90/1.10	.08/.12	"
26		"	"	"	"	"	"	"	1.90/2.10	"	"
27		"	"	"	"	"	"	"	2.90/3.10	"	"
28		"	"	"	"	"	"	"	3.90/4.10	"	"
29		"	"	"	"	"	"	"	4.90/5.10	"	"
30		"	"	"	"	"	2.25/2.75	"	.70/.80	0	"

TABLE I (Cont'd)

CHEMICAL SPECIFICATIONS

No.	C	Mn	P	S	Si	Ni	Cr	Mo	Va	W
31	.35/.45	.50/.80	<.02	<.02	.15/.25	2.25/2.75	0	.70/.80	0	0
32 Krupp	.30/.40	.40/.70	"	"	"	0	2.10/2.40	.45/.55	"	"
33 Navy	.35/.40	2.65/3.0	"	"	"	"	0	"	"	"
34 Navy	.30/.40	.30/.60	"	"	<.15	3.25/3.75	"	"	"	"
35 Sloan	.60/.70	.09/.17	"	"	.15/.25	1.90/2.1	1.9/2.1	0	"	"
36 Sloan	.60/.70	.09/.17	"	"	"	2.65/2.85	2.4/2.6	"	"	"
37 Midvale	.25/.35	.15/.30	"	"	"	3.5/4.0	1.75/2.0	"	"	"
38 Sloan	.30/.35	.30/.40	"	"	"	3.6/3.3	1.6/1.8	"	"	"
39	.35/.45	.50/.80	"	"	"	0	0	1.0	.10	.25
40	.35/.45	.50/.80	"	"	"	"	"	2.0	.10	.50

Heat Treatment

(1) Proper Hardening Temperature - In order to determine the proper quenching temperature, a series of one-half rounds (original forging 2 3/8" dia.) of each composition was quenched from 750, 780, 810, 840, 870, 900°C.

(2) Test Bars - Slugs 7/8 inch diameter and 3 1/8 inches long were heat treated according to the procedure outlined in Table III. The slugs were machined as follows:

(a) One .375 inch Tensile bar per heat.

(b) Two True Stress bars per heat.

Chemical Analyses

(a) Ingot - Samples were taken from the macro-section near the top of the ingot.

(b) Test Bars - Samples were taken from the True Stress bars after test.

Physical Tests

a. Yield Strength/0.00% set

b. Tensile Strength

c. True breaking Stress

d. Charpy Tension Impact

e. Brinell Hardness on test bars, - Tensile and Charpy bars

Results

Data on Forging the ingots is given in Table II.

TABLE 2

FORGING EXPERIMENTAL ARMOR PLATE INGOTS

4 x 4" Ingots Forged to 2 3/8 inch Rounds

Date of Forging	Ingot Position In Furnace	Ingot No.	Forging Data: Ingots Placed in Furn.	Forging Data: Ingots Reached Forg. Temp.	Forging Data: Started Forging	Forging Data: Temp. of Furnace	Forging Data: Forg.Fin. in one Heating	Forging Data: Forg.Fin. in two Heatings
10/16/34 Lot 1	Rear	19,22,10,24	7:30 A.M.	10 A.M. 1150-1175°C	1:30 P.M.	Hotter in rear of furnace 1120-1180°C from 10 A.M. to 2 P.M.	10X, 24, 22, 19, 27, 4X, 3	21, 2, 2X, 29, 11
	Middle	4X,27,3,2,29,11						
	Front	2X,21						
10/17/34 Lot 2	Rear	7X,13,25,20	7:30 A.M.	10 A.M. 1150-1175°C	1:30 P.M.	Hotter in rear of furnace 1165-1185°C last 1/2 hour		All Ingots
	Middle	9X,15,26,24,9,10						
	Front	14, 6X						
10/18/34 Lot 3	Rear	18,8,5X,17	7:30 A.M.	10:30 A.M. 1150-1175°C	1:30 P.M.	Hotter in rear, 1200°C at 2 P.M.		All Ingots. Ingots forged a bit hard.
	Middle	16,12,5,3,28,7						
	Front	4						
10/31/34 Lot 4	Rear	34,35,38,39,40, 18X	7:30 A.M.	10:30 A.M.	1:30 P.M.	All ingots appeared hotter than other lots.		
	Middle	13X,28X, 17X,33, 29X,32,36						
	Front	37						

TABLE 3

PROPER QUENCHING AND DRAWING TEMPERATURES ARMOR PLATE COMPOSITIONS

RD=Redrawn
RQ=Requench

			Quench	Draw
2	RD	900°C, 3 hrs, Fur. Cool;	840°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool
2X	RD	900°C, 3 hrs, Fur. Cool;	840°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool
3		900°C, 4 hrs, Fur. Cool;	840°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool
4X	RD	900°C, 3 hrs, Fur. Cool;	870°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool
5X		900°C, 3 hrs, Fur. Cool;	900°C, 2 hrs, Oil Quench;	900°F, 2 hrs, Air Cool
6X		900°C, 4 hrs, Fur. Cool;	780°C, 2 hrs, Air Cool;	850°F, 2 hrs, Fur. Cool
7X		900°C, 3 hrs, Fur. Cool;	780°C, 2 hrs, Air Cool;	850°F, 2 hrs, Fur. Cool
8		900°C, 3 hrs, Fur. Cool;	840°C, 2 hrs, Air Cool;	850°F, 2 hrs, Fur. Cool
9X		900°C, 3 hrs, Fur. Cool;	810°C, 2 hrs, Oil Quench;	900°F, 2 hrs, Air Cool
10X		900°C, 3 hrs, Fur. Cool;	780°C, 2 hrs, Oil Quench;	1000°F, 2 hrs, Air Cool
11		900°C, 3 hrs, Fur. Cool;	750°C, 2 hrs, Oil Quench;	1000°F, 2 hrs, Air Cool
12	RQ	900°C, 3 hrs, Fur. Cool;	780°C, 2 hrs, Oil Quench;	1000°F, 2 hrs, Air Cool
13X	RQ	900°C, 4 hrs, Fur. Cool;	780°C, 2 hrs, Oil Quench;	
14	RQ	900°C, 3 hrs, Fur. Cool;	780°C, 2 hrs, Oil Quench;	1000°F, 2 hrs, Air Cool
15		900°C, 3 hrs, Fur. Cool;	780°C, 2 hrs, Oil Quench;	1000°F, 2 hrs, Air Cool
16		900°C, 3 hrs, Fur. Cool;	780°C, 2 hrs, Oil Quench;	900°F, 2 hrs, Air Cool
17X		900°C, 4 hrs, Fur. Cool;	840°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool
18X		900°C, 4 hrs, Fur. Cool;	840°C, 2 hrs, Air Cool;	850°F, 2 hrs, Fur. Cool
19	RD	900°C, 3 hrs, Fur. Cool;	840°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool
20		900°C, 3 hrs, Fur. Cool;	780°C, 2 hrs, Oil Quench;	1000°F, 2 hrs, Air Cool
21		900°C, 3 hrs, Fur. Cool;	840°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool
22		900°C, 3 hrs, Fur. Cool;	870°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool
23	RD	900°C, 4 hrs, Fur. Cool;	870°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool
24	RQ	900°C, 4 hrs, Fur. Cool;	780°C, 2 hrs, Oil Quench;	900°F, 2 hrs, Air Cool
25		900°C, 3 hrs, Fur. Cool;	820°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool
26		900°C, 3 hrs, Fur. Cool;	870°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool
27		900°C, 3 hrs, Fur. Cool;	870°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool
28X		900°C, 4 hrs, Fur. Cool;	840°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool

TABLE 3 (Cont'd)

PROPER QUENCHING AND DRAWING TEMPERATURES ARMOR PLATE COMPOSITIONS

RD=Redrawn
RQ=Requench

			Quench	Draw
29X		900°C, 4 hrs, Fur. Cool;	870°C, 2 hrs, Oil Quench;	
32		900°C, 4 hrs, Fur. Cool;	900°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool
33		900°C, 4 hrs, Fur. Cool;	780°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool
34	RD	900°C, 4 hrs, Fur. Cool;	810°C, 2 hrs, Oil Quench;	900°F, 2 hrs, Air Cool
35	RQ	900°C, 4 hrs, Fur. Cool;	780°C, 2 hrs, Oil Quench;	1000°F, 2 hrs, Air Cool
36	RD	900°C, 4 hrs, Fur. Cool;	840°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool
37	RQ	900°C, 4 hrs, Fur. Cool;	780°C, 2 hrs, Oil Quench;	900°F, 2 hrs, Air Cool
38	RQ	900°C, 4 hrs, Fur. Cool;	810°C, 2 hrs, Oil Quench;	900°F, 2 hrs, Air Cool
39		900°C, 4 hrs, Fur. Cool;	820°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool
40		900°C, 4 hrs, Fur. Cool;	870°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool

REQUENCH

12	780°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool
13	780°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool
14	780°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool
35	780°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool
24	780°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool
35	780°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool
37	780°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool
34	810°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool
38	810°C, 2 hrs, Oil Quench;	850°F, 2 hrs, Air Cool

TABLE 3 (Cont'd)

PROPER QUENCHING AND DRAWING TEMPERATURES
ARMOR PLATE COMPOSITIONS

REDRAW

	Draw
2	900°F, 2 hrs, Air Cool
2X	900°F, 2 hrs, Air Cool
4X	900°F, 2 hrs, Air Cool
19	900°F, 2 hrs, Air Cool
23	900°F, 2 hrs, Air Cool
36	900°F, 2 hrs, Air Cool
34	800°F, 2 hrs, Air Cool
34	500°F, 2 hrs, Air Cool

Heat Treatment

The proper hardening temperatures of the series of alloy steels as determined in Figures 3 to 12 inclusive, are given in Table 3.

In some cases it was necessary to requench and redraw in order to obtain the desired hardness.

The slugs were heat treated first and later machined into tensile test and charpy impact bars.

Chemical Analysis

Chemical analyses of the ingots and check analyses made on the test bars are shown in Table 4.

Physical Properties

Physical properties of the series of steels are given in Table 4 and plotted in order of increasing the percentage of one or more elements in Figures 1 and 2.

A classification of the compositions having the best combination of strength, ductility and toughness is given in Table 5.

An analysis of the classification of armor plate compositions with best combination of strength, ductility and toughness is given in Table 6.

Priority ratings are given in Table 6; the selected compositions for ballistic study based upon the position of the composition in Table 5.

Ballistic Tests on Rolled Plate from Ingots 30, 31

1. Ingot 30 - 2.32% Ni, 1.00% Mo - Sand was intentionally added to this melt in order to determine the ballistic properties of steel containing sand inclusions. No sand inclusions were found in the rolled plate. Cracks were evident on the back of the 3/8" thick plate when tested with the Cal. .30, 2100 f/s. A.P. ammunition at a distance of 100 yards.

2. Ingot 31 - 2.28% Ni, .99% Mo - Screw Stock base. The object of this test was to determine the ballistic properties of high sulphur alloy steel. The 3/8" thick plate was not penetrated when tested with Cal. .30, 1700 f/s A.P. ammunition at a distance of 100 yards.

Discussion

When interpreting the graphical presentation of data on physical properties, as shown in Figures 1 and 2, several factors should be considered such as, segregation in the steel as revealed by fracture study, and the heat treatment of the test bars. It was originally intended to draw the test samples to a Brinell hardness, 418-430. Actually, a range of 364-460 Brinell hardness was determined on the test bars from which the physical data in Table 4 was calculated.

Ingot 2, Standard Composition .47% C, .92% Mn, 1.19% Cr, .67% Mo, .22% Va.

TABLE 5

CLASSIFICATION OF ARMOR PLATE COMPOSITIONS WITH BEST COMBINATION OF STRENGTH, DUCTILITY AND TOUGHNESS

Ingot No.	Y.S./0.00% set Lbs/sq.in.	Ingot No.	Tensile Strength #/sq.in.	Ingot No.	True Brk. Stress #/sq.in.	Ingot No.	% Elon. in 2" Stat.	% Elon. in 2" Dyn.	Ingot No.	Red. of Area % Stat.	Red. of Area % Dyn.	Ingot No.	Charpy Impact Ft.Lbs.
2	206,000	34	239,500	34	320,000	11	16.4	15.4	15	53.7	50.2	4X	342.1
3	204,000	4X	237,500	2X	316,000	15	16.4	15.2	38	52.5	52.5	24	342.1
2X	201,000	2	227,500	4X	315,000	38	15.0	15.9	9X	51.0	52.5	19	338.3
7X	197,000	8	226,000	19	310,000	40	15.0	13.8	25	51.0	52.5	8	334.4
13X	197,000	3	225,500	3	308,000	12	14.3	14.9	11	51.0	51.7	2X	326.9
14	196,000	28X	225,500	2	307,000	10X	14.3	14.6	10X	51.0	49.6	3	324.3
26	196,000	19	222,000	8	306,000	9X	14.3	14.1	12	50.6	51.9	6X	323.0
9X	195,000	33	219,000	28	295,000	2X	14.3	14.0	2X	50.6	49.2	10X	323.0
34	193,000	2X	218,500	7X	294,000	25	14.3	13.8	39	49.3	51.7	7X	319.2
28X	192,000	26	217,000	10X	290,000	19	14.3	13.3	37	49.0	51.5	11	319.2
36	191,000	9X	215,000	15	290,000	8	14.3	12.5	14	49.8	49.8	15	319.2
35	190,000	7X	212,000	25	290,000	24	13.6	15.0	7X	49.0	48.6	17X	319.2
24	188,000	35	210,000	33	290,000	39	13.6	15.2	3	47.0	49.0	2	315.4
25	188,000	36	210,000	9X	288,000	37	13.6	14.2	40	47.0	46.5	25	315.4
15	187,000	24	207,000	26	288,000	27	13.6	14.1	13X	46.5	49.9	33	315.4
10X	186,000	25	204,000	24	286,000	7X	13.6	14.0	19	-	45.5	9X	311.7
11	186,000	14	200,000	14	281,000	17X	13.6	14.0	24	46.5	46.3	26	311.7
4X	185,000	17X	200,000	17X	277,000	14	12.9	14.8	27	45.3	47.8	28X	311.7
33	180,000	6X	199,500	35	276,000	35	12.9	12.3	17	44.9	46.5	36	311.7
12	179,000	13X	198,000	13X	272,000	4X	12.9	11.9	34	44.6	44.1	34	307.9
19	179,000	15	195,500	6X	271,000	2	12.9	11.5	2	43.6	43.0	14	304.2
6X	175,000	10X	194,000	11	270,000	3	12.1	13.5	26	43.2	44.4	38	300.5
8	170,000	11	192,000	38	270,000	13X	12.1	12.9	35	43.2	43.8	39	300.5
17X	170,000	37	188,500	36	268,000	26	12.1	12.3	28X	38.9	43.4	12	296.8
37	156,000	38	188,500	12	262,000	33	12.1	11.9	6X	41.9	46.3	27	296.8
39	151,000	27	187,000	39	262,000	34	12.1	11.6	8	40.7	41.9	35	296.8
38	149,000	40	184,500	37	259,000	6X	11.4	13.3	33	38.9	42.1	37	293.1
27	[illegible]	12	183,000	27	252,000	36	11.4	12.7	4X	38.0	42.1	40	285.7
[illegible]	[illegible]	39	182,500	40	250,000	28X	11.4	[illegible]	36	35.8	39.5	13X	278.4

TABLE 6

PRIORITY RATING
of
SELECTED ARMOR PLATE COMPOSITIONS

Ingot No.	Yield Strength 0.00% Set Lbs./sq.in.	Tensile Strength Lbs/sq.in.	True Breaking Stress Lbs./sq.in.	Percentage Elongation in 2 inch Static	Reduction Of Area %	Charpy Impact Ft. Lbs.
2	1	3	6	21	21	13
2X	3	9	2	3	8	5
3	2	5	5	22	13	6
7X	4	12	9	16	12	9
9X	8	11	14	7	3	16
24	13	15	16	12	17	2
25	14	16	12	9	4	14
34	9	1	1	26	20	20

It is possible that greater ductility and resistance to impact would have been obtained with a drawing temperature higher than 900°F. Also, perhaps the high manganese content may have been responsible for the low ductility.

<u>Ingot 2X, Same as Standard Except</u> .38% C, .80% Mn, 1.21% Cr, .65% Mo, .21% Va.

Lowering the carbon and manganese apparently increases the ductility and slightly lowers the tensile strength and proportional limit, with the same drawing temperature 900°F. Internal cracks were evident in the fractured tensile bar.

<u>Ingots 3, 4X</u>, <u>Same as 2X, except increase in Chromium</u>,

3	-	1.77% Cr
4X	-	2.82% Cr

Increase in chromium raises the tensile strength, Brinell hardness, impact properties slightly, lowers the yield strength/0.00% set percentage elongation and reduction of area. Test bars from Ingot 3 were drawn at 850°F, while those from ingot 4X were drawn at 900°F. Internal cracks were evident in the fractured tensile test bars from ingot 3. Ingot 3 is a promising composition.

<u>Ingots 6X, 7X, 8</u>, <u>Same as 2X, except increase in Nickel</u>

6X	-	1.22% Ni
7X	-	2.38% Ni
8	-	4.60% Ni

With an addition of 1.22% Nickel, a decrease in the physical properties is noted. With an increase in Nickel up to 4.6% there is a noticeable increase in tensile strength, Brinell hardness, and percentage elongation. Increasing Nickel from 2.38 to 4.60% lowers the Yield Strength/0.00% set and reduction of Area. Internal cracks were found in test bars, Ingot 7 and, nonmetallics were present in test bars, Ingot 8. This fact may account for the irregularities in physical properties of this high nickel steel. Ingot 7 is a promising composition.

Ingots 9X, 10X, 11, Same as 6, 7X, 8 except no Chromium

9X	No Cr,	1.26% Ni,	.68% Mo,	.20% Va
10X	" "	2.36% Ni,	.61% Mo,	.21% Va
11	" "	4.55% Ni,	.60% Mo,	.23% Va

With the addition of Nickel alone, no marked improvement in the physical properties is apparent, save ductility which approaches that of the standard composition 2X with low carbon.

Ingot 9 is a promising composition.

Ingots 12, 13X, 14, 15, Same as 2X, No Chromium with 3.75% Nickel and .27% Mo, .49% Mo, .65% Mo, .88% Mo.

These nickel-molybdenum steels, according to the prescribed heat treatment, do not have exceptional physical properties.

Ingots 17X, 19, Same as 13X, 15, plus 1.20% Chromium

Chromium increases the tensile strength and impact properties as compared to the physical properties of Ingots 12, 13X, 14, and 15. Nonmetallics were present in the fracture of test bars from Ingot #19.

Ingot 24, Nickel Silicon 3.2% Nickel, 2.8% Silicon

This is a promising composition.

Ingots 25, 26, 27, 28X, .45% Carbon, 0.10% Vanadium with 1.0% Mo, 2.0% Mo, 3% Mo, 4% Mo

With the exception of Ingot 25, the physical properties of samples from Ingots 26, 27 and 28, are not exceptional when compared with those of Ingots 12, 13X, 14 and 15, containing 3.75% Nickel and increasing Molybdenum .27, .49, .65 and .88% Mo.

Three per cent Molybdenum, Ingot 27, has low yield strength/0.00% set and tensile strength, although the ductility is relatively good. Four per cent Molybdenum, Ingot 28X, increases the strength but decreases the ductility when compared with the three per cent Molybdenum steel. Nonmetallics were present in the fracture of test bars from Ingot 28X.

Ingot 25, - 1% Molybdenum, .10% Vanadium is a promising composition.

Ingot 33, 34, Navy Ingot 33, 2.4% Mn, .6% Mo;
Ingot 34, 4% Ni, .6% Mo

The Nickel-Molybdenum Steel, No. 34 has excellent physical properties and approaches those of the standard composition. The physical properties of Ingot No. 33 are relatively good. Nonmetallics were present in fractured samples of Ingot No. 33.

Ingot 35, 36, (Sloan); Ingot 35 - .56% C, 2% Ni, 2% Cr;
Ingot 36 - .61% C, 2% Ni, 2.6% Cr

The physical properties of these steels are not exceptional. Nonmetallics were present in fractured samples of Ingot 35.

Ingot 37, Midvale, 4% Ni, 2% Cr

The physical properties of this composition when heat treated according to the present practice, are inferior to those of the standard composition.

Ingot 38, (Sloan), .28% C, 4% Ni, 2% Cr

This composition has low strength but good ductility as compared with the physical properties of the standard composition.

Ingots 39, 40, Same as Ingots 25, 26 plus .16 - .32% W

Ingot 39 - .45% C, 1.0% Mo, .10% Va, .16% W

Ingot 40 - .45% C, 2.0% Mo, .10% Va, .32% W

Tungsten in the amounts noted above in combination with moderately high molybdenum and 0.10% Vanadium apparently does not increase the strength. On the other hand, the ductility is good.

Ballistic Tests on Rolled Plate from Ingots 30, 31

1. Ingot 30, Ni 2.32%, Mo 1.00%, Sand added.

No sand was present in the rolled plate, therefore, no definite results were obtained.

2. Ingot 31, Ni 2.28%, Mo .99%, Screwstock base.

A 3/8" thick plate with high sulphur cracked slightly at area of impact when tested with Cal. .30 1700 f/s velocity A.P. ammunition.

Chemical Composition

Check analyses indicated that some segregation of nickel and molybdenum was present in the ingots containing high percentages of these elements, - to illustrate, ingots 6, 8, 26, and 27.

The standard composition, Ingot No. 2X with .38% carbon, has the best combination of strength, ductility and toughness.

Recommendations

It is recommended that continuation on the development of experimental armor plate compositions be conducted as follows:

1. Study of the Macrostructures of the Ingots as cast.
2. Study of the Microstructures of the test bars, subjected to tensile test.

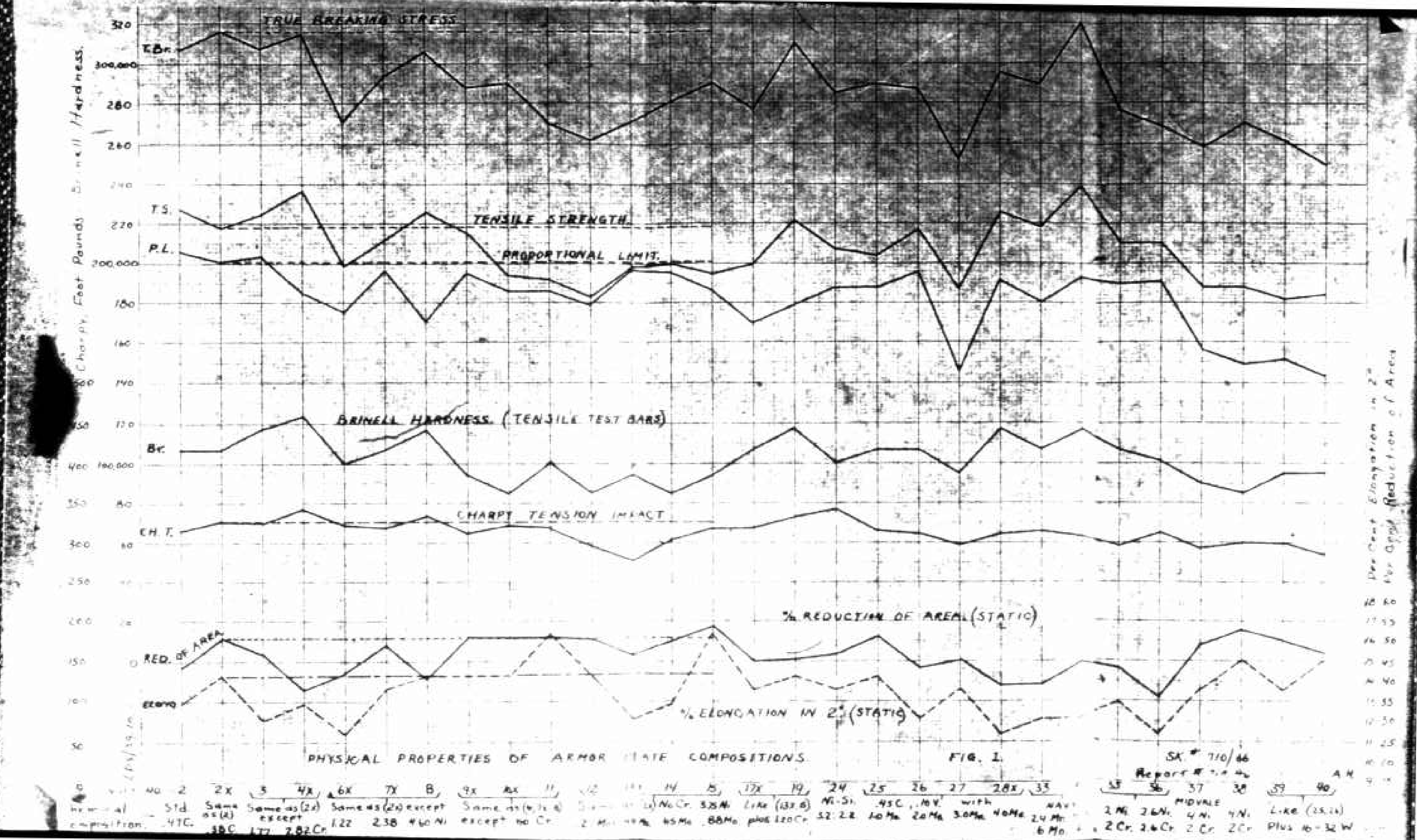
3. Completion of the Physical tests on Ingots 5X, 16, 18X, 20, 21, 22, 23, 29X, and 32.
4. Determine impact values with 0.1 inch notch bar under normal and high speed.
5. Study of the Physical properties of some of the well known compositions, such as Nickel-Molybdenum, hardened and drawn to Brinell hardness of 430.
6. Casting of 500 lb. induction heats of compositions, 2, 2X, 3, 7X, 9X, 24, 25, 34. These ingots to be rolled into plate at the plant of Henry Disston & Sons, Inc.
7. Ballistic tests to be made at Watertown Arsenal and Aberdeen Proving Ground on heat treated plate.
8. Correlation between ballistic and physical properties to be made.

Respectfully submitted,

E. L. Reed

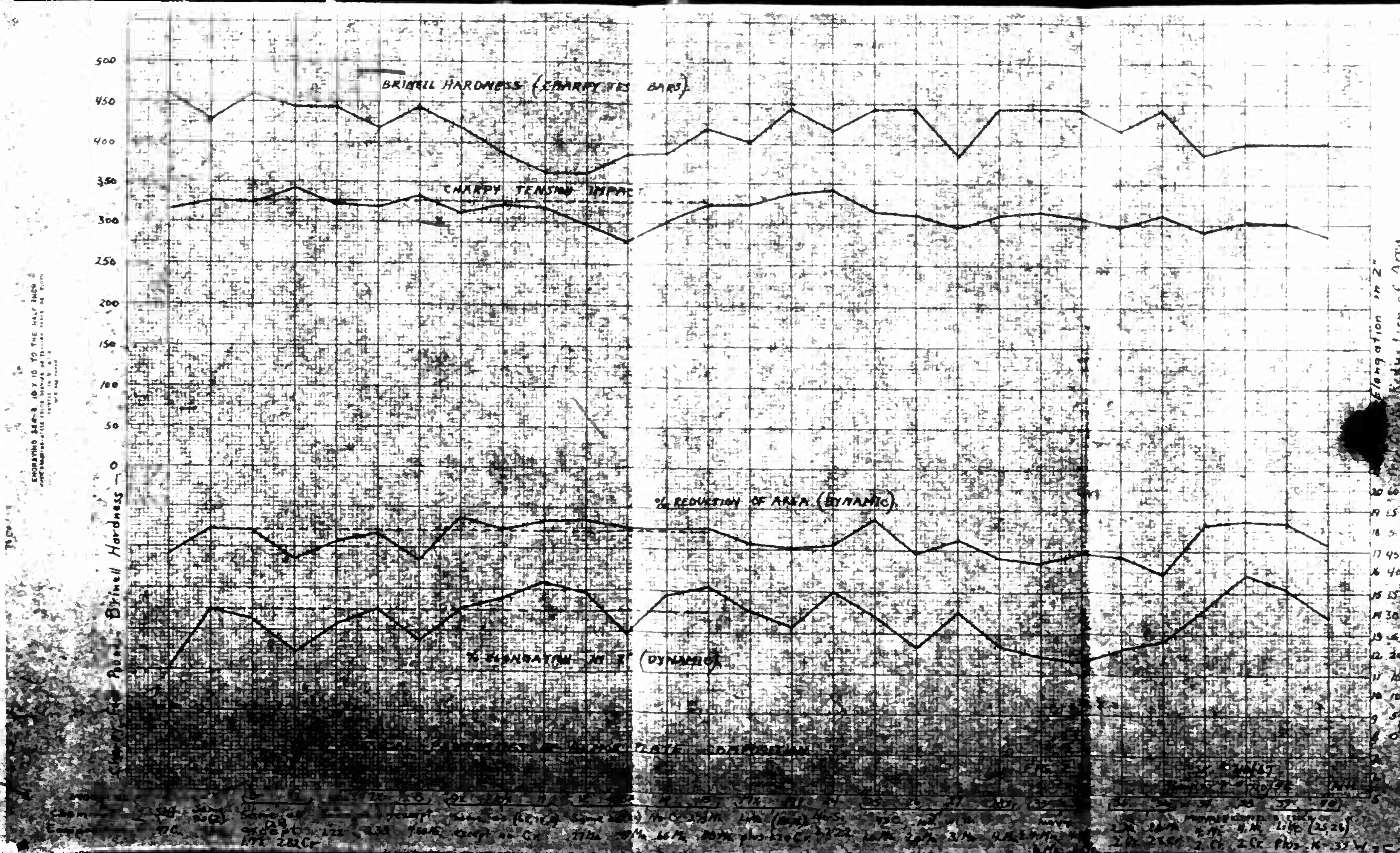
E. L. Reed,
Research Metallurgist

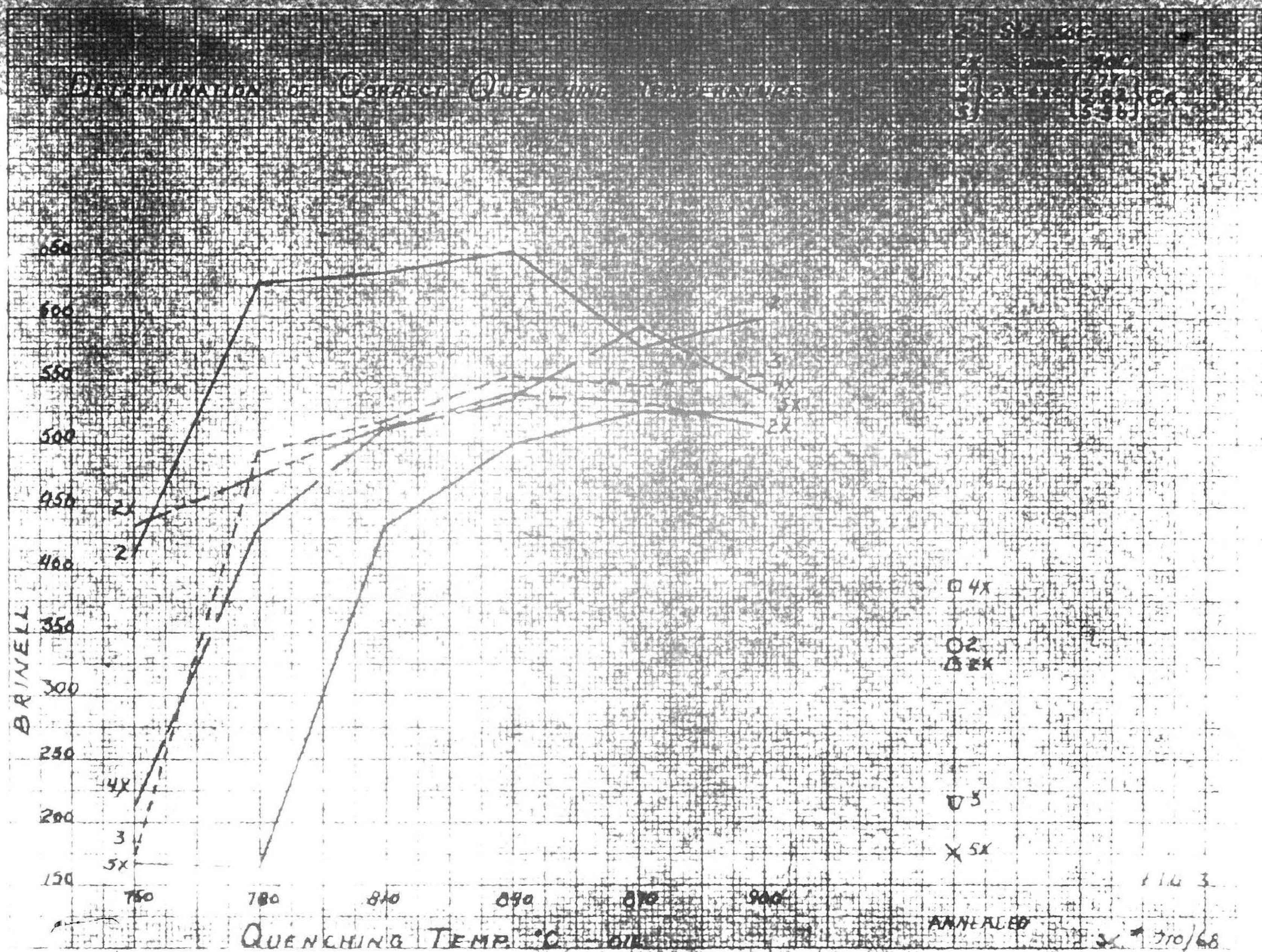
References: Report No. 322/3, dated May 8, 1935.

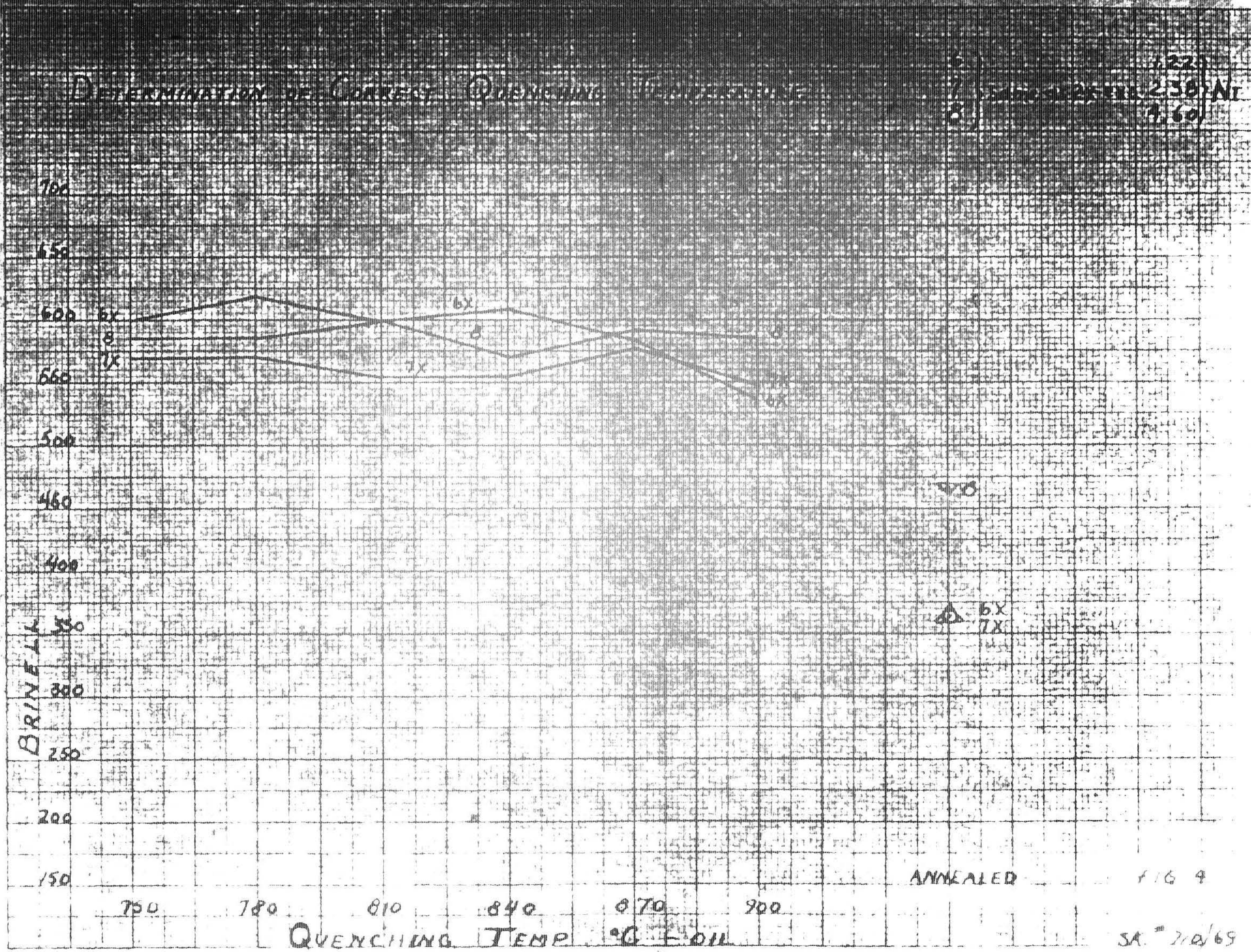


PHYSICAL PROPERTIES OF ARMOR PLATE COMPOSITIONS

FIG. 1


BRINELL HARDNESS (CHARPY TEST BARS)
CHARPY TENSION IMPACT
% REDUCTION OF AREA (DYNAMIC)
% ELONGATION IN 2" (DYNAMIC)
Brinell Hardness
Elongation in 2"
500
450
400
350
300
250
200
150
100
50
0


Determination of Correct Quenching Temperature
BRINELL
650
600
550
500
450
400
350
300
250
200
150
2
2X
4X
3
5X
750
780
810
840
870
900
Quenching Temp °C — Oil
□ 4X
○ 2
△ 2X
▽ 3
X 5X
ANNEALED
FIG 3


Determination of Correct Quenching
6
7
8
.22
2.30
4.60
Ni
700
650
600
550
500
450
400
350
300
250
200
150
BRINELL
6X
8
7X
ANNEALED
750
780
810
840
870
900
QUENCHING TEMP °C - OIL
FIG 4
SA. 7/2/69

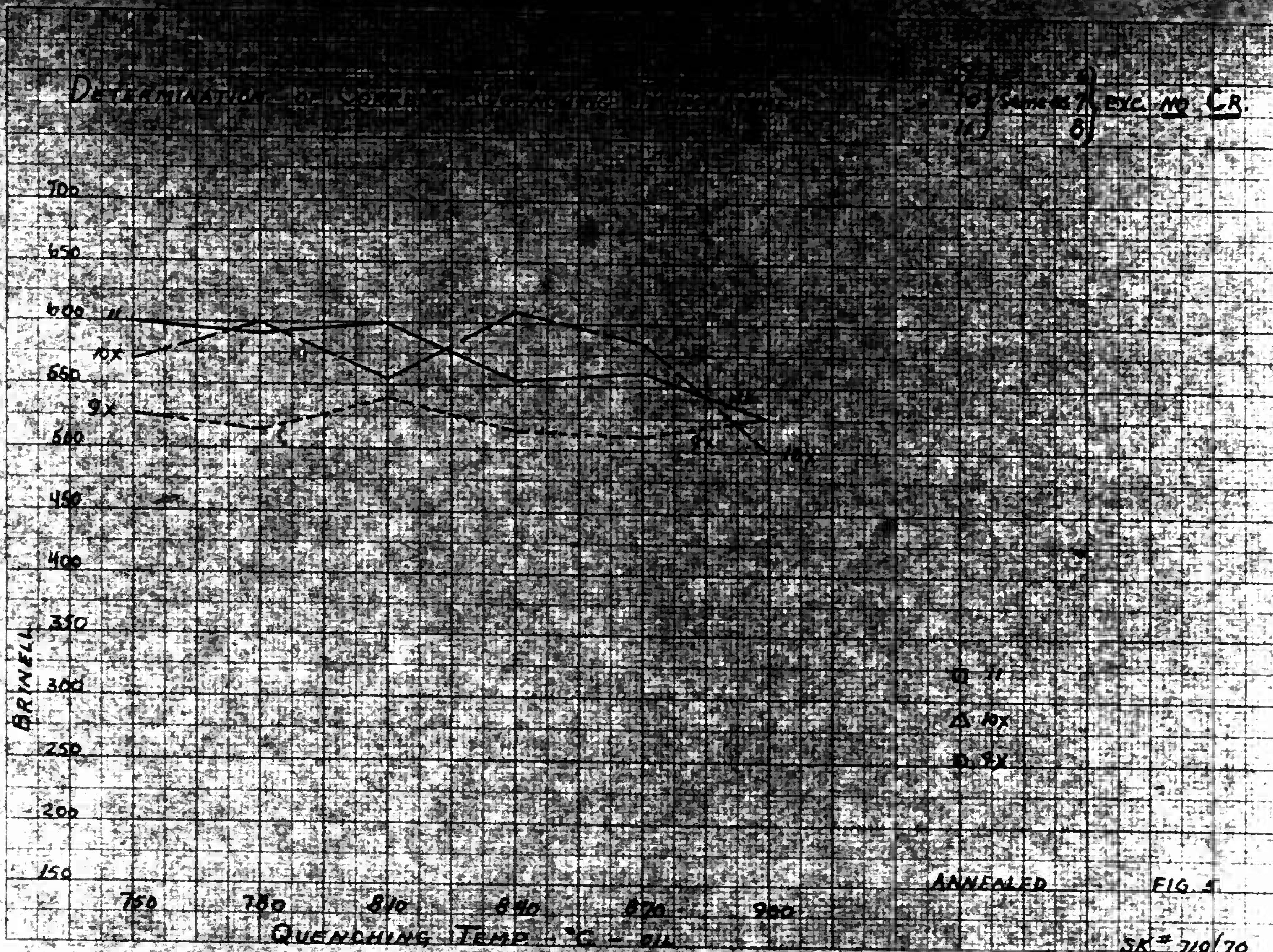
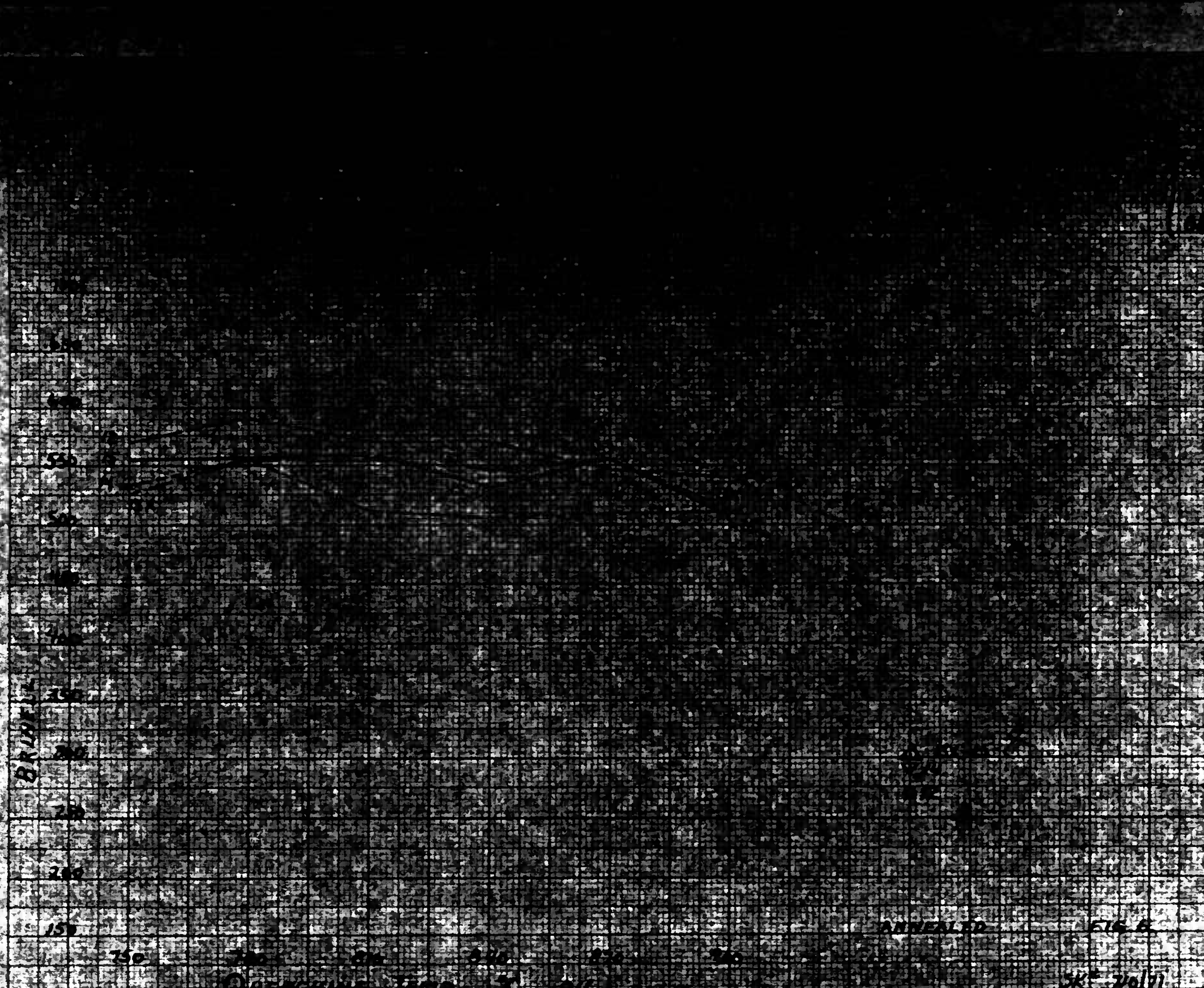


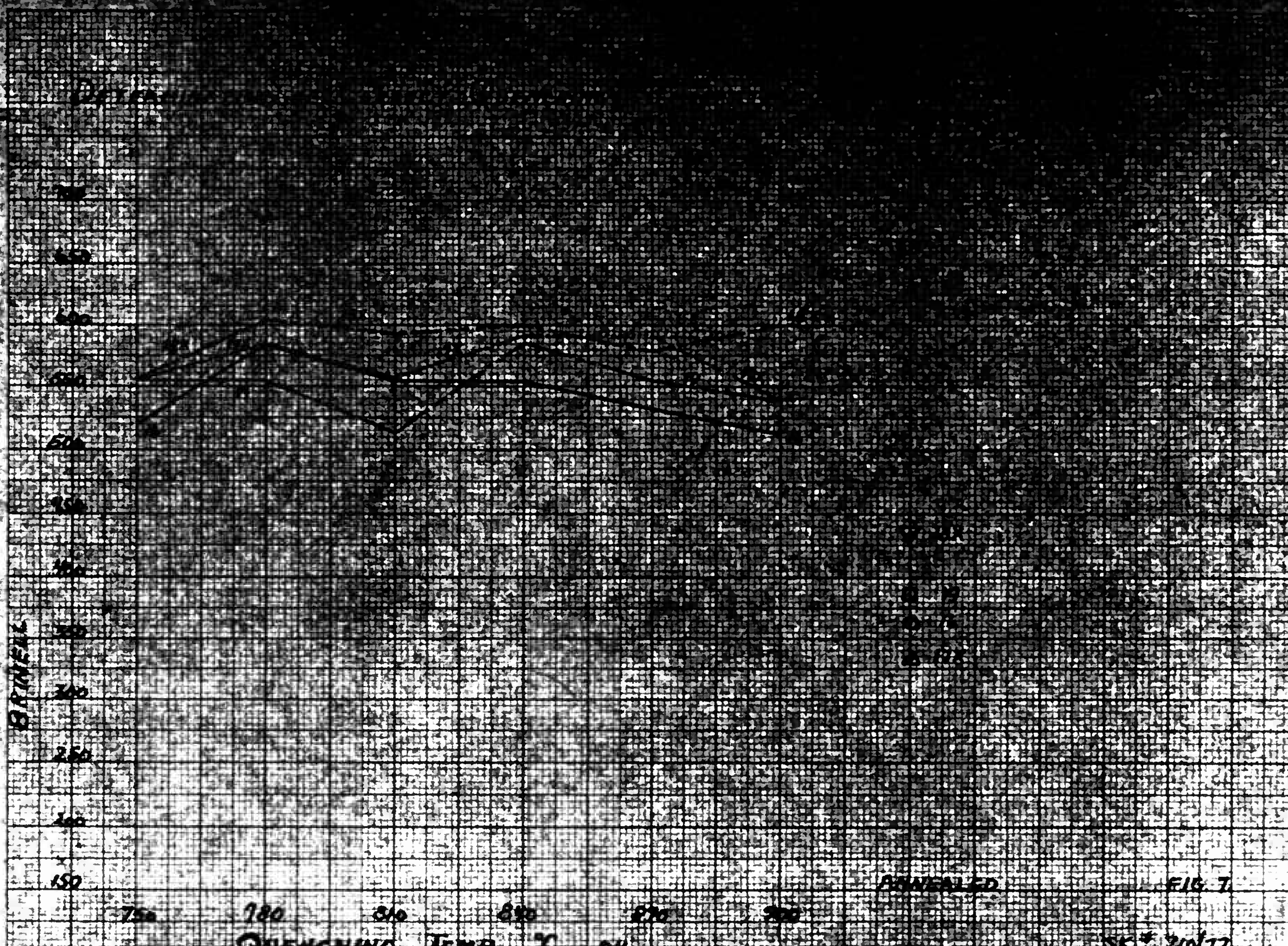
FIG. 5

SK # 710/70

Report # 10



Report # 710/46



Report # 710/46

Determination of Correct Quenching Temperature

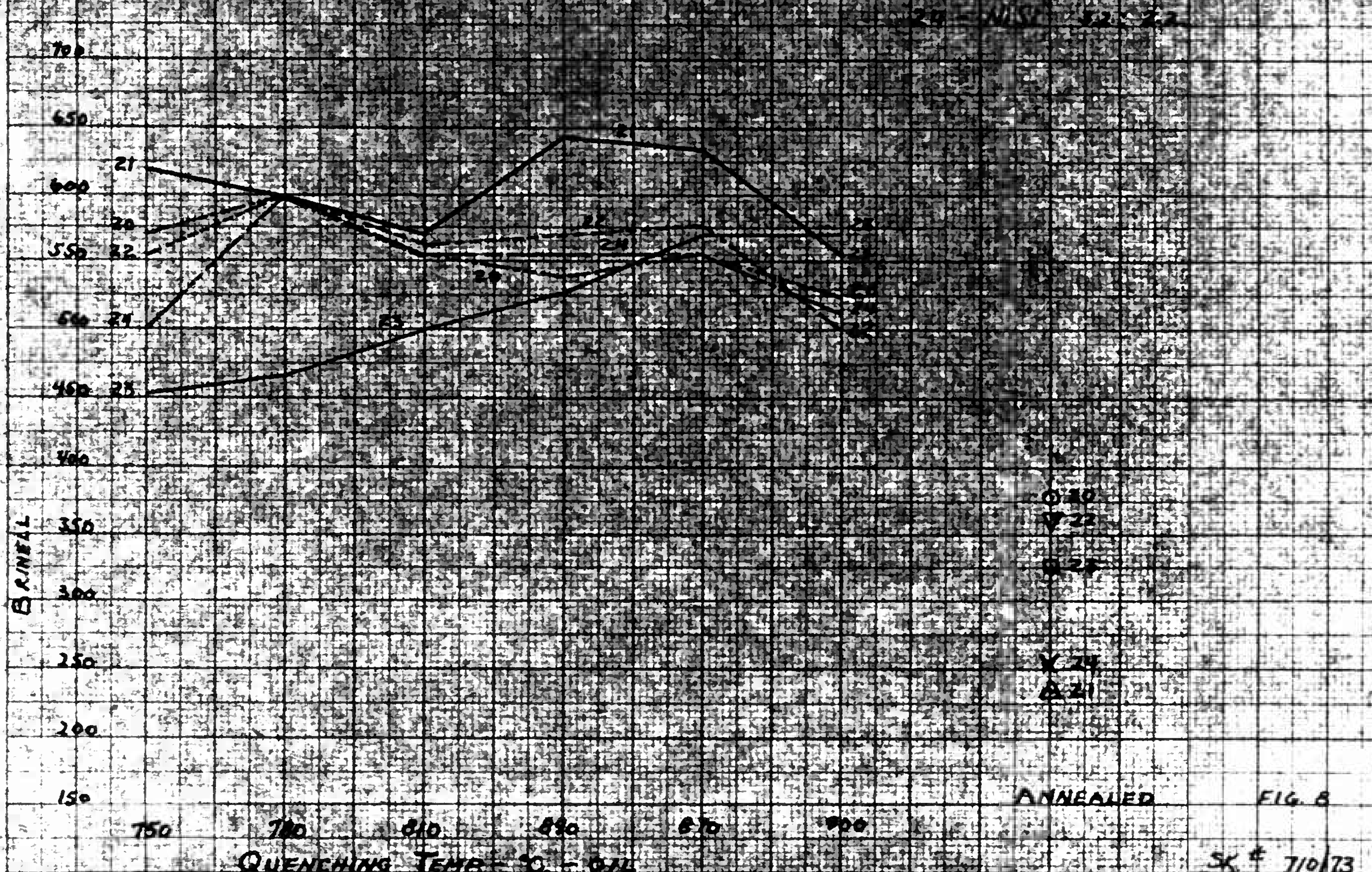


FIG. 8

SK # 710/73

Report # 10146

25

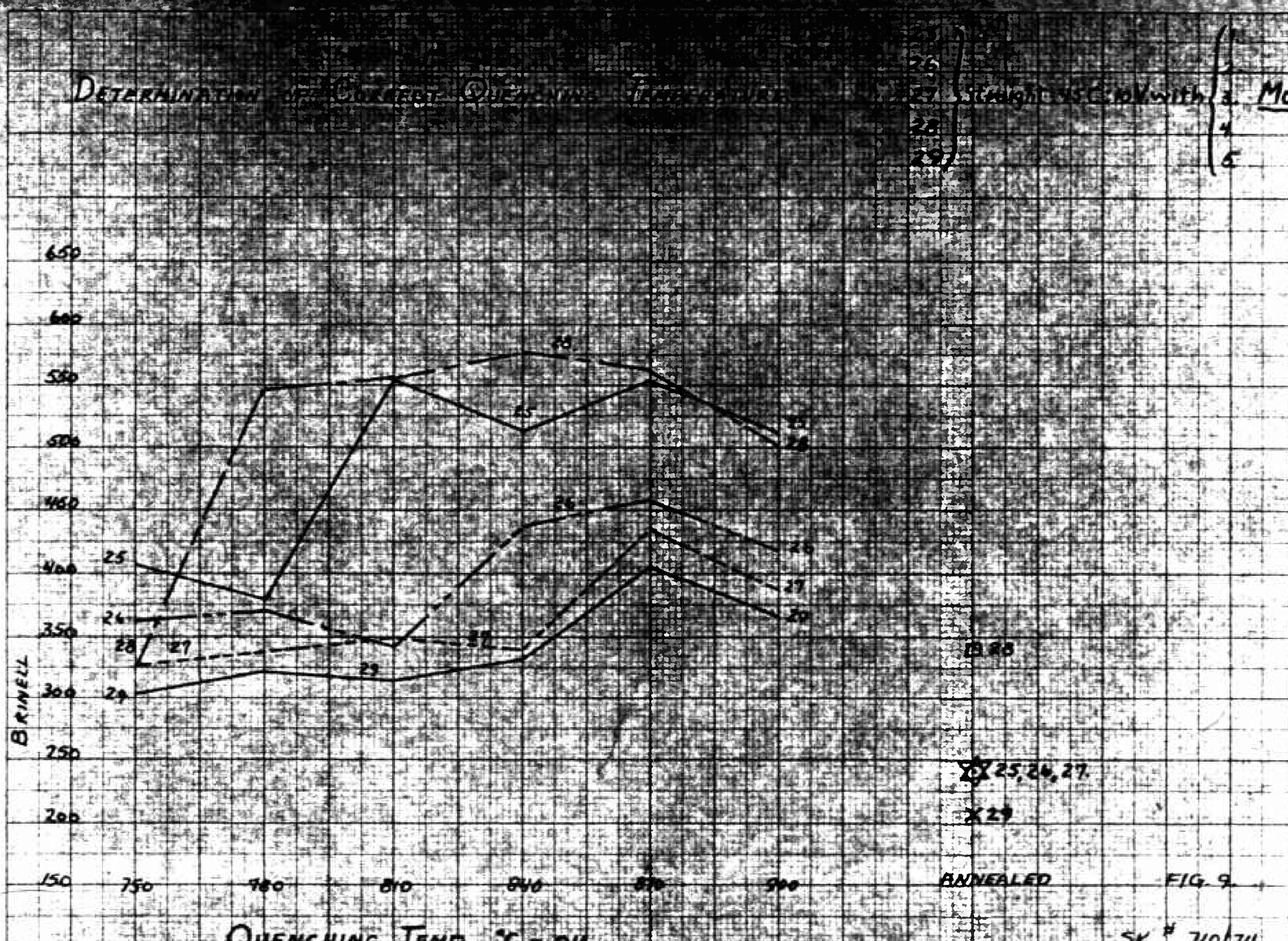
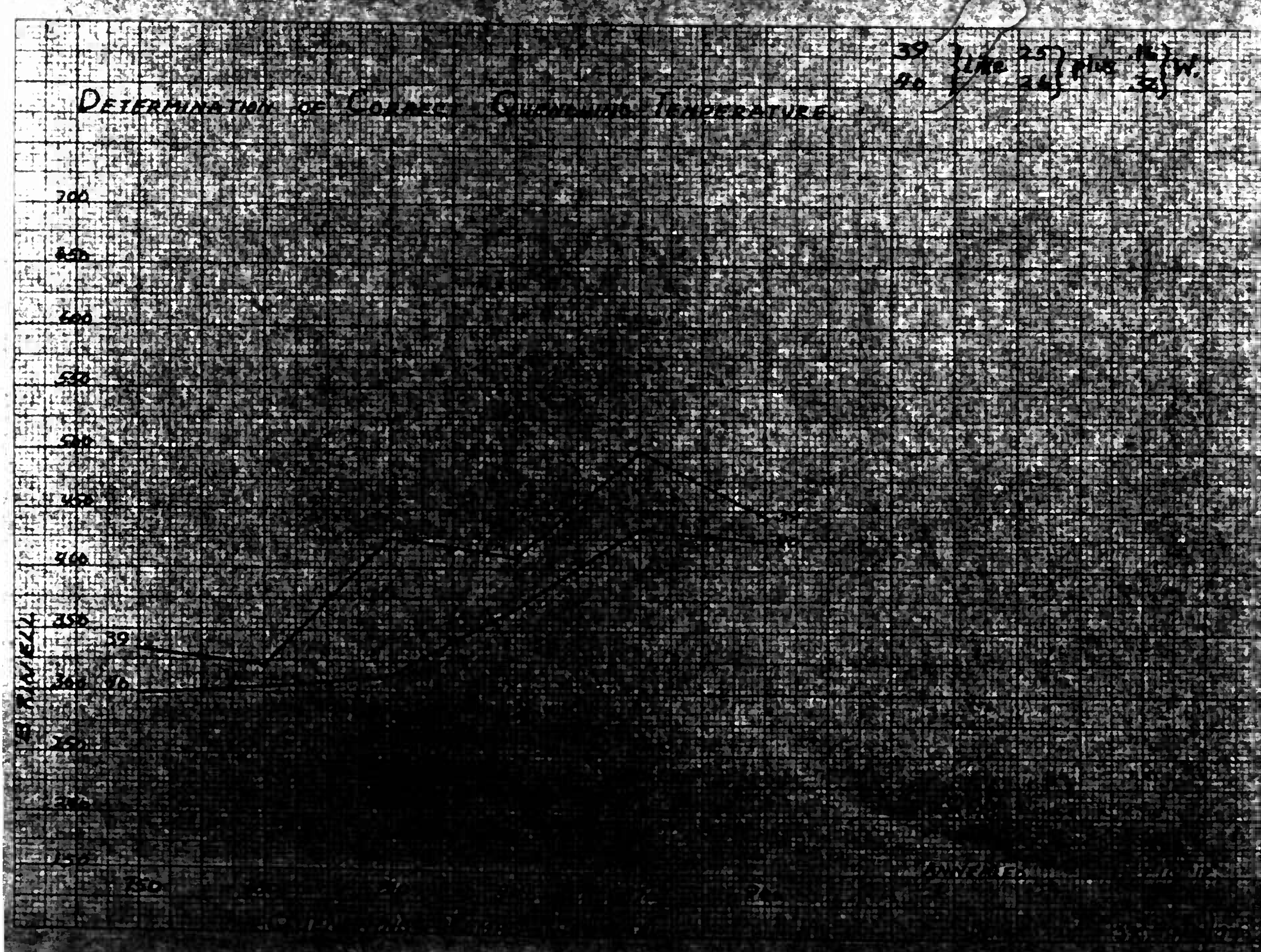

Determination of Correct Quenching Temperature
25
26
27
28
29
Straight 1% C 10V with
1
2
3 Mo
4
5
650
600
550
500
450
400
350
300
250
200
150
Brinell
750
780
810
840
870
900
Annealed
25, 26, 27
28
29
Quenching Temp °C - Oil
FIG. 9.
SK # 710/74

FIG. 10

FIG. 11



DETERMINATION OF CORRECT QUENCHING TEMPERATURE
39 } LIKE 25 } PLUS 16 } W.
40 } LIKE 24 } PLUS 32 } W.
BRINELL
700
650
600
550
500
450
400
350
300
250
200
150
39
40
750
ANNEALED

TABLE [illegible] PLATE COMPOSITION.

[illegible] CHEMICAL ANALYSIS AND ME[illegible]

[illegible] INGOTS.

FORGED [illegible] REDUCTION TO 2 3/8 ROUND BA[illegible]

TEST SLUG OIL QUENCHED DRAWN.

TEST BARS MACHINED FROM SLUGS AT ½

INGOT NO.	NO.	C.	Mn.	P.	S.	Si.	Ni.	Cr.	Mo.	Va.	W.	PROPORTIONAL LIMIT LBS. PER SQ. IN.	TENSILE STRENGTH LBS. PER SQ. IN.	TRUE BREAKING STRESS LBS. PER SQ. IN.	Elongation % in 2" STATIC	Elongation % in 2" DYNAMIC
2	A	.41	.82	.007	.020	.39	—	1.19	.67	.22	—	206,000	227,500	307,000	12.9	11.5
	B	.47	.81	.005	.017	.440	—	1.16	.57	.25	—					
2X	A	.38	.80	.007	.015	.35	—	1.21	.65	.21	—	201,000	218,500	316,000	14.3	14.0
	B	.37	.74	.005	.017	.365	—	1.16	.68	.24	—					
3	A	.36	.69	.007	.018	.39	—	1.77	.52	.24	—	204,000	225,500	308,000	12.1	13.5
	B	.37	.60	.006	.020	.325	—	1.71	.52	.24	—					
4X	A	.39	.85	.007	.016	.32	—	2.82	.63	.23	—	185,000	237,500	315,000	12.9	11.9
	B	.37	.69			.368	—	2.70	.68	.255	—					
5X	A	.37	.53	.007	.016	.37	—	5.36	.65	.24	—					
	B										—					
6X	A	.41	.73	.007	.015	.25	1.22	1.20	.65	.21	—	175,000	199,500	271,000	11.4	13.3
	B	.405	.69			.350	.94	1.14	.64	.21	—					
7X	A	.41	.67	.007	.015	.20	2.58	1.20	.60	.20	—	197,000	212,000	294,000	13.6	14.0
	B	.40	.59	.007	.020	.245	2.36	1.21	.53	.24	—					
8	A	.40	.68	.007	.018	.31	4.60	1.15	.62	.23	—	170,000	226,000	306,000	14.3	12.5
	B	.395	.64			.320	4.42	.99	.65	.225	—					
9X	A	.41	.60	.007	.016	.14	1.26	—	.60	.20	—	195,000	215,000	288,000	14.3	14.1
	B	.405	.60	.006	.018	.280	1.34	—	.72	.21	—					
10X	A	.43	.60	.007	.014	.24	2.36	—	.61	.21	—	186,000	194,000	290,000	14.3	14.6
	B	.455	.63			.280	2.24	—	.62	.21	—					
11	A	.42	.60	.007	.014	.21	4.55	—	.60	.23	—	186,000	192,000	270,000	16.4	15.4
	B	.41	.60			.230	4.45	—	.64	.195	—					
12	A	.42	.69	.007	.018	.28	3.71	—	.27	.23	—	179,000	183,000	262,000	14.3	14.9
	B	.415	.67			.310	3.66	—	.30	.21	—					
13X	A	.41	.67	.008	.020	.30	4.02	—	.49	.30	—	197,000	198,000	272,000	12.1	12.9
	B	.43	.65			.305	3.94	.08	.59	.225	—					
14	A	.37	.59	.012	.018	.28	3.57	—	.65	.21	—	196,000	200,000	281,000	12.9	14.8
	B	.40	.57			.310	3.47	.06	.64	.21	—					
15	A	.40	.62	.011	.016	.25	3.45	—	.88	.22	—	187,000	195,500	290,000	16.4	15.2
	B	.395	.60			.260	3.35	.06	.92	.20	—					
16	A	.39	.68	.009	.017	.17	3.65	1.15	.31	.20	—					15.2
	B	.405	.53			.195	3.57	1.10	.34	.21	—					
17X	A	.44	.63	.007	.019	.27	3.86	1.26	.47	.27	—	170,000	200,000	277,000	13.6	14.0
	B															
18X	A	.37	.60	.012	.019	.290	5.57	1.15	.78	.225	—					11.9
	B															
19	A	.38	.70	.009	.017	.25	3.75	1.17	.89	.20	—	179,000	222,000	310,000	14.3	13.3
	B	.375	.64			.285	3.74	1.15	.67	.24	—					

OR PLATE COMPOSITION.
EXO. 67.
OF CHEMICAL ANALYSIS AND MECHANICAL PROPERTIES.
– 4" x 4" INGOTS.
3 TO 1 REDUCTION TO 2 3/8" ROUND BARS
G - OIL QUENCHED - DRAWN.
RS MACHINED FROM SLUGS AT 1/2 RADIUS.

CHEMICAL ANALYSES –
ANALYSIS A MADE FROM INGOT.
ANALYSIS B MADE FROM TEST SPECIMEN.

LE STRENGTH PER SQ. IN.	TRUE BREAKING STRESS LBS PER SQ. IN.	Elongation % in 2"		Reduction of Area		CHARPY TENSION IMPACT FT. LBS.	BRINELL HARDNESS		REMARKS
		STATIC	DYNAMIC	STATIC	DYNAMIC		ON TENSILE TEST BARS	ON CHARPY TEST BARS	APPEARANCE OF FRACTURE – TENSILE TEST BARS
227,500	307,000	12.9	11.5	43.6	43.0	315.4	410	460	90° BREAK, SMOOTH STAR FRACTURE.
218,500	316,000	14.3	14.0	50.6	49.2	326.9	418	430	COARSE STAR FRACTURE, INTERNAL CRACKS.
225,500	308,000	12.1	13.5	47.0	49.0	324.3	444	460	STAR FRACTURE, INTERNAL CRACKS.
237,500	315,000	12.9	11.9	38.0	42.1	342.1	460	444	3/4 SHALLOW CUP, SMOOTH STAR FRACTURE.
199,500	271,000	11.4	13.3	41.9	46.3	323.0	402	444	90° BREAK, SMOOTH STAR FRACTURE.
212,000	294,000	13.6	14.0	49.0	48.6	319.2	418	418	COARSE STAR FRACTURE, INTERNAL CRACKS.
226,000	306,000	14.3	12.5	40.7	41.9	334.4	444	444	CUPPED PITTED, FAN STRUCTURE RADIATING FROM NON-METALLIC NEAR CENTER OF FRACTURE.
215,000	288,000	14.3	14.1	51.0	52.5	311.7	387	418	STAR FRACTURE.
194,000	290,000	14.3	14.6	51.0	49.6	323.0	364	387	3/4 CUP, PITTED, SLIGHT INDICATION OF STAR FRACTURE.
192,000	270,000	16.4	15.4	51.0	51.7	319.2	402	364	CUPPED, SOMEWHAT PITTED AT CENTER, STAR FRACTURE.
183,000	262,000	14.3	14.9	50.6	51.9	296.8	364	364	FULL DEEP CUP, PITTED.
198,000	272,000	12.1	12.9	46.5	49.9	278.4	387	387	FULL DEEP CUP, PITTED
200,000	281,000	12.9	14.8	49.8	49.8	304.2	364	387	3/4 CUP, PITTED.
195,500	290,000	16.4	15.2	53.7	50.2	319.2	387	418	CUPPED, PITTED, PARTIAL STAR FRACTURE
			15.2		50.3	315.4		387	
200,000	277,000	13.6	14.0	44.9	46.5	319.2	418	402	90° BREAK, SMOOTH STAR FRACTURE.
			11.9	46.1	39.3	338.3		444	
222,000	310,000	14.3	13.3		45.5	338.3	444	444	3/4 CUP, PITTED FAN STRUCTURE RADIATING FROM NON-METALLICS NEAR CENTER OF FRACTURE

	B	[illegible]	[illegible]			.285	[illegible]	[illegible]	[illegible]	[illegible]	—				
20	A	.38	.60	.012	.014	.22	4.60	1.12	.60	.10	—				
	B	.30	.35			.25	3.90	1.09	.70	.12	—				
21	A	.45	.67	.018	.020	[illegible]	[illegible]	[illegible]	—	—	—				
	B														
22	A	.39	.74	.011	.016	.20	2.00	1.04	.69						
	B														
23	A	.40	1.60	.012	.017	1.73	—	—	.70	—	—				
	B														
24	A	.40	.85	.007	.019	2.20	3.20	—	—	—	—	188,000	207,000	286,000	13.6
	B	.385	.82			2.19	3.29	.04	—	—	—				
25	A	.42	.67	.009	.016	.28	—	—	1.04	.10	—	188,000	204,000	290,000	14.3
	B	.45	.64			.305	—	.10	1.14	.16	—				
26	A	.44	.68	.011	.016	.39	—	—	2.08	.10	—	196,000	217,000	288,000	12.1
	B	.46	.66			.375	—	.08	2.24	.10	—				
27	A	.44	.61	.012	.015	.39	—	—	3.15	.16	—	145,000	187,000	252,000	13.6
	B	.46	.60			.410	—	.08	3.35	.10	—				
28X	A	.44	.56	.009	.019	.34	—	—	4.07	.12	—	192,000	225,500	295,000	11.4
	B														
29X	A	.47	.63	.009	.020	.33	—	—	5.07	.14	—				
	B														
30	A	.37	.59	.011	.019	.18	2.32	—	1.00	—	—				
	B														
31	A	.36	1.75	.012	.125	.39	2.28	—	.99	—	—				
	B														
32	A	.37	.57	.009	.017	.19	—	2.18	.60	—	—				
	B	.425	.59			.205	—	2.12	.69	—	—				
33	A	.41	2.40	.011	.010	.37	—	—	.61	—	—	180,000	219,000	290,000	12.1
	B	.385	2.26			.370	—	.20	.66	—	—				
34	A	.40	.44	.011	.017	.15	3.88	—	.60	—	—	193,000	239,500	320,000	12.1
	B	.36	.41			.150	3.90	.04	.70	—	—				
35	A	.56	.26	.010	.022	.23	2.16	1.92	—	—	—	190,000	210,000	276,000	12.9
	B	.555	.25			.245	2.15	1.84	—	—	—				
36	A	.61	.18	.009	.018	.28	2.66	2.59	—	—	—	191,000	210,000	268,000	11.4
	B	.60	.25			.290	2.70	2.54	—	—	—				
37	A	.36	.38	.009	.020	.21	3.86	2.07	—	—	—	156,000	188,500	269,000	13.6
	B	.315	.39			.220	3.90	2.04	—	—	—				
38	A	.28	.45	.009	.020	.19	3.90	1.87	—	—	—	149,000	188,500	270,000	15.0
	B	.32	.46			.195	3.96	1.95	—	—	—				
39	A	.36	.65	.007	.015	.30	—	—	1.22	.10	.16	151,000	182,500	262,000	13.6
	B	.40	.65			.300	—	.09	1.25	.10	.14				
40	A	.43	.55	.007	.015	.33	—	—	2.14	.09	.32	143,000	184,500	250,000	15.0
	B	.415	.60			.350	—	.11	2.21	.10	.30				

			11.9		41.9	293.1	402	450	FULL SHALLOW CUP, PITTED.
000	286,000	13.6	15.0	46.5	46.3	342.1	402	418	FULL SHALLOW CUP, PITTED, NON-METALLICS AT CENTER OF FRACTURE.
000	290,000	14.3	13.8	51.0	62.5	315.4	418	444	STAR FRACTURE.
00	288,000	12.1	12.3	43.2	44.4	311.7	418	444	3/4 CUP, PITTED.
[illegible]	252,000	13.6	14.1	45.3	47.8	296.8	387	387	3/4 CUP, PITTED.
[illegible]	295,000	11.4	12.4	38.9	43.4	311.7	444	444	3/4 CUP, PITTED, PARTIAL STAR FRACTURE. NON-METALLICS NEAR CENTER OF FRACTURE
000	290,000	12.1	11.9	38.9	42.1	315.4	418	444	3/4 CUP, PITTED NON-METALLIC INCLUSIONS.
500	320,000	12.1	11.6	44.6	44.1	307.9	444	444	CUPPED, PITTED.
000	276,000	12.9	12.3	43.2	43.8	296.8	418	418	3/4 CUP PITTED, FAN STRUCTURE RADIATING FROM NON-METALLICS AT CENTER OF FRACTURE.
000	268,000	11.4	12.7	35.8	39.5	311.7	402	444	CUPPED, SMOOTH STAR FRACTURE.
500	259,000	13.6	14.2	49.0	51.5	293.1	375	387	CUPPED, STAR FRACTURE.
500	270,000	15.0	15.9	52.5	52.5	300.5	364	402	CUPPED, STAR FRACTURE.
500	262,000	13.6	15.2	49.8	51.7	300.5	387	402	FULL CUP, PITTED, INDICATIONS OF STAR FRACTURE.
500	250,000	15.0	13.8	47.0	46.5	285.7	387	402	3/4 CUP, PITTED.

ARMOR PLATE SECTION.
SK # 710/65. Report #
A. H.