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NRL-54

REPORT NO. 0-2262

FR-2262

DATE 18 March 1944

SUBJECT

Report On

Effect of Plate Temperature

Upon the Performance of Homogenous Armor

[redacted]

NAVAL RESEARCH LABORATORY

BELLEVUE, D. C.

U. S. GOVERNMENT PRINTING OFFICE 16-21000

DECLASSIFIED

SERIAL No. 8

[redacted]

FR-2262

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NAVY DEPARTMENT

Report on

Effect of Plate Temperature

Upon the Performance of Homogeneous Armor.

[redacted]

NAVAL RESEARCH LABORATORY
ANACOSTIA STATION
WASHINGTON, D. C.

Authorization:	BuOrd Ltr. S13-1(4/173)(OB) of 13 December 1934.
Number of Pages:	Text 6 Tables 8 Plates 11
Date of Tests:	March 1943 to December 1943
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Approved by:	A. H. Van Keuren Rear Admiral, USN Director
Distribution:	BuOrd (10) BuShips (2) NRL (13)

Classification Changed From [redacted]
To [redacted]
By Navy Regulation, Art 76
pp-5 b and c, Dated 1920

hlh

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ABSTRACT

Variationsof the hardness and ballistic resistance of homogeneous steel armor with temperature were determined for several different compositions and hardnesses at Cal. 30 and Cal. 50 scale.

Sufficiently ductile material exhibits an increase in hardness and ballistic resistance on cooling and a decrease on heating. The increase in hardness by cooling results in greater ballistic resistance than the same increase in hardness obtained by heat treatment. However, it is shown that harder material may exhibit brittle failure and decreased ballistic resistance when cooled.

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Effect of Plate Temperature

Upon the Performance of Homogeneous

Armor

INTRODUCTION

1. The problem was authorized by Bureau of Ordnance letter S13-1(4/173)(QB) of 13 December 1934. The following references are also of interest:

(a) NPG ltr. S1301/L5-2(17)(B16021) of 8 July 1941.
(b) 10th Partial Report on Light Armor, NRL Report No. O-1892.
(c) BuOrd ltr. S13-6(2637)(Re3) of 24 July 1941.
(d) Gensamer, "Strength of Metals" published by the American Society for Metals, 1941.
(e) 9th Partial Report on Armor, NRL Report No. O-1778.
(f) Takehide Inokuty, Sci. Rep. of the Tôhoku Imperial University, 17 (1928), 791, 817.

2. A study of the effects of temperature on the ballistic resistance and hardness of soft homogeneous steel armor and face-hardened bullet proof steel is presented in the Tenth Partial Report on Light Armor, reference (b). The Tenth Partial Report shows that increasing the hardness of STS (Brinell hardness 266 Kg/mm^2 at 28° C) by cooling improves the ballistic resistance more than the same increase in hardness obtained by heat treatment. This has raised the following questions:

(a) Will STS heat treated to the hardness which gives best performance (Brinell hardness 370-400 Kg/mm^2 at room temperature) show improvement when the temperature is lowered? Will the hardness for best performance at low temperatures be the same as the hardness for best performance at room temperature?

(b) Will the temperature effect for armor shot with Cal .50 be the same as for armor shot with Cal .30?

(c) Will homogeneous armor which has been heat treated to above its optimum hardness and which therefore exhibits brittle failure also improve when the temperature is lowered?

The purpose of the investigations reported here is to provide the answers to these questions.

3. For this work, the <u>limit</u> <u>velocity</u> of a sample of armor for a given projectile obliquity, yaw and temperature is taken as the striking

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velocity for which the probability of complete penetration by the core (bullet without jacket) is 0.5. The source of the scatter of reaults requiring this convention is plate quality and projectile form factors, not bullet breakage. Following the usual practice at this Laboratory, the performance number used in this report is as follows:

$$P = \frac{1.374 \times 10^{-4} \frac{M}{d^3} V_L^2 \cos \Theta}{\frac{e}{d}}$$

Where P is the average deformation pressure resisting penetration in pounds per square inch, and

M and d are the mass and diameter of the core.

For Cal .30 AP M1922, M/d^3 = 1300 pounds/cu.ft.

For Cal .50 AP M2 plate testing bullets, M/d^3 = 1277 pounds per cu.ft.
d = 0.4276 inch.

e is the plate thickness in the same units as d.

Θ is the angle of obliquity in degrees, in this case zero.

V_L is the limit velocity in ft/sec.

EQUIPMENT AND EXPERIMENTAL PROCEDURE

4. Plate material used is described in Table 1. Samples were flame cut, then heat treated when necessary to change the hardness. STS shot with Cal .30 was wet ground equal amounts on both surfaces after heat treatment to remove most of the decarburized layer. Corresponding to each series of ballistic samples, a hardness sample was prepared with the same heat treatment. Hardness samples were ground flat on one face and to a depth of 0.04 inch on the face on which impressions were made.

5. All Cal .30 impacts were made with Cal .30 M1922 armor piercing bullets. Measurements were made on 20 bullets picked at random from the supply of about one thousand. The average and extreme values for d, M and M/d^3 and the probable deviation from the mean for an individual core are:

Weight of whole bullet - 167.4 grains
d = 0.2550 ± 0.0002 inch (± 0.07%), max. 0.2556 inch,
min. 0.2546 inch

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$$M = 86.8 \pm 2 \text{ grains } (\pm 0.2\%), \text{ Max. } 87.2 \text{ gr.}$$
$$\text{Min. } 86.5 \text{ gr.}$$
$$M/d^3 = 1292. \pm 3. \text{ pounds/ft}^3 (\pm 0.2\%), \text{ Max. } 1302. \text{ lbs/ft}^3$$
$$\text{Min. } 1282. \text{ lbs/ft}^3.$$

However, in this work, as in previous work at N.R.L., M/d^3 for the Cal .30 M1922 cores is taken as 1300 lb/ft^3.

6. The Cal .30 bullets were fired from a Springfield model 1903 rifle barrel, without stock, mounted in a vee rest. Cartridges were individually loaded with powder drawn from Cal .30 M1 ball ammunition.

7. Cal .50 impacts were made with Cal .50 APM2 plate testing bullets. A survey of 25 bullets picked at random from the supply of five thousand gave the following average and extreme values and probable deviations from the mean for an individual core:

Weight of the whole bullet = 709.1 grains

$$d = 0.4276 \pm 0.0002 \text{ inch } (\pm 0.05\%), \text{ Max. } 0.4282 \text{ in.,}$$
$$\text{Min. } 0.4270 \text{ in.}$$
$$M = 404.4 \pm 2.4 \text{ grains } (\pm 0.6\%), \text{ Max. } 411.8 \text{ gr.}$$
$$\text{Min. } 401.5 \text{ gr.}$$
$$M/d^3 = 1277 \pm 8 \text{ lb/ft}^3 (\pm 0.6\%), \text{ Max. } 1298 \text{ lb/ft}^3,$$
$$\text{Min } 1252 \text{ lb/ft}^3.$$

Cal .50 APM2 plate testing bullets with an above or below average total weight were found to have a correspondingly high or low core weight. Bullets used in the ballistic tests were selected so that the total weight was within 1/2% of the average, therefore, the probable deviation from the mean of M and M/d^3 of the bullets used was only about half as great as for the bullets selected at random, or about $\pm$ 0.3%.

8. A smoothbore heavy machine gun barrel mounted in a vee rest was used for Cal .50 impacts. Cartridges were individually loaded and several different powders were tried in a not entirely successful attempt to obtain good velocity control. Powder drawn from Cal .30 APM1 cartridges was the best of those tried in the velocity range 1600 to 1900 ft/sec.

9. Striking velocities were measured using the 122 pound Cal .30 plate testing ballistic pendulum described in reference (e) and a 370 pound Cal .50 pendulum of similar design. In the Cal .30 pendulum, cores which went through the samples were stopped by a piece of 1/4 inch plywood and a series of paper pads. Cores which failed to penetrate the plywood had negligible residual velocity and the number of paper pads penetrated was a rough measure of higher residual velocities. In the Cal .50 pendulum, two pieces of 5/8 inch plywood one bullet length apart were placed in back of the specimen. Approximate limit velocities of this plywood were determined for normal and yawed Cal .50 APM2 plate testing cores. A Cal .45 revolver barrel fitted with Springfield bolt

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action was used and velocities were measured in the Cal .30 pendulum. For 0°, 30° and 90° yaw, the limit velocities were found to be 216, 263 and 290 ft/sec respectively.

10. Residual velocities under 400 ft/sec were determined with a maximum error of about 20% which corresponds to an error of about 1% in the limit velocity for striking velocity of 1800 ft/sec and residual velocity of 400 ft/sec and 1/2% in the limit velocity for 1800 ft/sec striking velocity and 300 ft/sec residual velocity. Partial penetration curves (Plate 3) were used to estimate the additional energy for complete penetration of stuck projectiles. The penetration of the point of the core beyond the back of the plate was measured by means of a small spherometer.

11. A few Cal .30 impacts were made with the plate held in a thin waterproof box filled with a partly frozen alcohol-water mixture. There was 5/8 inch of cooling medium in front and in back of the plate. This caused an apparent increase in limit velocity of several percent. Since the effect was not consistent, no correction could be made and this method was discarded in favor of the following.

12. For impacts at temperatures above or below room temperature the plate was heated or cooled, wrapped in several layers of felt and shot when the desired temperature was reached. Plate temperature at the time of impact was measured with a type K potentiometer and a copper-constantin thermocouple fastened to the back of the plate with a spring clip. A reference junction at 0° C was used and the thermocouple was calibrated.

13. Hardness measurements were made with a 10.00 mm diameter tungsten carbide ball and 3000 Kg load applied for 20 to 30 seconds. The room temperature hardness of ballistic samples is given in tables (2-8). For hardness vs. temperature studies the sample was placed in the jig shown on plate (2). Below room temperature, alcohol cooled with dry ice was used, and above room temperature glycerin was used as a heating medium. The jig was sufficiently well insulated so that the temperature could be held nearly constant while the sample acquired a uniform temperature and a hardness indent was made. The thermocouple junction was placed so as to touch both the ball and the specimen while the impression was being made. The individual hardness measurements are probably accurate to better than $\pm$ 0.2% and the temperatures are probably accurate to $\pm$ 1% of the absolute temperature.

<u>DISCUSSION OF DATA</u>

14. Impact data are given in tables 2-8. Impacts from which limit velocities were estimated are indicated by brackets. P values computed from these limit velocities are plotted against temperature in plates 4, 6, 8, and 10. The variation of Brinell hardness with temperature (Plates 5,6, 9, and 10) was determined for a sample from each of the six sets of armor material. These hardness vs. temperature graphs show that within the range

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investigated, the hardness and rate of change of hardness increase with decreasing temperature. The actual change of hardness with temperature (not the percentage change) is nearly the same for all the materials tested, indicating that this effect is not strongly influenced by heat treatment and small variations in composition. The scatter of points on these graphs is mainly due to actual hardness variations in the material. The hardness variation is about ± 1/3% for the sample of Cal .30 STS plate material, ± 1/2% for the .50 carbon, chrome. moly. vanadium steel and Cal .50 STS, and 1% for the 1% nickel steel. The 1% nickel material was inhomogeneous, the hardness differing as much as 20 points Brinell on impressions less than an inch apart.

15. The P vs. temperature curves show that the performance of the materials tested improves with decreasing temperature until a brittle point is reached and the P value drops. The 1% nickel steel becomes brittle just below room temperature and the .225 inch, 381 Brinell and .514 inch, 371 Brinell STS apparently become brittle below the lowest temperature at which they were tested. The other materials do not become brittle at the lowest test temperature, if at all.

16. Plate 1 shows sections of impacts made at three different temperatures on the 1% nickel steel. Unlike the other materials tested, this was of poor quality. The laminations become more apparent at lower temperatures, as does back brittleness.

17. The scatter in P values is 2/3% for the STS samples shot with Cal .30 and 1% for the .50 carbon, chrome. moly. vanadium steel. For the 260-1/2 Brinell and 371 Brinell STS shot with Cal .50, the scatter was 1% and 2% respectively, and for the 1% nickel material, 3%. This scatter in P values is about double the hardness variation on the hardness samples, due partly to the fact that a number of individually heat treated ballistic samples were necessary for each plate material, while all the hardness vs. temperature measurements for one material could be made on one sample. Also, the measurements of limit velocities are less accurate than the hardness measurements and the limit velocities are affected by laminations and other defects not detected in the hardness readings. The greater scatter in P values for the 1% nickel material and 1/2 inch 371 Brinell STS at low temperatures is due to inhomogeneities in the material, which affect brittle failure more than ductile failure.

18. The room temperature P coefficient for STS heat-treated to varying hardness is given in Plates 7 and 11. These curves were drawn through the room temperature P and hardness values of the STS used in the P vs. temperature study. The shapes of the curves were determined from the experimental points shown and from earlier NRL curves. The five different hardnesses of STS shot with Cal .50 (table 8) were apparently of poorer quality than the material used in the P vs. temperature study. The curves of P vs. hardness varied by temperature were obtained from

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the P vs. temperature and hardness vs. temperature curves. The comparison of P vs. hardness varied with temperature and P vs. hardness varied by heat treatment shows that low temperatures can cause an improvement in armor which is not obtainable by heat treatment.

CONCLUSIONS

19. Down to -50° C, STS heat treated to a hardness to give best performance at room temperature shows about the same improvement in ballistic resistance with decreasing temperature as does 260-270 Brinell hardness STS. This does not answer the question of whether or not the hardness for best room temperature performance also gives the best cold temperature performance, and it will be necessary to make some additional tests before a definite answer can be given. However, the flatness of the performance vs. hardness curve in the vicinity of the maximum performance at room temperature combined with the fact that the increase in performance by cooling was about the same at the 266 and at the 370 Brinell hardness levels suggests that the performance curve at cold temperature will likely be flat and merely shifted upward and to the right.

20. The temperature effect on armor shot with Cal .50 is similar to that observed for armor shot with Cal .30.

21. Homogeneous steel armor heat treated to a sufficiently high hardness so that the failure is brittle at room temperature may become poorer and more brittle as the temperature is lowered.

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TABLE 1

ARMOR SAMPLES

Material	Manufacturer	Mfgr.'s Plate No.	N.R.L. Sample No.	Dimensions of Samples (inches)	Average Brinell Hardness at 28° C (Kg/mm²)	Composition (percent)	Use
.50 Carbon Chrome Moly. Vanadium Steel	Jessop Steel Co.		4,6,7,8	3 x 4 x 0.270	411	C .51 Mn .49 S .010 P .018 Si .21 Cr 1.08 Mo .62 Va .14	Cal .30 P vs. Temperature
.50 Carbon Chrome Moly. Vanadium Steel	Jessop Steel Co.			3 x 4 x 0.23 (ground from 0.270)	411	C .51 Mn .49 S .010 P .018 Si .211 Cr .08 Mo .62 Va .14	Hardness vs. Temperature
STS	Carnegie-Ill. Steel Corp.	75899	5,6,7, 28,32	3 x 4 x 0.350 (ground from 3/8)	reheat treated to 384	C .31 Mn .24 S .022 P .012 Si .07 Cr 1.17 Ni 3.15	Cal .30 P vs. Temperature
STS	Carnegie-Ill. Steel Corp.	75899	24	3 x 4 x 0.29) (ground from 3/8)	reheat treated to 397	C .31 Mn .24 S .022 P .012 Si .071 Cr .173 Ni .15	Hardness vs. Temperature
STS	Carnegie-Ill. Steel Corp.	75898	12,14,16, 17,22	3 x 4 x 0.225 (ground from 1/4)	reheat treated to 381	C .31 Mn .24 S .022 P .012 Si .071 Cr .173 Ni .15	Cal .30 P vs. Temperature
STS	Carnegie-Ill. Steel Corp.	75907B1 & 75907B4	6,7,8,9, 10,11,12	6 x 6 x 0.514	reheat treated to 371	C .31 Mn .24 S .022 P .012 Si .071 Cr .173 Ni .15	Cal .50 P vs. Temperature
STS	Carnegie-Ill. Steel Corp.	75907B19	1	3 x 4 x 0.45 (ground from 0.514)	reheat treated to 375	C .31 Mn .24 S .022 P .012 Si .071 Cr .173 Ni .15	Hardness vs. Temperature
STS	Carnegie-Ill. Steel Corp.	75907B19	2	3 x 4 x 0.45 (ground from 0.515)	266-1/2	C .31 Mn .24 S .022 P .012 Si .071 Cr .173 Ni .15	Hardness vs. Temperature
STS	Carnegie-Ill. Steel Corp.	75907B1 & 75907B16	14,15,16, 17,18	6 x 6 x 0.515	260-1/2	C .31 Mn .24 S .022 P .012 Si .071 Cr .173 Ni .15	Cal .50 P vs. Temperature
STS	Carnegie-Ill. Steel Corp.	75907B4	1	6 x 6 x 0.510	reheat treated to 377	C .31 Mn .24 S .022 P .012 Si .071 Cr .173 Ni .15	Cal .50 P vs. Hardness
STS	Carnegie-Ill. Steel Corp.	75907B4	2	6 x 6 x 0.514	reheat treated to 313	C .31 Mn .24 S .022 P .012 Si .071 Cr .173 Ni .15	Cal .50 P vs. Hardness
STS	Carnegie-Ill. Steel Corp.	75907B4	3	6 x 6 x 0.514	reheat treated to 338	C .31 Mn .24 S .022 P .012 Si .071 Cr .173 Ni .15	Cal .50 P vs. Hardness
STS	Carnegie-Ill. Steel Corp.	75907B4	4	6 x 6 x 0.512	reheat treated to 295	C .31 Mn .24 S .022 P .012 Si .071 Cr .173 Ni .15	Cal .50 P vs. Hardness
STS	Carnegie-Ill. Steel Corp.	75907B4	5	6 x 6 x 0.514	258	C .31 Mn .24 S .022 P .012 Si .071 Cr .173 Ni .15	Cal .50 P vs. Hardness
1% Nickel Steel	Carnegie-Ill. Steel Corp.	71094	1,2,3,4, 5,6,7	6 x 6 x 0.515	reheat treated to 415	C .28 Mn 1.03 S .024 P .015 Si .20 Cr .41 Ni 1.01 Mo .42	Cal .50 P vs. Temperature
1% Nickel Steel	Carnegie-Ill. Steel Corp.	71094	8	3 x 6 x 0.45 (ground from 0.515)	reheat treated to 403	C .28 Mn 1.03 S .024 P .015 Si .20 Cr .41 Ni 1.01 Mo .42	Hardness vs. Temperature

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TABLE 2

CAL .30 IMPACT DATA .50 CARBON CHROME MOLY. VANADIUM STEEL

AVERAGE BRINELL HARDNESS 411 Kg/mm^2 at 28° C

N.R.L. Sample Number	Thickness (inches)	Striking Velocity (ft/sec)	Residual Velocity (inches)	Penetration (inches)	Limit Velocity (ft/sec)	$P \times 10^{-3}$ (lb/in^2)	Temperature (°C)	Impact Number	Remarks
5	.269	1815					+ 25	1019	Core thru to second pad 6 petals, all on
5	.269	1712					+ 26	1020	Core rebounded 5 petals, all on
5	.269	1780		.61			+ 27	1021	5 petals, 1 off
4	.270	1878		.72			- 51-1/2	1023	4 petals, 1 off
4	.270	1882					- 50	1024	Core thru to second pad 4 petals, 1 off
					1880	596	- 51		
4	.270	1855	<200				- 14-1/2	1025	4 petals, 1 off
4	.270	1851					- 14-1/2	1026	Core thru to first pad 5 petals, all on
					1850	577	- 14-1/2		
4	.270	1819		.524			+ 6	1027	5 petals, all on
4	.270	1822		.411			+ 6	1028	6 petals, all on
4	.270	1839					+ 6	1029	Core thru to first pad 4 petals, all on
					1830	565	+ 6		
4A	.270	1721					+ 60	1030	Core rebounded 6 petals, all on
4A	.270	1764		.310			+ 60	1031	4 petals, all on
4A	.270	1730					+ 60	1032	Core rebounded 4 petals, all on
4A	.270	1764		.320			+ 60	1033	5 petals, all on
6	.270	1802		.540	1805	549	+ 60	1034	5 petals, all on
6	.270	1802					+ 105	1035	Core thru to first pad 6 petals, 1 off
6	.270	1802		.535			+ 29	1036	
6	.270	1794		.429			+ 29	1037	4 petals, all on
					1805	549	+ 29		
6	.270	1778		.565	1785	537	+ 105	1047	5 petals, all on
7	.263	1772		.550	1775	545	+ 28	1038	5 petals, all on
7	.263	1802					+ 60	1039	Core thru to first pad 6 petals, all on
7	.263	1805					+ 60	1040	Core thru to second pad 5 petals, 1 off
7	.263	1787		.625			+ 60	1041	5 petals, all on
					1790	564	+ 60		
8	.270	1751		.401			+ 150	1048	5 petals, all on
8	.270	1764		.687			+ 150	1049	4 petals, all on
					1770	534	+ 150		

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TABLE 3

CAL .30 IMPACT DATA .225 INCH THICK STS

AVERAGE BRINELL HARDNESS 381 Kg/mm^2 at 28° C

N.R.L. Sample No.	Brinell Hardness at 28° C (Kg/mm^2)	Striking Velocity (ft/sec)	Residual Velocity (ft/sec)	Penetration (inches)	Limit Velocity (ft/sec)	P x 10^{-3} (lb/in^2)	Temperature (°C)	Impact Number	Remarks
17	381	1588		.447	1600	519	+ 29-1/2	1053	6 petals, all on
17	381	1592		.417	1590	512	+ 60	1055	5 petals, all on
17	381	1637		.603	1645	549	- 52	1065	5 petals, all on
17	381	1620		.625	1625	535	- 14-1/2	1066	5 petals, all on
17	381	1627					+ 6	1067	Core thru to first pad 5 petals, all on
17	381	1620		.688	1620	532	+ 6 + 6	1068	
16	385	1693					+ 29	1050	Core thru to third pad 4 petals, all on
16	385	1578		.504	1590	512	+ 60	1054	4 petals, all on
16	385	1616		.625	1620	532	- 52	1064	4 petals, 1 off
22	380	1618					+ 29	1051	Core thru but did not stick in first pad
22	380	1632		.362	1640	545	- 52	1065	4 petals, all on
12	379	1637					+ 29	1052	Core thru but did not stick in first pad. 5 petals, all on
12	379	1618					+ 31	1056	Core thru but did not stick in first pad. 5 petals, all on
12	379	1578					+ 105	1058	Core thru but did not stick in first pad. 5 petals, all on
12	379	1528		.299	1555	490	+ 105 + 105	1059	5 petals, all on
14	380	1629		.69	1630	539	- 14-1/2	1073	5 petals, all on
14	380	1602					+ 105	1073a	Core thru to first pad 5 petals, all on
14	380	1542		.462	1555	490	+ 105 + 105	1074	5 petals, all on
14	380	1566					+ 150	1075	Core thru but did not stop in first pad. 5 petals, all on
14	380	1423					+ 150	1076	
14	380	1499					+ 150	1077	Core broke and went thru 5 petals, 2 off
14	380	1507		.376	1530	475	+ 150 + 150	1078	5 petals, all on

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TABLE 4

CAL .30 IMPACT DATA .350 INCH THICK STS

AVERAGE BRINELL HARDNESS 384 Kg/mm^2 at 28° C

N.R.L. Sample Number	Brinell Hardness at 28° C (Kg/mm^2)	Striking Velocity (ft/sec)	Residual Velocity (ft/sec)	Penetration (inches)	Limit Velocity (ft/sec)	P x 10^{-3} (lb/in^2)	Temperature (°C)	Impact Number	Remarks
5	384	2029		.244			+ 30-1/2	1079	5 petals, all on
5	384	2088		.447			+ 31-1/2	1080	5 petals, all on
5	384	2122					+ 32-1/2	1081	Core thru but did not stick in first pad. 5 petals, all on
					2106	577	+ 32		
5	384	2131	<200		2130	590	+ 6	1082	Core stuck in 1/4 inch plywood. 5 petals, all on
5	384	2145		.625			- 14-1/2	1083	4 petals, 1 off
5	384	2168					- 14-1/2	1084	Core thru to first pad
					2151	602	- 14-1/2		
6	381	2152		.625	2158	605	- 14-1/2	1085	6 petals, all on
6	381	2176		.621	2184	621	- 52	1086	5 petals, all on
6	381	2067		.610	2074	560	+ 60	1087	6 petals, all on
6	381	2065					+ 105	1088	Core thru but did not stick in first pad, plate laminated
6	381	2063					+ 105	1089	Core thru to first pad, plate laminated
32	384	2040		.428	2059	551	+ 105	1090	5 petals, all on
32	384	2092					+ 60	1091	Core broke, point went thru
32	384	2067		.428	2086	566	+ 60	1092	6 petals, all on
32	384	2074		.373	2097	572	+ 32	1093	6 petals, all on
32	384	2035					+ 150	1094	Core thru to first pad
32	384	2020					+ 150	1095	Core thru to second pad
7	383	2084		.80			+ 31	1096	4 petals, 1 off
7	383	2052		.327			+ 32-1/2	1097	5 petals, all on
					2089	567	+31		
7	383	1981		.359			about + 150	1104	5 petals, all on
7	383	1996		.536			+ 150	1105	
					2008	524	+ 150		
28	386	2082		.299			+ 31-1/2	1098	5 petals, all on
28	386	2109		.479			+ 31-1/2	1099	5 petals, all on
					2120	584	+ 31-1/2		
28	386	2008		.570	2017	529	+ 150	1100	6 petals, all on
28	386	2029		.271			+ 60	1101	4 petals, all on
28	386	2067		.529			+ 60	1103	5 petals, all on
					2079	562	+ 60		

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TABLE 5

CAL .50 IMPACT DATA 1% NICKEL STEEL

AVERAGE BRINELL HARDNESS 415 Kg/mm^2 at 28° C

N.R.L. Sample Number	Brinell Hardness at 28° C (Kg/mm^2)	Thickness (inches)	Striking Velocity (ft/sec)	Residual Velocity (ft/sec)	Penetration (inches)	Limit Velocity (ft/sec)	P x 10^{-3} (lb/in^2)	Temperature (°C)	Impact Number	Remarks
3	407	.512	1847	400	]	1800	475	+ 32	802a	Button started to form, no petals off
3	407	.512	1838	350	]	1805	478	+ 33-1/2	803	Botton started to form, 1 petal off
3	407	.512	1700					- 51-1/2	808	1-1/8" botton off, 1/3 of secondary petals off
3	407	.512	1776	150	]	1768	458	+ 150	809	No petals off, lamination not apparent
3	407	.512	1761		.85]	1765	457	+ 6	811	Very ragged petals, 1/3 off
3	407	.512	1764		1.13]	1765	457	+ 60	812	Very ragged petals, 1 off
2	409	.512	1876	>400				- 51-1/2	804	1-1/8" button off, 1 secondary petal off
2	409	.512	1793	225	]	1783	466	- 51-1/2	805	1-1/4" button almost off, no secondary petals off
2	409	.512	1746		.70]	1766	457	+ 150	806	No petals off
2	409	.512	1796	>400				+ 150	807	1 petal off, lamination not apparent
2	409	.512	1810		1.23]	1810	480	+ 32	810	1 petal almost off, button started to form
5	419	.514	1812	300	]	1786	465	+ 30	813	No petals off
5	419	.514	1796	100	]	1793	469	+ 31-1/2	814	Very ragged petals, none off
5	419	.514	1735	310	]	1705	424	- 51-1/2	815	1-1/4" button off, no secondary petals off
5	419	.514	1763		1.29]	1763	454	+ 6	816	Button partly off
5	419	.514	1753		.56]	1786	465	+ 60	817	No petals off
5	419	.514	1777		.66]	1795	470	+ 60	818	Very ragged petals, none off
5	419	.514	1768	300	]	1742	443	+ 150	819	Button started to form, no petals off
7	422	.517	1782	150	]	1775	457	+ 29-1/2	820	Button started to form, no petals off
7	422	.517	1747	150	]	1740	439	+ 6	821	Button partly off
7	422	.517	1763					- 51-1/2	826	1" button off, most secondary petals off
7	422	.517	1687	340	]	1652	396	- 51-1/2	827	1" button off, most secondary petals off
7	422	.517	1715		.53]	1745	442	+ 60	832	Button started to form, no petals off
7	422	.517	1682		.56]	1706	422	+ 60	833	Very ragged petals, 1 off
7	422	.517	1710		.80]	1720	429	+ 150	836	Botton partly formed, no petals off
6	415	.518	1772		.81]	1782	460	+ 28-1/2	828	Button started to form, no petals off
6	415	.518	1686		.69]	1699	418	- 51-1/2	829	1" button off, no secondary petals off
6	415	.518	1732	360	]	1695	416	+ 6	830	1-1/8" button off, 1/2 of secondary petals off
6	415	.518	1743		.56]	1766	452	+ 60	831	Very ragged petals, 1 off, lamination not apparent
6	415	.518	1747	300	]	1773	455	+ 150	837	Button started to form, no petals off
4	412	.518	1813		.93]	1818	479	+ 30	822	Button started to form, no petals off
4	412	.518	1807		1.27]	1807	473	+ 6	823	Button started to form, no petals off
4	412	.518	1714	300	]	1686	412	- 51-1/2	824	1-1/8" button off, 1/3 of secondary petals off
4	412	.518	1703		.56]	1720	429	- 51-1/2	825	1" button off, no secondary petals off
4	412	.518	1734		.55]	1757	447	+ 60	834	Button started to form, no petals off
4	412	.518	1771	300	]	1745	441	+ 150	835	Very ragged petals, none off
1	420	.513	1776	300	]	1750	448	+ 27	838	Button partly off, no secondary petals off
1	420	.513	1724		.70]	1740	443	+ 6	839	Very ragged petals, none off
1	420	.513	1686	280	]	1662	404	- 51-1/2	840	1-1/4" button off, most secondary petals off
1	420	.513	1736		.70]	1750	448	+ 60	841	Button started to form, 1 petal off
1	420	.513	1705		.97]	1710	428	+ 150	842	Button started to form,no petals off

TABLE 6

CAL .50 IMPACT DATA STS

AVERAGE BRINELL HARDNESS 371 Kg/mm^2 at 28° C

N.R.L. Sample Number	Brinell Hardness at 28° C (Kg/mm^2)	Thickness (inches)	Striking Velocity (ft/sec)	Residual Velocity (ft/sec)	Penetration (inches)	Limit Velocity (ft/sec)	P x 10^{-3} (lb/in^2)	Temperature (°C)	Impact Number	Remarks
7	374	.514	1787					+ 31	743	No petals off, core rebounded
7	374	.514	1812		.73]	1823	485	+ 29	744	Petals very ragged, 2 loose
7	374	.514	1802		.67]	1819	483	+ 6	745	1 Petal off
7	374	.514	1857	300	]	1821	484	- 51-1/2	754	2 petals off
7	374	.514	1778					- 51-1/2	755	2 petals off, core rebounded
7	374	.514	1788		1.09]	1790	467	+ 150	763	1 petal loose
7	374	.514	1813		.67]	1828	487	+ 30	764	4 petals off
9	372	.515	1859					- 51-1/2	753	Core broke, point stuck in plate, 1 petal off
9	372	.515	1853		.69]	1870	510	+ 6	746	1 petal off
9	372	.515	1783					+ 60	747	No petals off, core rebounded
9	372	.515	1826		.59]	1848	497	+ 60	748	1 petal loose
9	372	.515	1789					+ 60	749	No petals off, core rebounded
9	372	.515	1814		.68]	1827	486	+ 60	750	1 petal off
9	372	.515	1864	0	]	1864	505	- 51-1/2	752	2 petals off
6	375	.512	1788					- 51-1/2	756	1 petal loose, core rebounded
6	375	.512	1847					- 51-1/2	759	1 petal off, core rebounded
6	375	.512	1838					- 51-1/2	760	No petals off, core rebounded
6	375	.512	1833		.70]	1849	501	- 51-1/2	761	1 petal off, 1 loose
6	375	.512	1796		.91]	1800	475	+ 150	762	2 petals off
11	370	.513	1885		.73]	1895	525	- 51-1/2	765	1 petal off
11	370	.513	1845		.58]	1870	511	- 51-1/2	766	1 petal off
11	370	.513	1836		.72]	1847	500	+ 29-1/2	777	1 petal loose
11	370	.513	1838		.50]	1859	506	+ 6	787	No petals off
11	370	.513	1833					+ 6	788	No petals off, core rebounded
11	370	.513	1864		.58]	1889	522	+ 6	789	2 petals loose
11	370	.513	1807	225	]	1792	470	+ 150	797	1 petal off
11	370	.513	1823		1.20]	1825	487	+ 105	798	No petals off
10	371	.513	1807					- 51-1/2	767	2 petals off
10	371	.513	1903	225	]	1892	524	- 51-1/2	768	2 petals off
10	371	.513	1854		.74]	1865	509	+ 29	778	1 petal loose
10	371	.513	1855	300	]	1830	490	+ 105	779	1 petal off
10	371	.513	1881	350	]	1846	499	+ 60	780	2 petals off
10	371	.513	1796		.66]	1812	480	+ 60	781	1 petal loose
10	371	.513	1876	>400				+ 150	782	2 petals off
10	371	.513	1835	>400				+ 150	783	1 petal loose
10	371	.513	1764		.73]	1775	460	+ 150	784	No petals off
12	370	.515	1774		.61]	1796	470	+ 105	785	No petals off
12	370	.515	1781		.72]	1792	468	+ 150	786	No petals off
12	370	.515	1828		.52]	1863	505	- 51-1/2	772	No petals off
12	370	.515	1877		.61]	1898	525	- 51-1/2	773	2 petals off, 1 loose
12	370	.515	1834		.63]	1854	500	+ 30-1/2	775	No petals off
12	370	.515	1850		.67]	1865	506	+ 29-1/2	776	1 petal loose
12	370	.515	1777					+ 29-1/2	774	No petals off, core rebounded
8	365	.515	1801					+ 30	794	No petals off, core rebounded
8	365	.515	1892	>400				+ 31	795	2 petals off
8	365	.515	1857		.81]	1866	507	+ 32-1/2	796	1 petal off
8	365	.515	1861		.56]	1888	519	- 51-1/2	799	1 petal off
8	365	.515	1889		.87]	1895	523	-51-1/2	800	2 petals off
8	365	.515	1782		1.13]	1783	463	+ 150	801	No petals off
8	365	.515	1823		.95]	1825	485	+ 150	802	1 petal off

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TABLE 7

CAL .50 IMPACT DATA STS

AVERAGE BRINELL HARDNESS 260-1/2 Kg/mm^2 at 28° C

N.R.L. Sample Number	Thickness (inches)	Striking Velocity (ft/sec)	Residual Velocity (ft/sec)	Penetration (inches)	Limit Velocity (ft/sec)	P x 10^{-3} (lb/in^2)	Temperature (°C)	Impact Number	Remarks
15	.516	1622					+ 29	676	Petals somewhat ragged, none off
15	.516	1806					+ 29	677	" " "
15	.516	1736					+ 30-1/2	678	" " "
15	.516	1710		1.12]	1710	425	+ 31-1/2	679	" " "
15	.516	1763					+ 31-1/2	680	" " "
15	.516	1682		.69]	1706	424	+ 29-1/2	681	" " "
15	.516	1672		.65]	1704	423	+ 30	682	" " "
15	.516	1687		.71]	1705	423	+31	683	" " "
15	.516	1688		.78]	1700	420	+ 31	684	" " "
17	.513	1766					+ 31	685	" " "
17	.513	1724		1.20]	1766	435	+ 32	686	" " "
17	.513	1733		1.19]	1735	440	+ 6	723	" " "
17	.513	1797	250	]	1777	462	- 51-1/2	724	" " "
17	.513	1667		.80]	1675	410	+ 60	731	" " "
17	.513	1667	350	]	1632	390	+ 105	732	" " "
17	.513	1688	>400				+ 105	733	" " "
17	.513	1567		.56]	1637	392	+ 105	734	" " "
14	.514	1756		.66]	1790	465	- 51-1/2	725	" " "
14	.514	1672	400	]	1620	383	+ 150	729	" " "
14	.514	1723	225	]	1711	427	+ 30	721	" " "
14	.514	1736		1.17]	1738	440	+ 6	722	" " "
14	.514	1625	200	]	1613	380	+ 150	730	" " "
18	.515	1779		.97]	1786	465	- 51-1/2	726	" " "
18	.515	1782	320		1750	449	- 14	727	" " "
18	.515	1763	100		1760	451	- 14	728	" " "
18	.515	1688		1.30]	1688	415	+ 60	735	" " "
18	.515	1557					+ 105	736	Core rebounded, petals somewhat ragged, none off
18	.515	1638	350	]	1603	374	+ 105	738	Petals somewhat ragged, none off
18	.515	1620		1.00]	1625	384	+ 105	739	" " "
18	.515	1613	350	]	1573	360	+ 150	740	" " "
16	.516	1692		.75]	1706	424	+ 32	742	" " "

TABLE 8

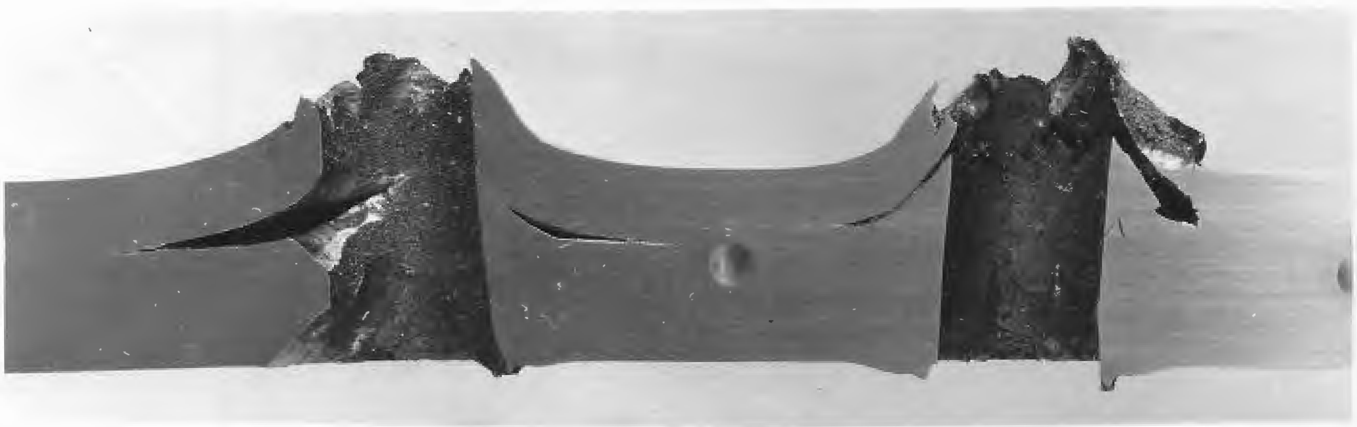
CAL .50 IMPACT DATA STS HEAT TREATED TO VARIOUS HARDNESSES

N.R.L. Sample Number	Brinell Hardness at 28° C (Kg/mm²)	Thickness (inches)	Striking Velocity (ft/sec)	Residual Velocity (ft/sec)	Penetration (inches)	Limit Velocity (ft/sec)	P x 10^{-3} (lb/in²)	Temperature (°C)	Impact Number	Remarks
5	258	.514	1828					+ 28-1/2	462	Petals somewhat ragged, none off
5	258	.514	1676		.69			+ 29	463	" " "
5	258	.514	1660		.50			+ 29	464	" " "
5	258	.514	1795					+ 29-1/2	465	" " "
5	258	.514	1729					+ 29-1/2	466	" " "
5	258	.514	1728					+ 33-1/2	483	" " "
5	258	.514	1703					+ 33-1/2	484	" " "
						1694	419	+ 29		
4	295	.512	1857					+ 30-1/2	467	" " "
4	295	.512	1687		.59			+ 30-1/2	468	" " "
4	295	.512	1732		.66			+ 31	469	" " "
4	295	.512	1792					+ 31-1/2	470	" " "
4	295	.512	1762					+ 31-1/2	471	" " "
4	295	.512	1763					+ 33-1/2	485	" " "
4	295	.512	1755					+ 34-1/2	486	" " "
4	295	.512	1758					+ 34-1/2	487	" " "
						1750	449	+ 31		
3	338	.514	1810		.88			+ 32	473	1 petal almost off
3	338	.514	1820		.87			+ 33-1/2	477	Petals somewhat ragged, none off
3	338	.514	1805		.67			+ 33-1/2	478	" " "
3	338	.514	1870					+ 33-1/2	479	" " "
						1822	485	+ 33		
2	313	.514	1786		1.27			+ 32	472	" " "
2	313	.514	1784		1.06			+ 33-1/2	481	2 petals almost off
2	313	.514	1779		1.27			+ 33-1/2	482	Petals somewhat ragged, none off
						1785	465	+ 33		
1	377	.510	1880					+ 32	474	" " "
1	377	.510	1832					+ 33	475	" " , 3 off
1	377	.510	1815		.75			+ 33	476	" " , none off
1	377	.510	1855					+ 33-1/2	480	" " , 1 off
						1827	492	+ 33		

Cal. .50 Impacts on 0.515 Inch Thick 1% Nickel Steel

Impact Number 809
Testing Temperature +150°C
Plate Number 3

Brinell Hardness { 407 Kg/mm^2 at +28°C
393 Kg/mm^2 at +150°C }



Impact Number 813
Testing Temperature +30°C

Impact Number 814
Testing Temperature +31 1/2°C

Plate Number 5
Brinell Hardness 419 Kg/mm^2 at +28°C

Impact Number 829
Testing Temperature - -51 1/2°C
Plate Number 6
Brinell Hardness 415 Kg/mm at 28°C
437 Kg/mm^2 at - -51 1/2°C

[redacted]

PLATE I

METHOD OF CONTROLLING TEMPERATURE OF HARDNESS SAMPLES

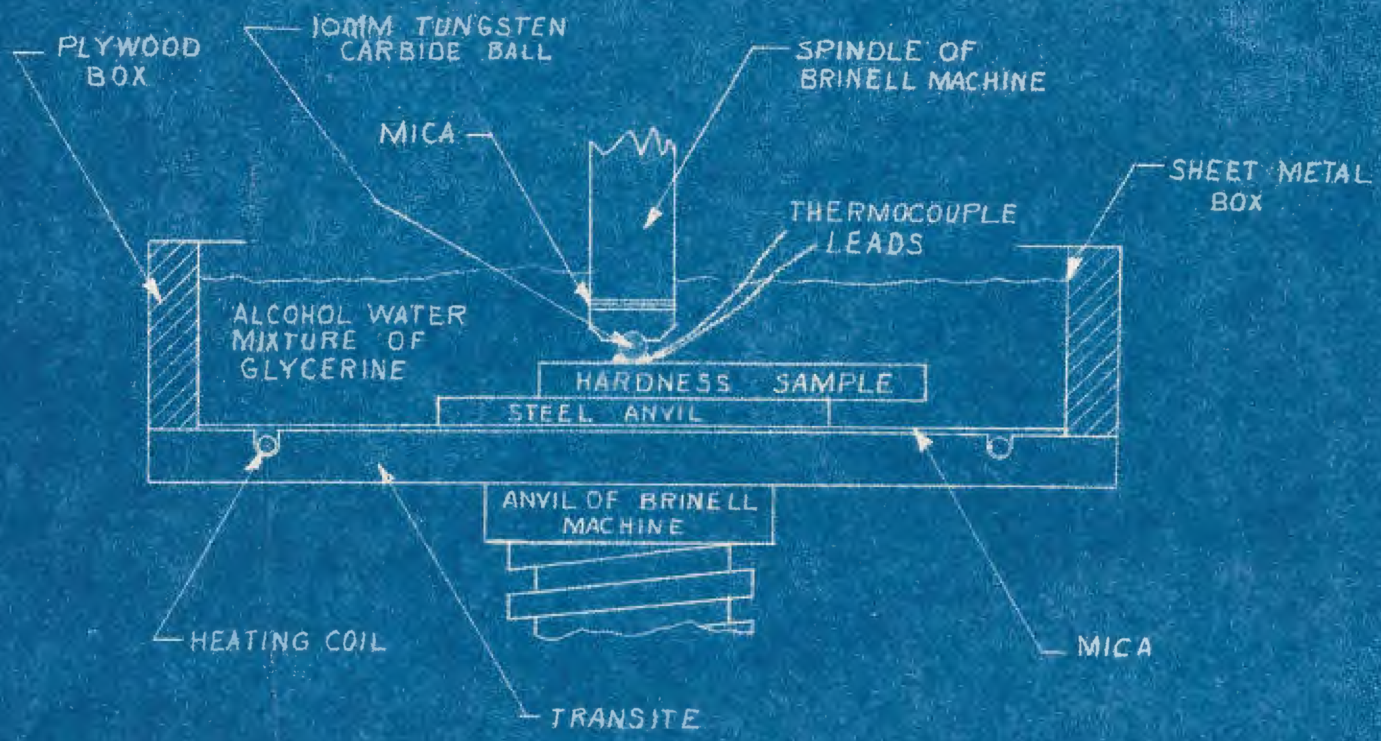
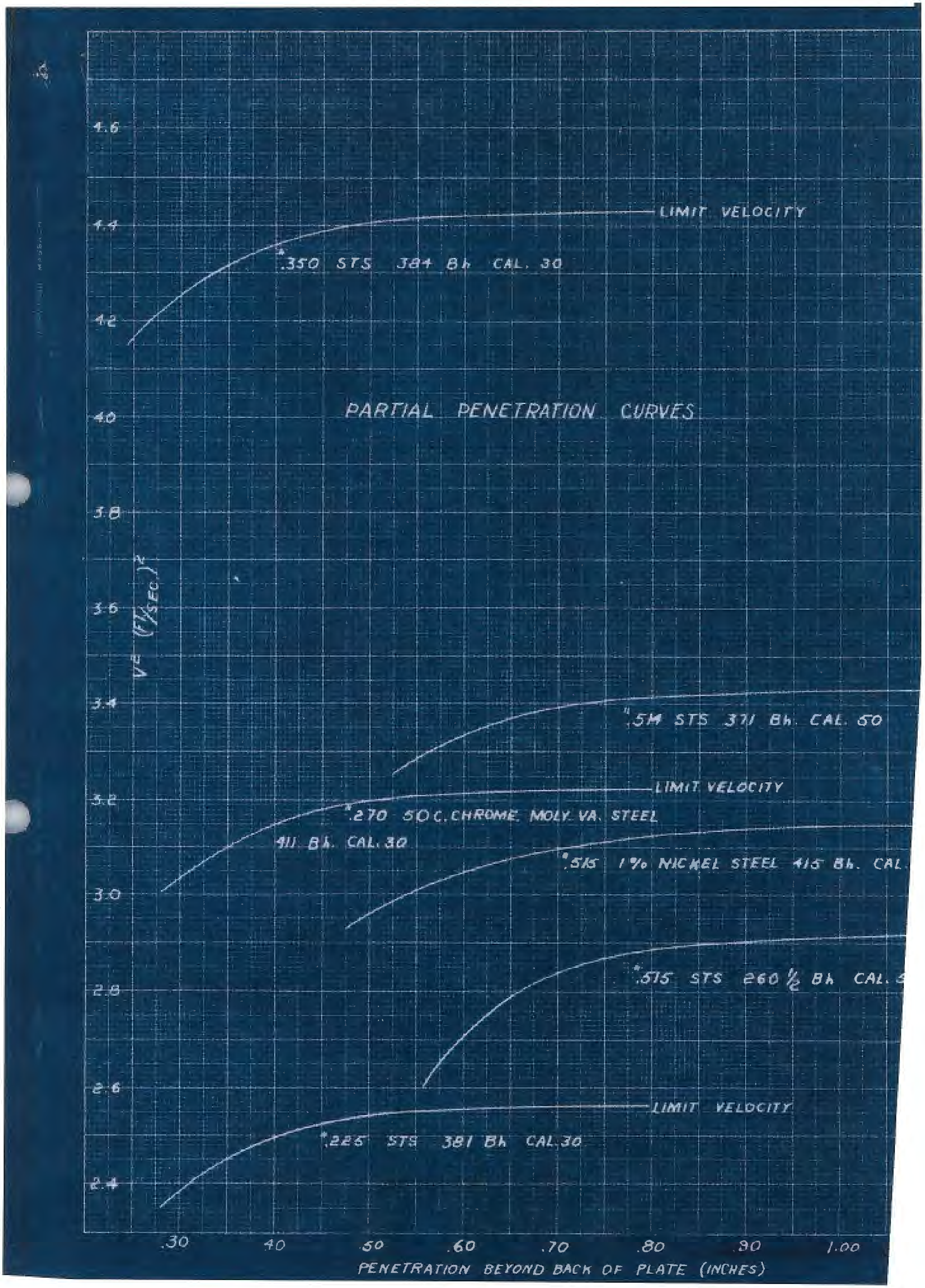
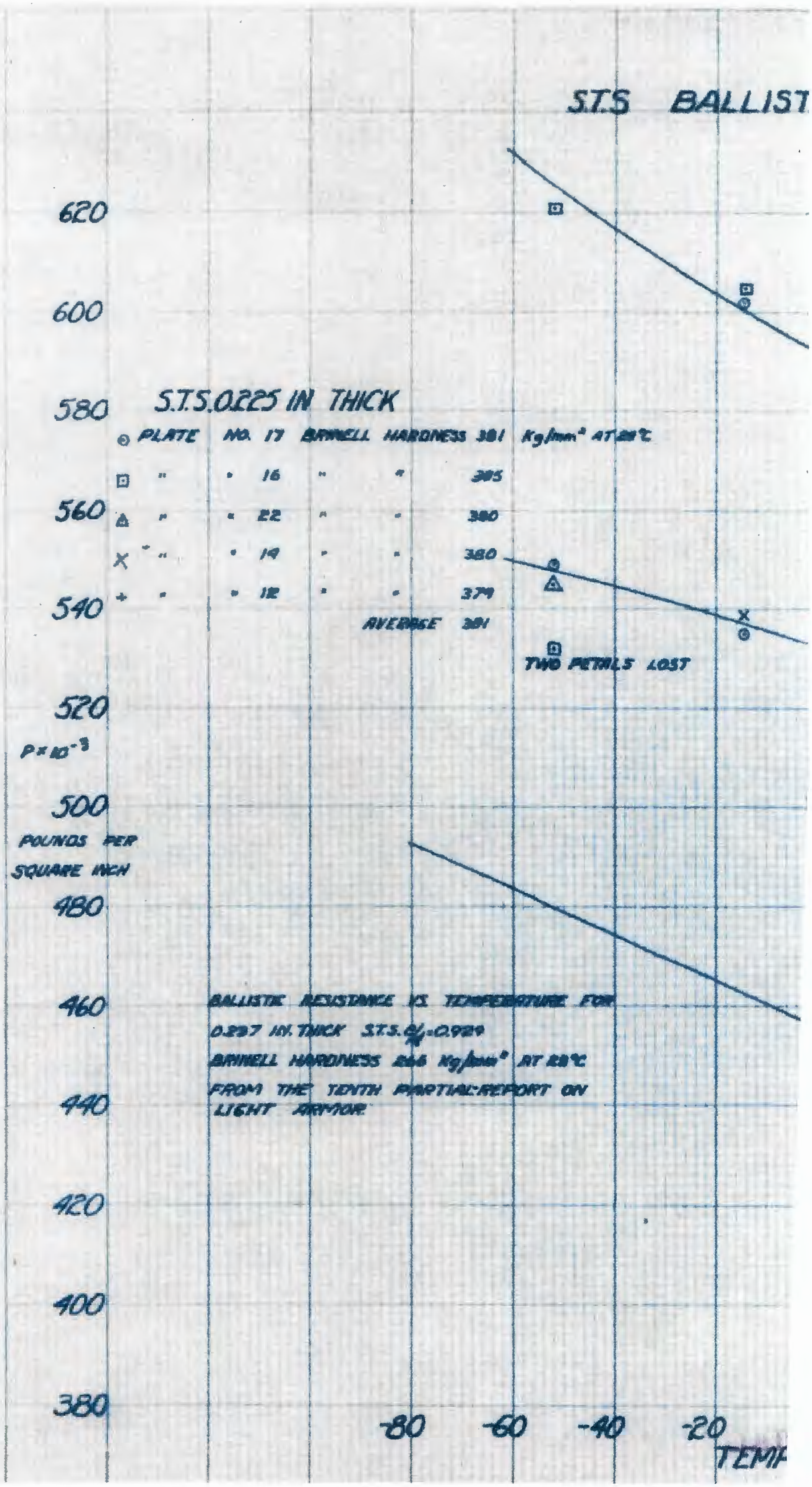


PLATE 2



PARTIAL PENETRATION CURVES
LIMIT VELOCITY
.350 STS 384 Bh CAL. 30
.5?? STS 371 Bh CAL. 50
LIMIT VELOCITY
.270 50 C. CHROME MOLY. VA. STEEL
411 Bh. CAL. 30
.515 1% NICKEL STEEL 415 Bh. CAL.
.515 STS 260 ½ Bh CAL.
LIMIT VELOCITY
.225 STS 381 Bh CAL. 30
4.6
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
2.4
V^2 (FT/SEC)^2
.30
.40
.50
.60
.70
.80
.90
1.00
PENETRATION BEYOND BACK OF PLATE (INCHES)


S.T.S BALLIST
620
600
580
560
540
520
500
480
460
440
420
400
380
P × 10⁻³
POUNDS PER
SQUARE INCH
S.T.S. 0.225 IN THICK
PLATE NO. 17 BRINELL HARDNESS 381 Kg/mm² AT
" " 16 " " 385
" " 22 " " 380
" " 19 " " 380
" " 12 " " 379
AVERAGE 381
TWO PETALS LOST
BALLISTIC RESISTANCE VS. TEMPERATURE FOR
0.297 IN. THICK S.T.S.
BRINELL HARDNESS
FROM THE TENTH PARTIAL REPORT ON
LIGHT ARMOR
-80
-60
-40
-20
TEMP

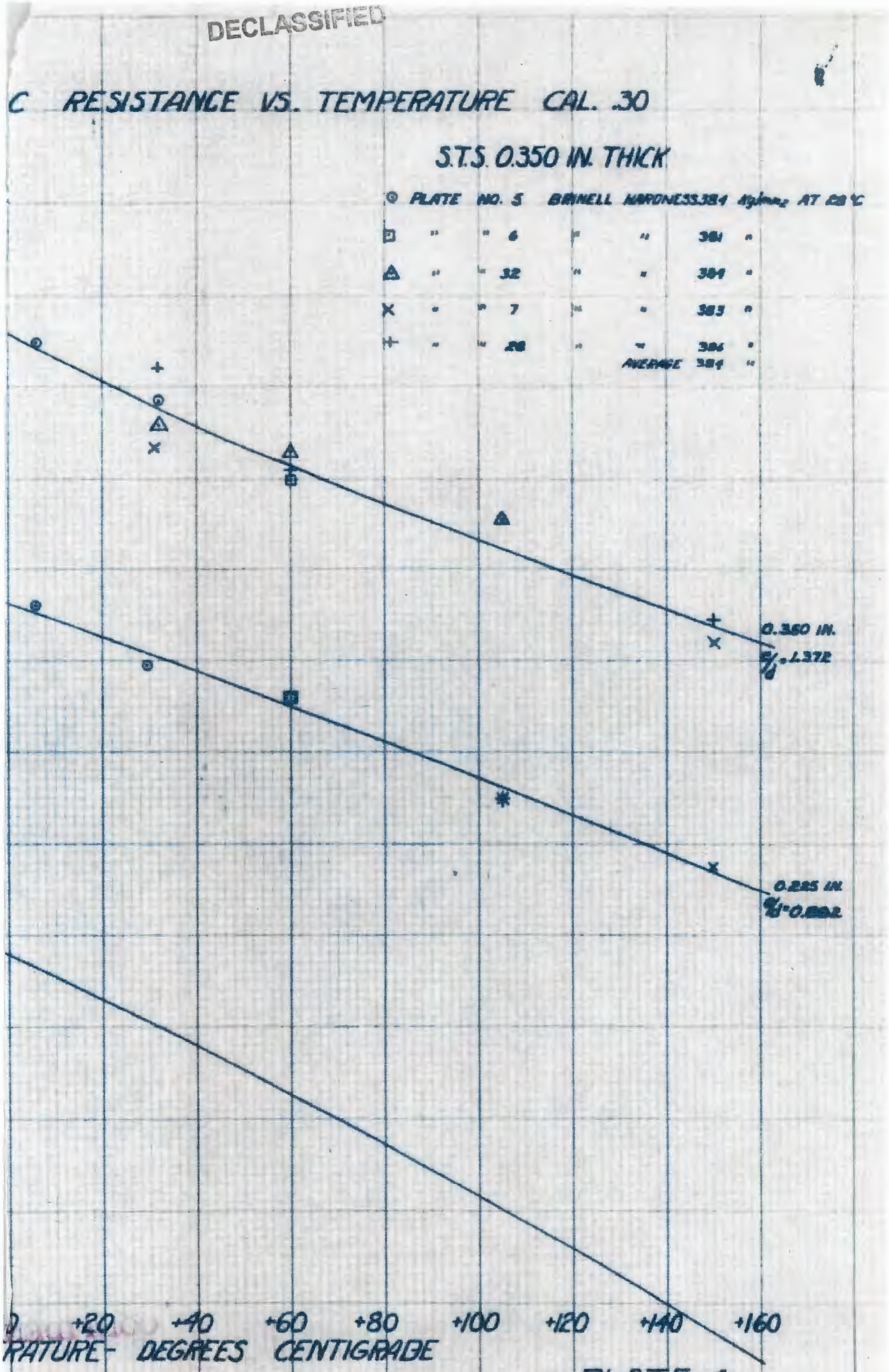
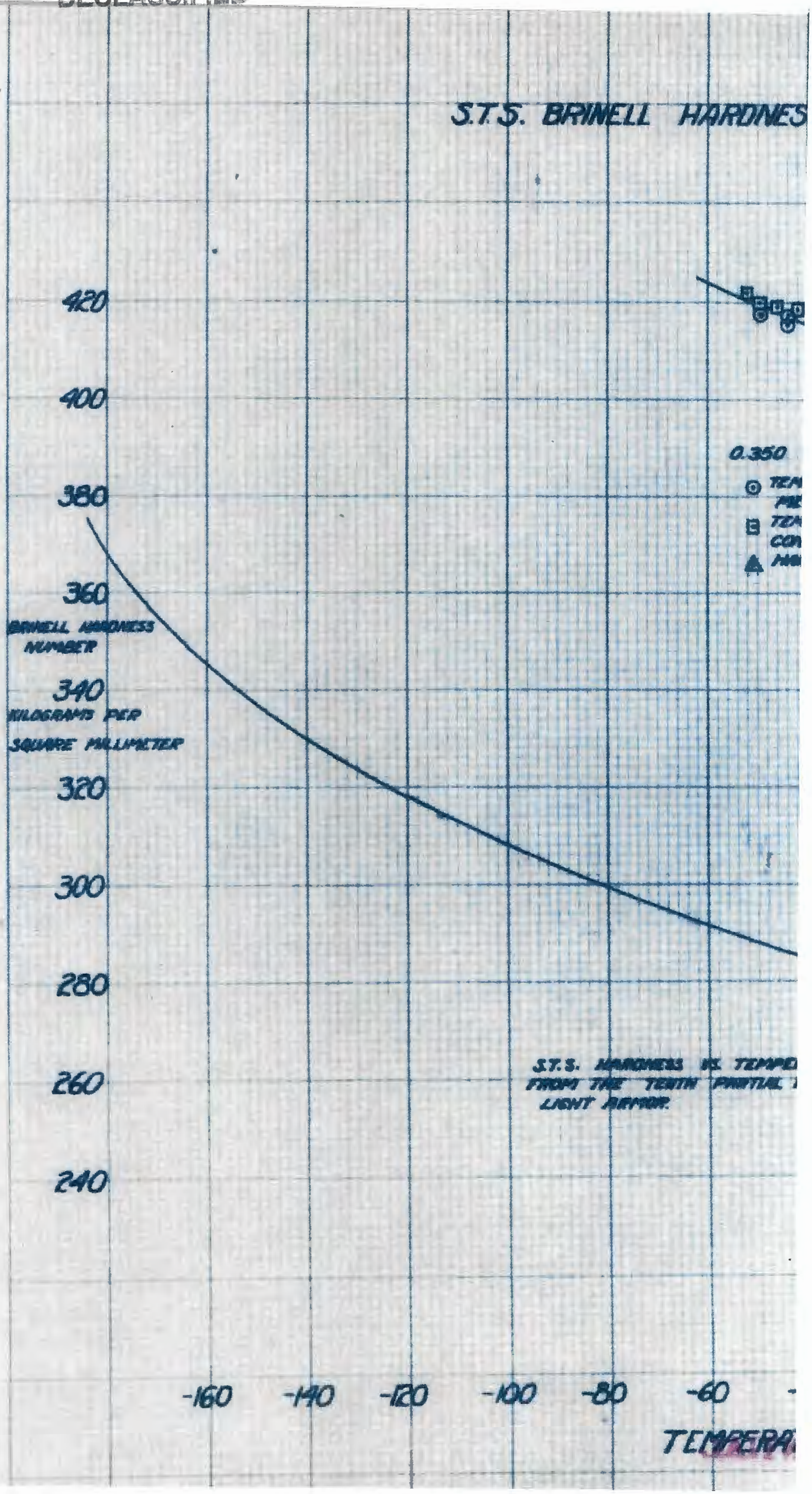
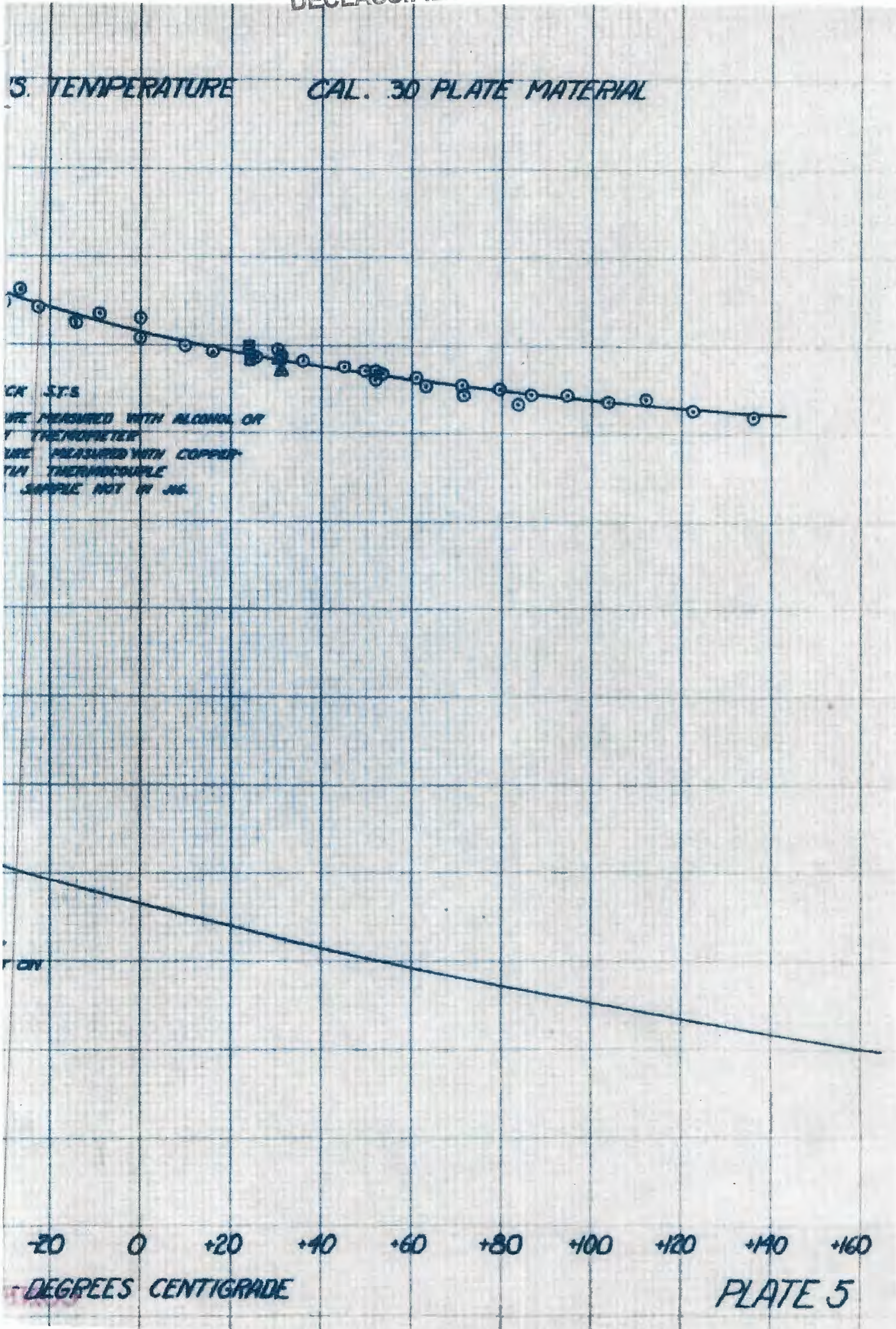
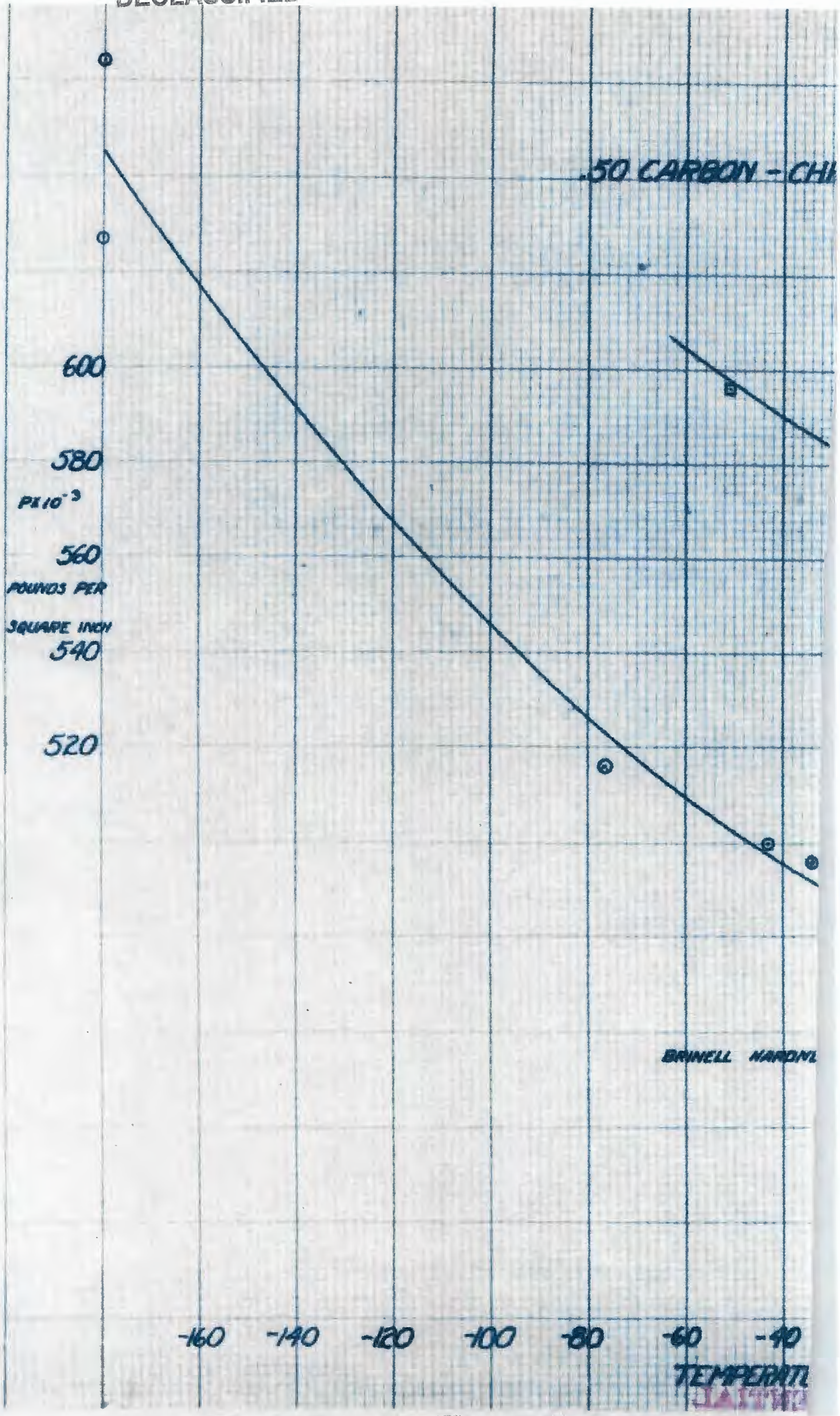
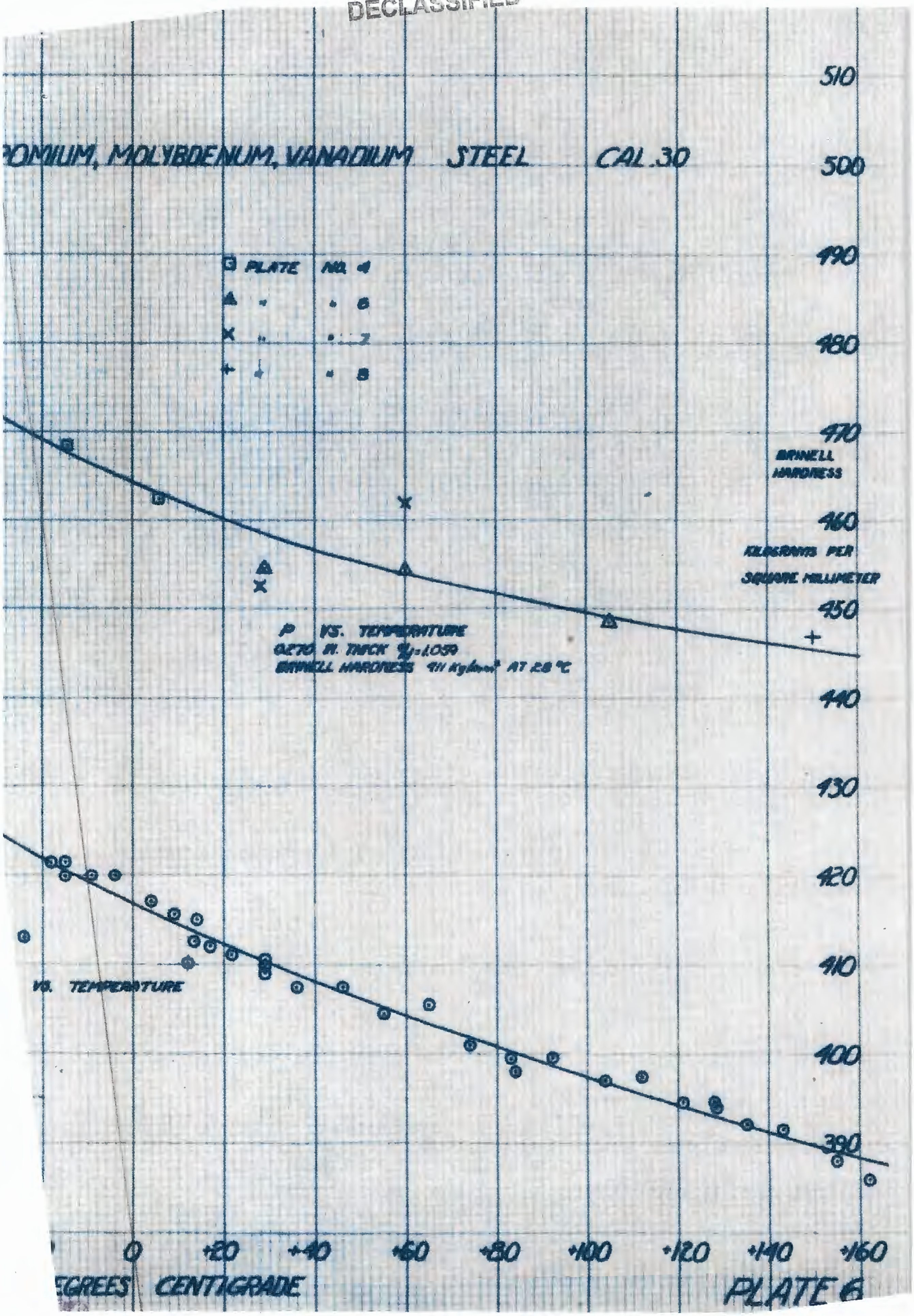

C RESISTANCE VS. TEMPERATURE CAL. .30
S.T.S. 0.350 IN. THICK
PLATE NO. 5
0.350 IN.
0.225 IN.
0 +20 +40 +60 +80 +100 +120 +140 +160
RATURE- DEGREES CENTIGRADE

PLATE 4

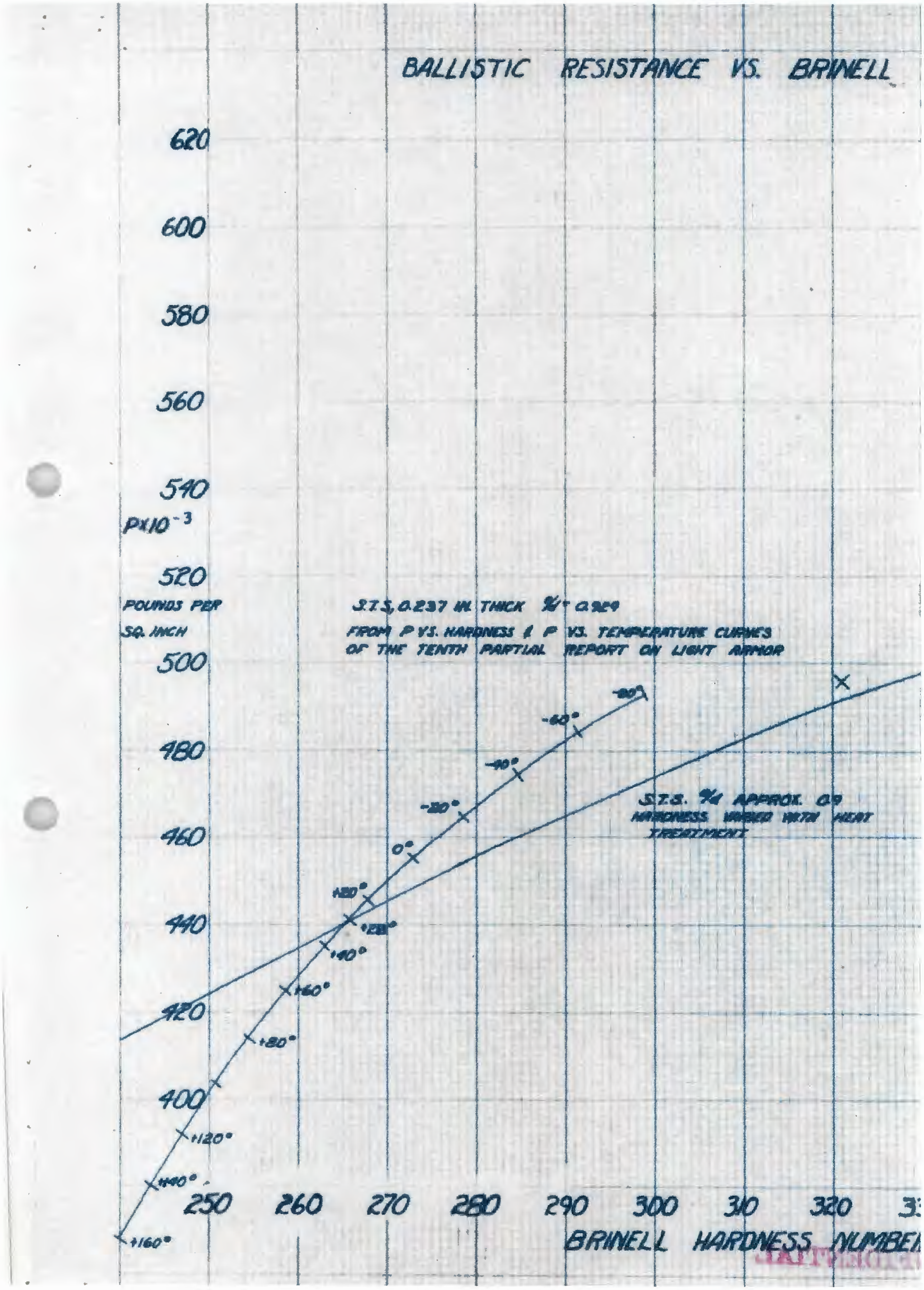

S.T.S. BRINELL HARDNES
420
400
380
360
340
320
300
280
260
240
BRINELL HARDNESS NUMBER
KILOGRAMS PER SQUARE MILLIMETER
0.350
S.T.S. HARDNESS VS. TEMPE
FROM THE TENTH PARTIAL
LIGHT ARMOR
-160
-140
-120
-100
-80
-60
TEMPERA


S. TEMPERATURE CAL. 30 PLATE MATERIAL
CK S.T.S
MEASURED WITH ALCOHOL OR
THERMOMETER
MEASURED WITH COPPER-
THERMOCOUPLE
SAMPLE NOT IN JIG.
-20
0
+20
+40
+60
+80
+100
+120
+140
+160
- DEGREES CENTIGRADE
PLATE 5

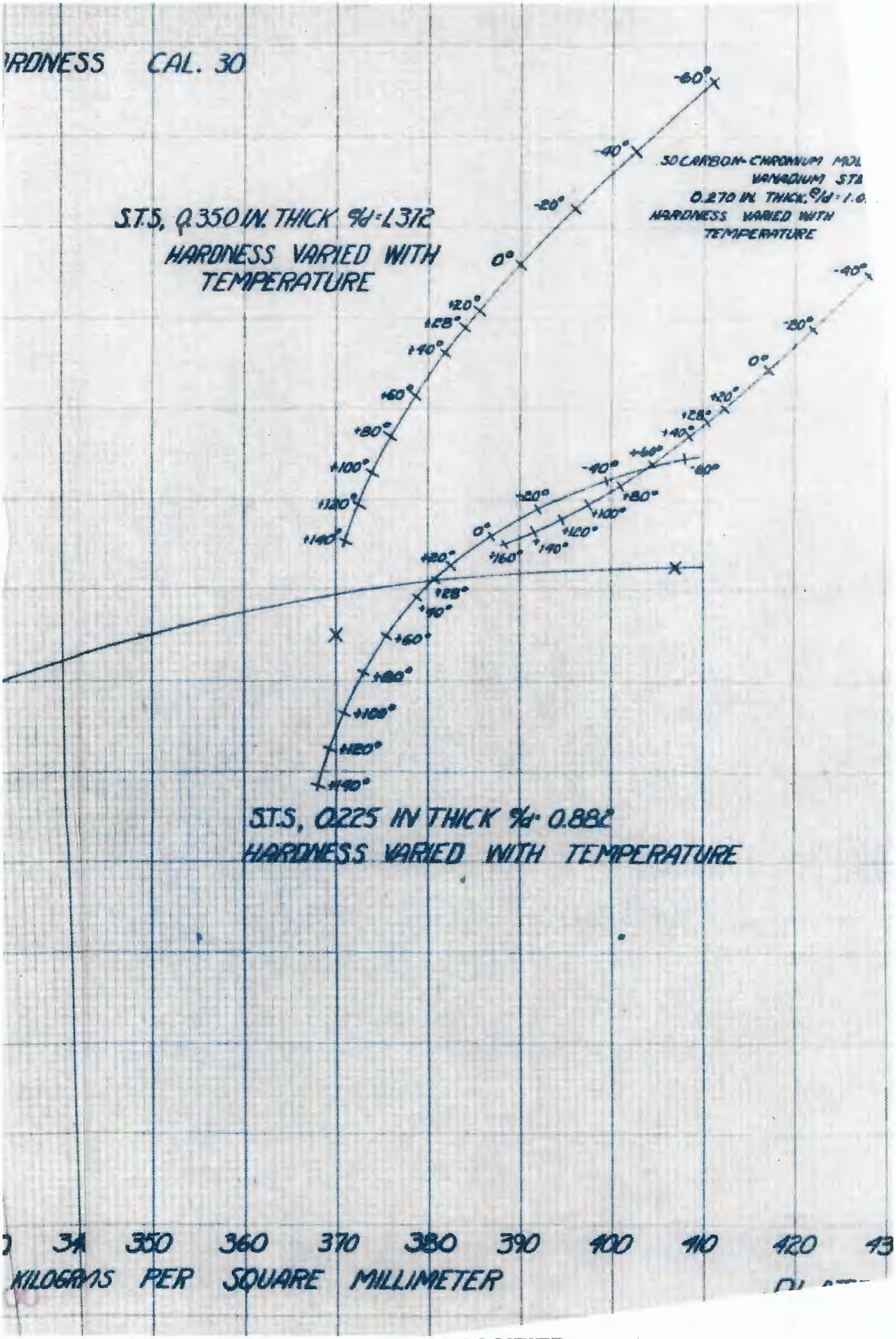

.50 CARBON - CH
600
580
PX10^-3
560
POUNDS PER
SQUARE INCH
540
520
BRINELL HARDN
-160
-140
-120
-100
-80
-60
-40
TEMPERAT



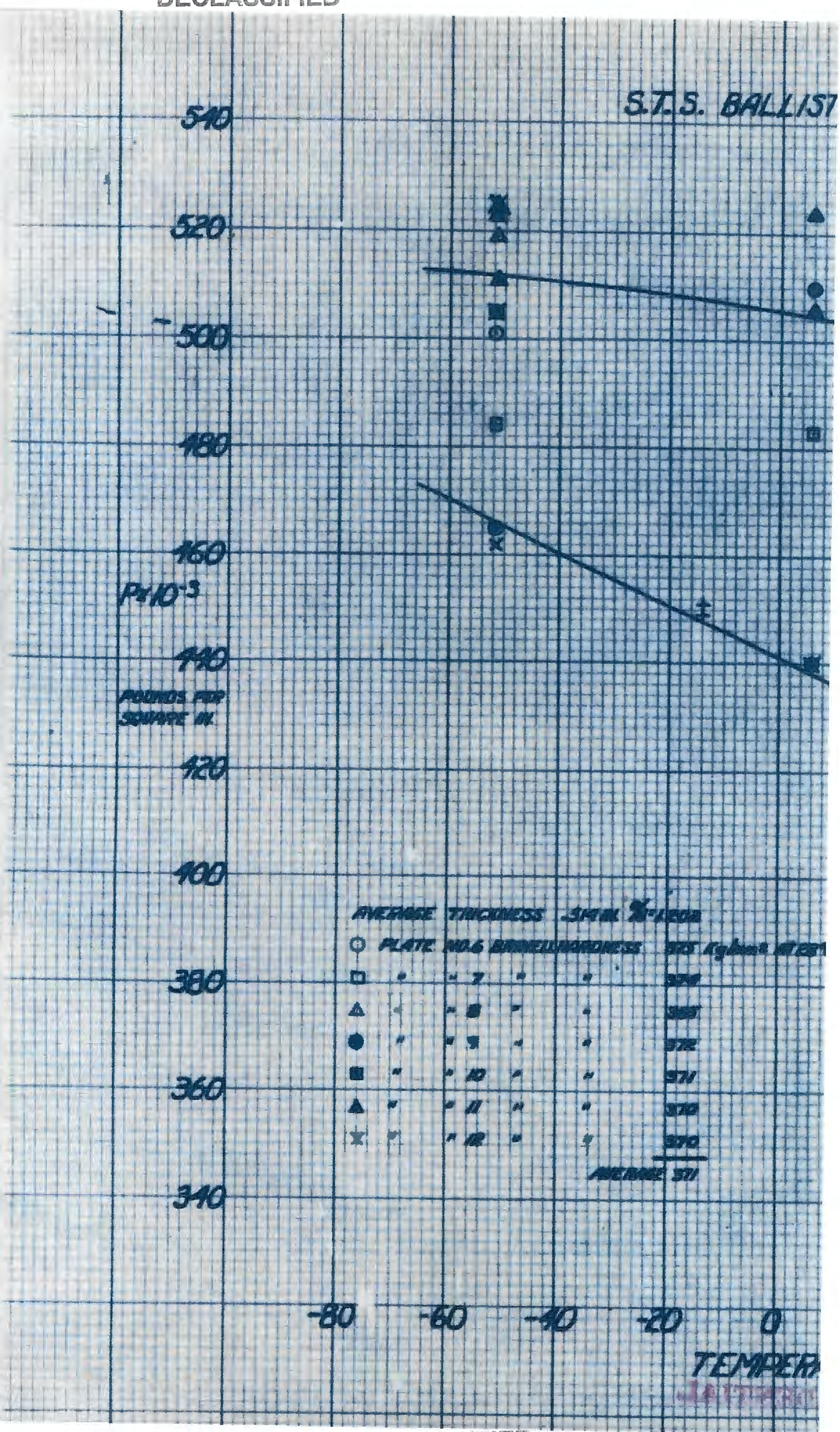
...ROMIUM, MOLYBDENUM, VANADIUM STEEL CAL .30
PLATE NO. 4
" " 6
" " 7
" " 8
P VS. TEMPERATURE
VS. TEMPERATURE
BRINELL HARDNESS
KILOGRAMS PER SQUARE MILLIMETER
510
500
490
480
470
460
450
440
430
420
410
400
390
0
+20
+40
+60
+80
+100
+120
+140
+160
...EGREES CENTIGRADE
PLATE 6


BALLISTIC RESISTANCE VS. BRINELL
620
600
580
560
540
P x 10^-3
520
POUNDS PER
SQ. INCH
500
480
460
440
420
400
S.T.S. 0.237 IN. THICK
FROM P VS. HARDNESS & P VS. TEMPERATURE CURVES
OF THE TENTH PARTIAL REPORT ON LIGHT ARMOR
-80°
-60°
-40°
-20°
0°
+20°
+40°
+60°
+80°
+120°
+140°
+160°
S.T.S. APPROX. 0.9
HARDNESS VARIED WITH HEAT
TREATMENT
250
260
270
280
290
300
310
320
BRINELL HARDNESS NUMBER

DECLASSIFIED



DECLASSIFIED


S.T.S. BALLIST
540
520
500
480
460
P x 10^-3
440
POUNDS PER
SQUARE IN.
420
400
380
360
340
AVERAGE THICKNESS
PLATE NO.6
372
371
370
370
AVERAGE 371
-80
-60
-40
-20
0
TEMPER

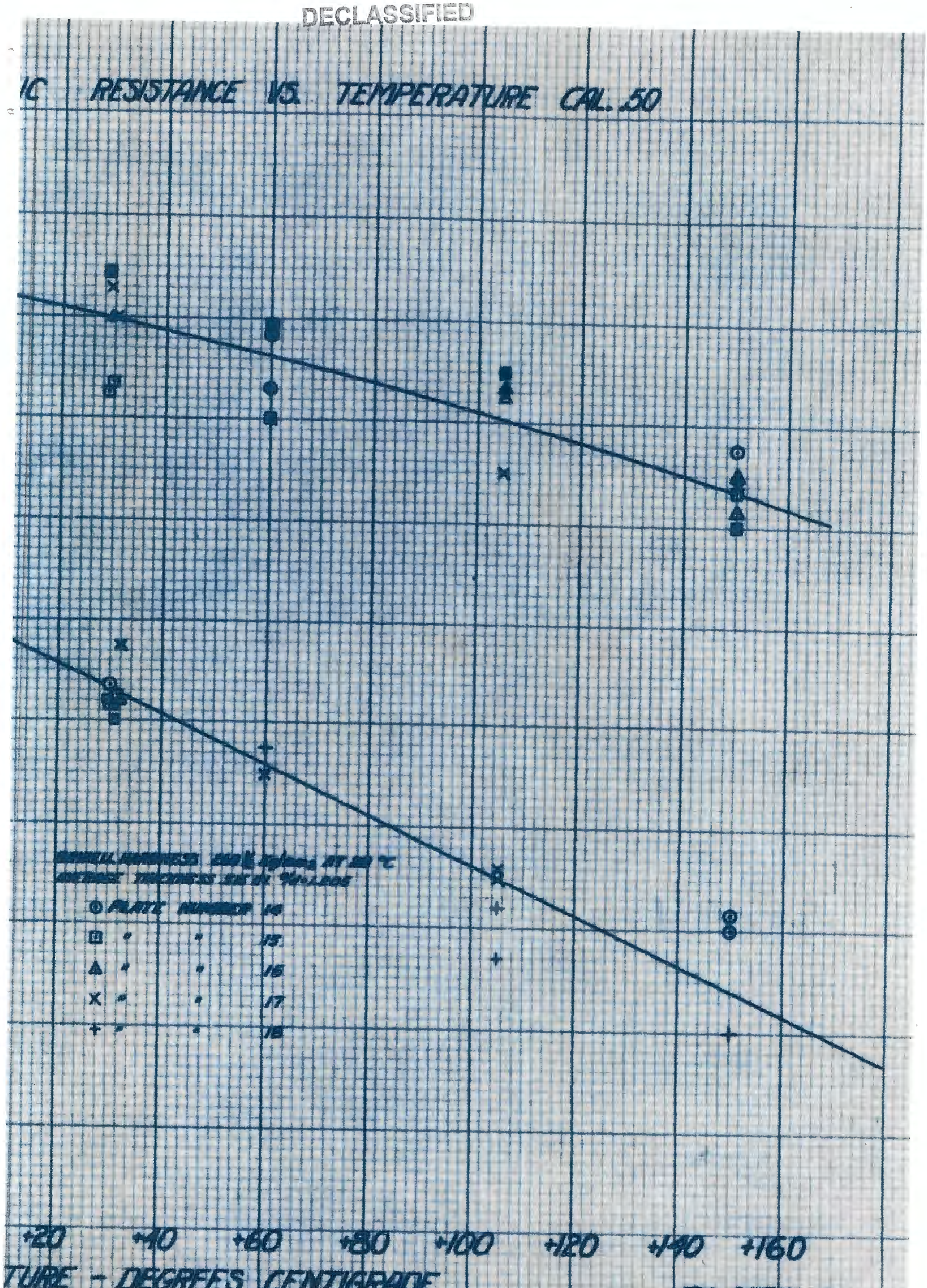
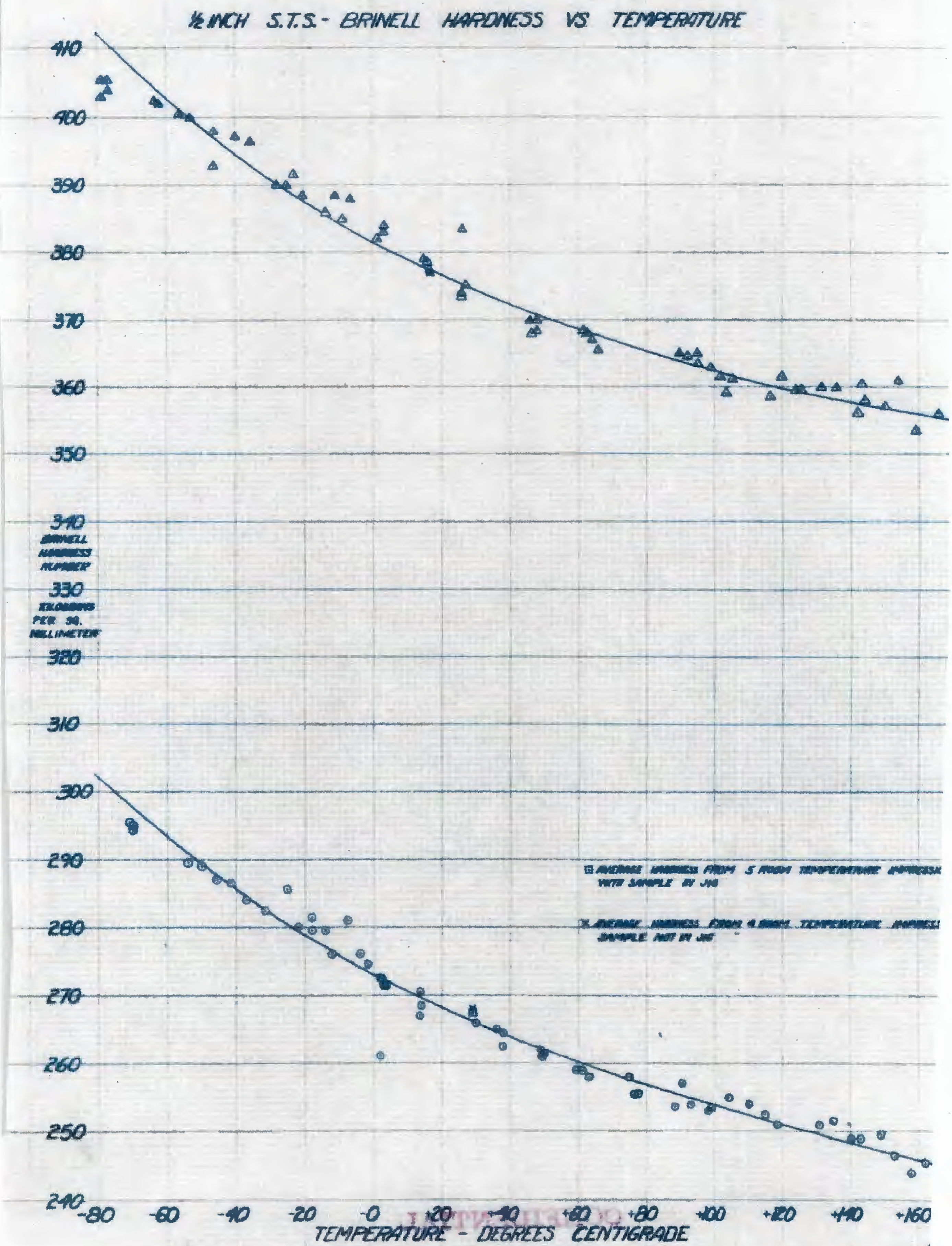
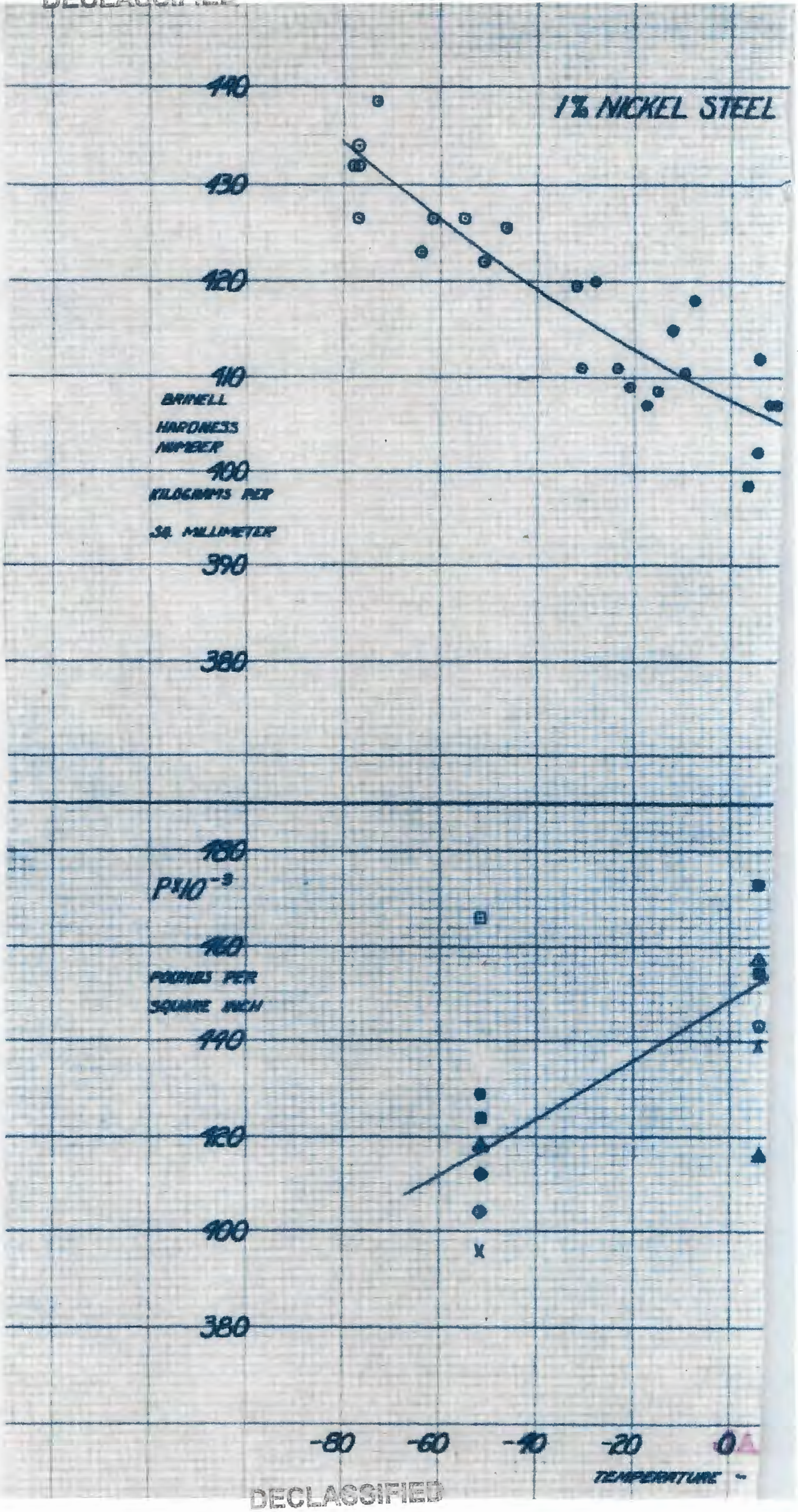

IC RESISTANCE VS. TEMPERATURE CAL. .50
PLATE NUMBER 14
" " 15
" " 16
" " 17
" " 18
+20
+40
+60
+80
+100
+120
+140
+160
TURE - DEGREES CENTIGRADE

PLATE 8


½ INCH S.T.S. - BRINELL HARDNESS VS TEMPERATURE
410
400
390
380
370
360
350
340
BRINELL HARDNESS NUMBER
330
KILOGRAMS PER SQ. MILLIMETER
320
310
300
290
280
270
260
250
240
-80
-60
-40
-20
-0
+20
+40
+60
+80
+100
+120
+140
+160
TEMPERATURE - DEGREES CENTIGRADE


1% NICKEL STEEL
440
430
420
410
BRINELL HARDNESS NUMBER
400
KILOGRAMS PER SQ. MILLIMETER
390
380
480
P X 10^-3
460
POUNDS PER SQUARE INCH
440
420
400
380
-80
-60
-40
-20
0
TEMPERATURE

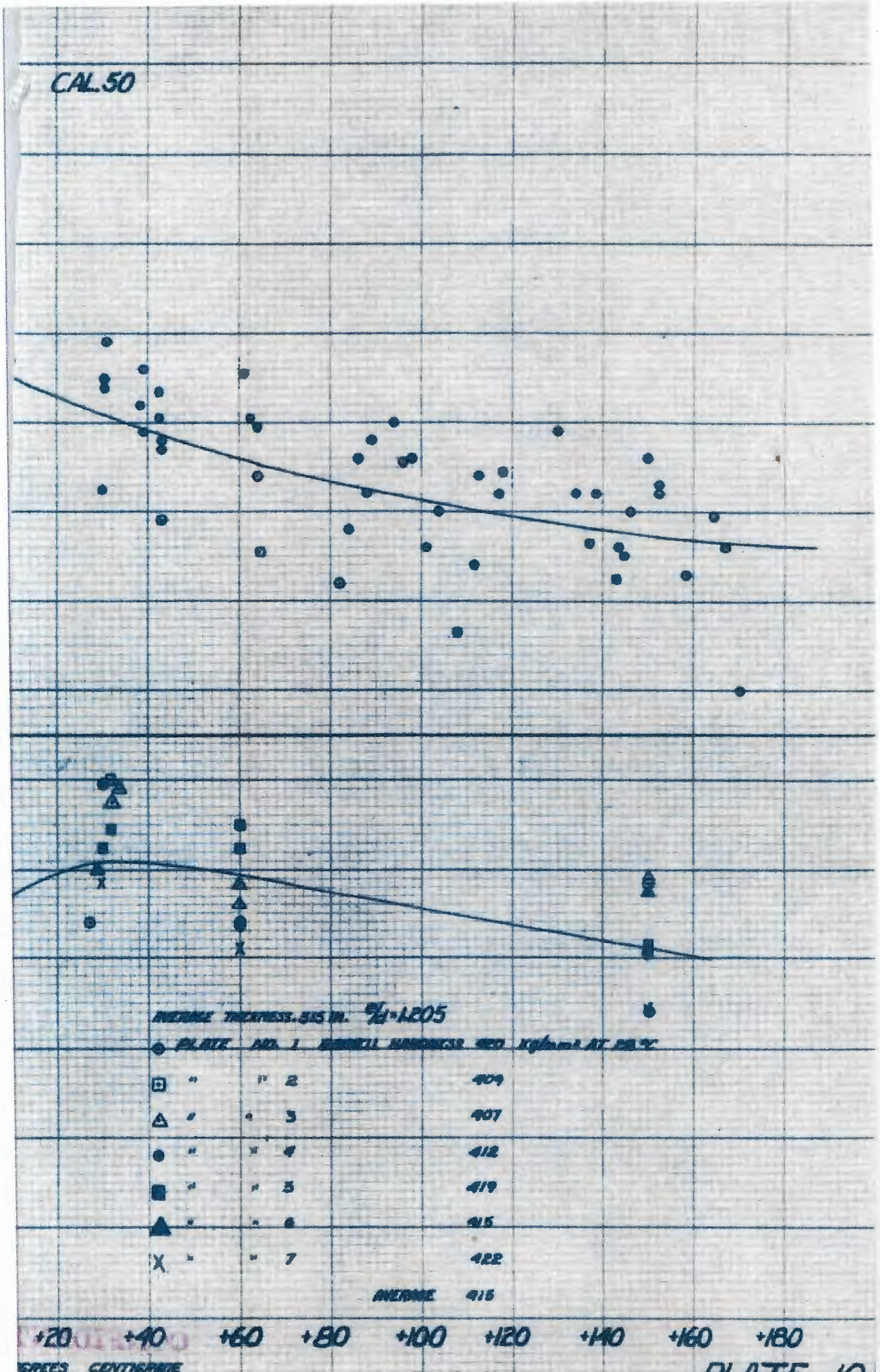
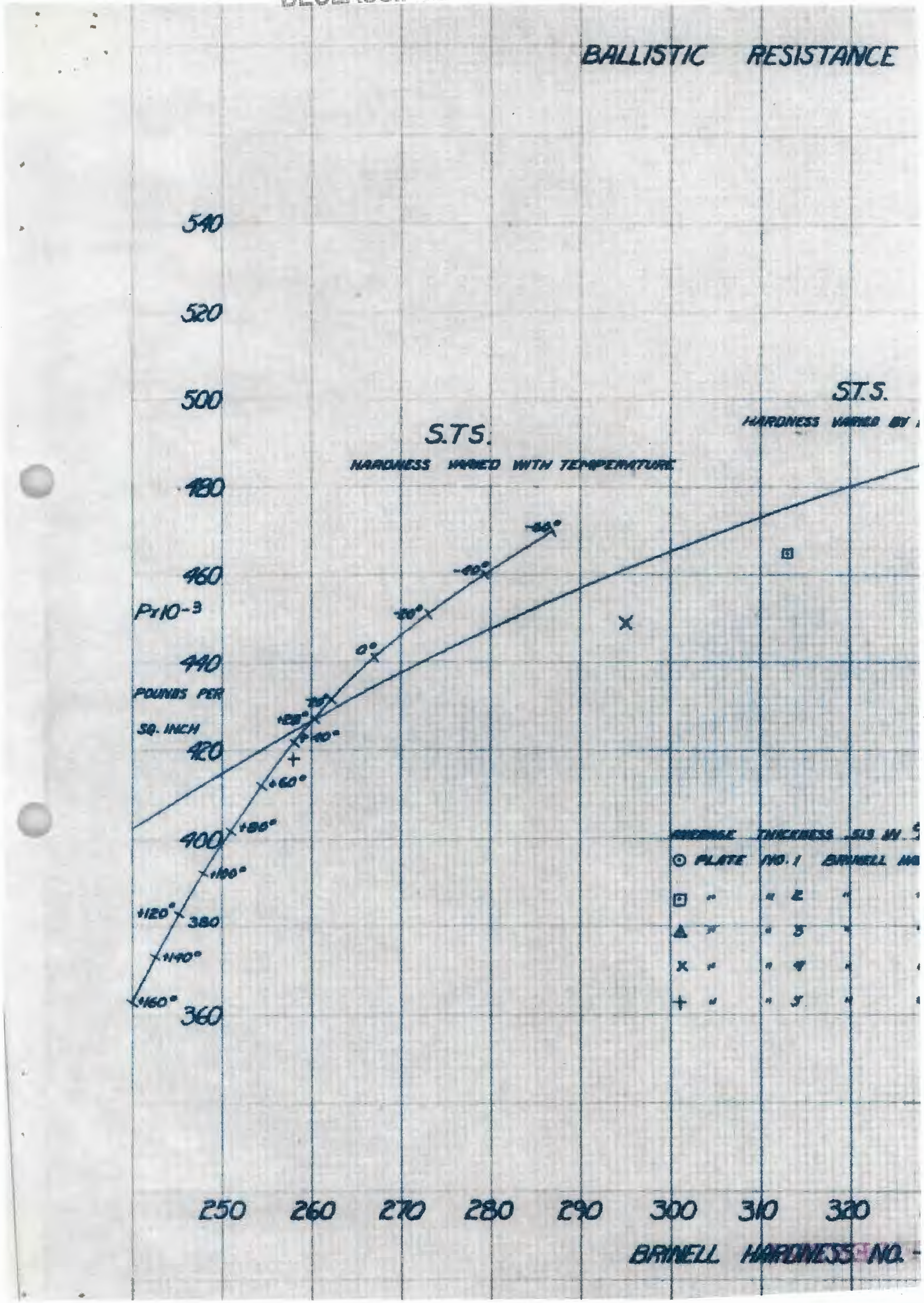
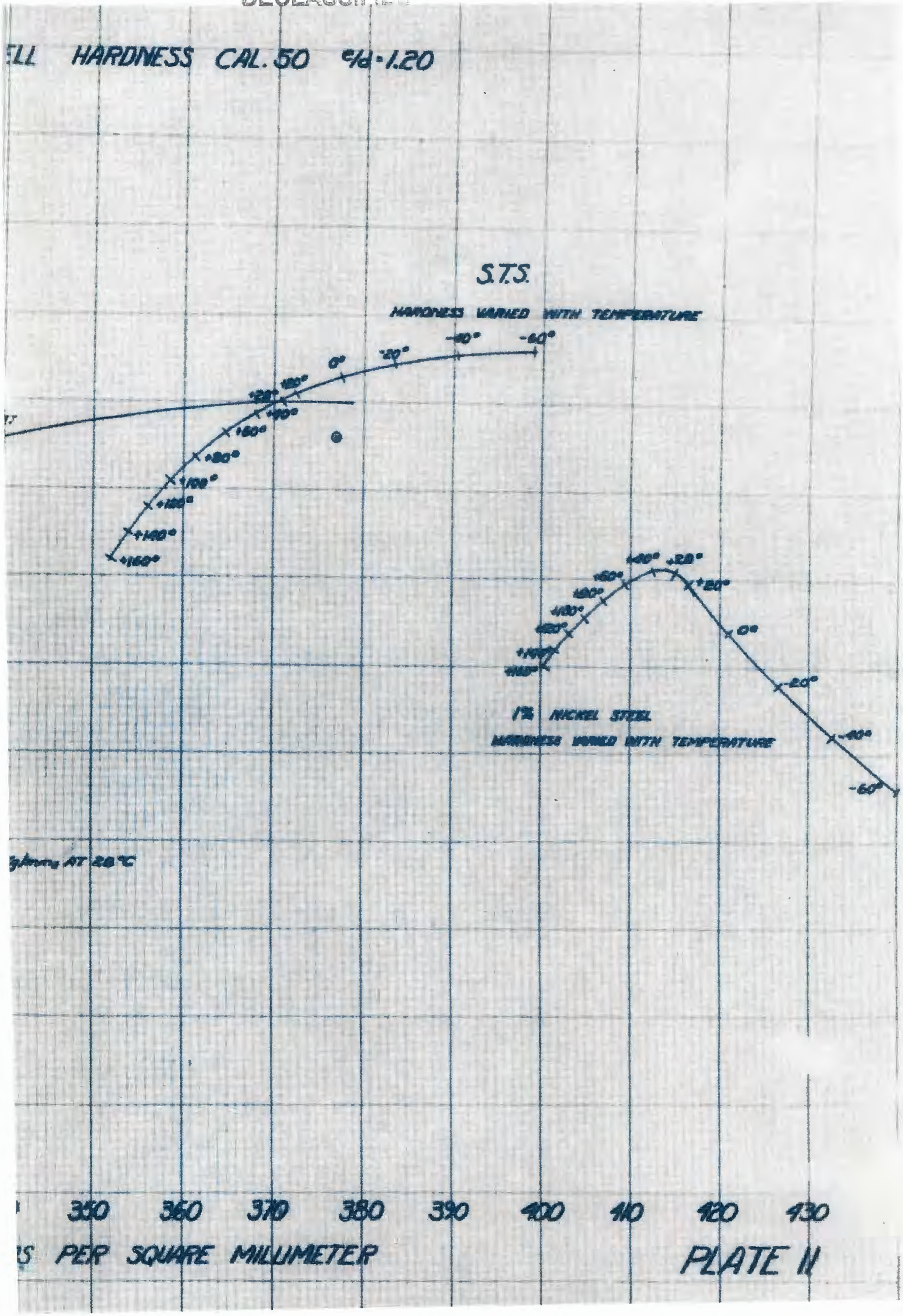

CAL.50
AVERAGE THICKNESS .515 IN. e/d=1.205
PLATE NO. 1 BRINELL HARDNESS 420
" " 2 409
" " 3 407
" " 4 412
" " 5 419
" " 6 415
" " 7 422
AVERAGE 415
+20 +40 +60 +80 +100 +120 +140 +160 +180
DEGREES CENTIGRADE

PLATE 10


BALLISTIC RESISTANCE
S.T.S.
HARDNESS VARIED WITH TEMPERATURE
S.T.S.
HARDNESS VARIED BY
540
520
500
480
460
P x 10^-3
440
POUNDS PER SQ. INCH
420
400
380
360
-60°
-40°
-20°
0°
+20°
+40°
+60°
+80°
+100°
+120°
+140°
+160°
AVERAGE THICKNESS .513 IN.
⊙ PLATE NO. 1 BRINELL
250
260
270
280
290
300
310
320
BRINELL HARDNESS NO.


ELL HARDNESS CAL.50 c/d-1.20
S.T.S.
HARDNESS VARIED WITH TEMPERATURE
1% NICKEL STEEL
HARDNESS VARIED WITH TEMPERATURE
kg/mm2 AT 28°C
350
360
370
380
390
400
410
420
430
S PER SQUARE MILLIMETER
PLATE II