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Report on
The Influence of Heat Treatment on the
Magnetic Properties of Some Armor-Plate Steels of
the "N-A-X" and "STS Types

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TABLE OF CONTENTS

	<u>Page No.</u>
Abstract	.
Authorization	1
Statement of Problem	1
Known Facts Bearing on Problem	1
Experimental Work	1
Discussion of Results Obtained	2
Conclusions	3
Recommendations	3

APPENDICES

Chemical Analysis of Materials Used	Table 1
Log of Heat Treatments	2
Summary of Results	3
Fahy Simplex Permeameter	Plate 1
Magnetic Tests 1 & 2 - A Comparison between Ring and Bar Specimen Tests of "N-A-X" Steel	2
Magnetic Tests 3 & 4 - "N-A-X" Specimens in As-received Condition (300 BHN)	3
Magnetic Tests 5 & 6 - "N-A-X" Specimens in As-quenched Condition (500 BHN)	4
Magnetic Tests 7 & 8 - "N-A-X" Specimens in Quench-drawn Condition (350 BHN)	5
Magnetic Tests 9 & 10 - "N-A-X" Specimens in Quench-drawn Condition (265 BHN)	6
Magnetic Tests 11 & 12 - "N-A-X" Specimens in Quench-drawn Condition (240 BHN)	7
Magnetic Tests 13 & 14 - "N-A-X" Specimens in Austempered Condition (240 BHN)	8

APPENDICES (Continued)

Magnetic Tests 15 & 16 - "N-A-X" Specimens in Quench-drawn Condition (200 BHN)	Plate 9
Magnetic Tests 17 & 18 - "N-A-X" Specimens in Furnace-cooled Condition (200 BHN)	10
Magnetic Tests 19 & 20 - "STS" Specimens in As-received Condition (245 BHN)	11
Magnetic Tests 21 & 22 - "STS" Specimens in As-quenched Condition (415 BHN)	12
Magnetic Tests 23 & 24 - "STS" Specimens in Quench-drawn Condition (315 BHN)	13
Magnetic Tests 25 & 26 - "STS" Specimens in Quench-drawn Condition (280 BHN)	14
Magnetic Tests 27 & 28 - "STS" Specimens in Quench-drawn Condition (220 BHN)	15
Illustrating Methods of Obtaining $[BH]_{max}$. Points / μ_{max} . Values	16
The Variation of $B_r \times H_c$ with Brinell Hardness	17
The Variation of $[BH]_{max}$. with Brinell Hardness	18
The Variation of $k = \frac{[BH]_{max.}}{B_r \times H_c}$ with Brinell Hardness	19

ABSTRACT

A magnetic investigation has been made on some armor-plate steels of the "N-A-X" and "STS" types which were subjected to various conditions of heat treatment. Such magnetic properties as maximum permeability, remanence, coercive force, and hysteresis losses were found to be greatly influenced by heat treatment. The magnetic qualities of these steels were observed to be more sensitive to changes at higher than at lower hardness values. However, no significant differences in magnetic properties can be claimed between the "N-A-X" or "STS" steels.

AUTHORIZATION

1. The investigation described in this report was conducted in accordance with an authorization issued by Bureau of Ordnance Project Order 2151-Ord. of 7 August 1941.

STATEMENT OF PROBLEM

2. The purpose of the work was to investigate how the magnetic properties of armor-plate steel of the "STS" type are affected by various heat treatments. An "N-A-X" steel was also studied for comparison since it has been shown to be ballistically comparable to the standard "STS" armor-plate steel, but has the added advantage of being lower in alloy content. Special consideration was given to heat treatments which produced the hardnesses normally experienced in practice for these steels.

KNOWN FACTS BEARING ON PROBLEM

3. Armor-plate steels of the types under consideration have a high capacity for becoming permanently magnetized, and as such, can become very troublesome in the general vicinity of a magnetic compass needle; particularly if this property is a variable one. Furthermore, in a structure the presence of a part having considerable permanent magnetization may cause a magnetic field to be generated by this part throughout the adjacent steel structure.

4. Ferromagnetic properties of steels are determined by the manner in which they respond to magnetizing fields. This is characterized by the hysteresis loops they describe in going through a complete cycle of magnetization, and by the curve of normal induction starting from unmagnetized state. By altering the internal state of the material, the general features of these loops (i.e., the permeability, remanence, or coercive force) can be made to change. Heat treatment has a pronounced influence on the state of the material, and consequently on its magnetic properties. To obtain some knowledge of their magnetic nature, a number of samples of "STS" and "N-A-X" steels were subjected to a series of heat treatments and analyzed magnetically.

EXPERIMENTAL WORK

5. For this investigation, the steels having the chemical compositions given in Table 1 were considered. Specimens about 1/2" x 2" x 10" prepared from each type of steel were used. These were austenitized at 840°C. for one hour in a neutral atmosphere, and finally oil-quenched. A range of hardnesses was obtained by tempering the quenched specimens in salt baths or in muffle furnaces for either low or high temperature treatments, respectively, or by furnace cooling. A log of heat treatments is given in Table 2. Duplicate specimens were used in each experiment. The Brinell hardness was found in good agreement in duplicate specimens which were subjected to identical heat treatments. This was indicative of good homogeneity in both the material and heat treatment. In one case the technique of "austempering" was employed.

6. The magnetic properties of these steels in heat-treated conditions were determined with a Fahy Simplex permeameter. The details of the apparatus and its operation are well known and need no further explanation here. The general set-up of the particular permeameter used in this work is shown by Plate 1.

7. For very high accuracy, ring specimens are recommended since errors due to magnetic leakage and end-effects are absent. The obvious disadvantages of such specimens are the tedious labor involved in winding each ring, and the limited value of magnetizing (current) force which may be used without excessive heating. On the other hand, bar specimens (1/2" x 2" x 10") are more convenient to make and easier to handle. A comparison between tests performed on the two types of specimens made from "N-A-X" steel and subjected to similar heat treatment is shown in Plate 2. The general agreement is surprisingly good and favors the use of magnetic yoke bar-test for these steels because of its comparable accuracy and its greater rapidity.

DISCUSSION OF RESULTS OBTAINED

8. Normal induction curves and hysteresis loops obtained from magnetic analyses of a number of heat-treated "N-A-X" and "STS" specimens are contained in Plates 3 to 15, inclusively. The data used in plotting each curve were compiled from results obtained on duplicate tests. The accuracy of the work is estimated to be about 5 per cent.

9. Magnetic saturation was generally realized in tempered specimens, while magnetizing fields higher than those employed were needed to saturate specimens in the as-quenched condition. Moreover, it was commonly noted that by tempering quenched specimens, the remanence was increased and the coercive force decreased. Remanence is greatly affected by the state of aggregation (i.e. size and shape of the magnetic particles); whereas the coercive force is not as much, since it depends mostly on the extent to which the aggregation is distorted. It is possible, furthermore, to obtain the same degree of hardness by two different cycles of heat treatment, and yet have the magnetic properties differ appreciably. This is best illustrated by the results shown in Plates 7 and 8. In one case, the specimens were oil-quenched and then drawn for one hour at 650°C.; and in the other, they were "austempered" for 48 hours at 500°C. (see Table 2). The explanation is, obviously, a difference in the final states of aggregation.

10. The ease with which a steel can be magnetized is indicated by its normal induction curve (see lower portion of Plate 16). A measure of this behavior is often determined by a line drawn from the origin tangent to the curve at a point, such as T; the slope is termed the "maximum permeability" of the material. The important magnetic characteristics of a material, however, are indicated by the demagnetization loop lying between the residual induction (B_r) and the coercive force (H_c), and a curve plotted between B and H for the same part of the loop (see the upper portion of Plate 16). These products are proportional to the magnetic energy stored at the given values of induction. The maximum value of the energy-product (which may also be determined graphically from the demagnetization curve in the manner illustrated by Plate 16) is often regarded as an index of the

magnetic quality. The product $B_r \times H_c$ has also been used as a measure of quality, but lacks validity if the demagnetization curve departs, as it often does, from the general form. Recently, a ratio between the two above products, that is,

$$k = \frac{[BH] \text{ max.}}{B_r \times H_c}$$

has been advocated as a possible criterion by which magnetic qualities might be judged.

11. In Table 3 are compiled values of these factors based on the results of this investigation. Furthermore, curves of these factors as a function of hardness are given in Plates 17 to 19, inclusively. Although some scattering exists between points, nonetheless there seems to be a general indication that these factors are more sensitive to changes at the higher than at the lower hardness values. Little or no differences between the magnetic qualities of "N-A-X" and "STS" steels have been found in this work.

CONCLUSIONS

12. Magnetic analyses made on steels of the "N-A-X" and "STS" types subjected to various conditions of standard heat treatments showed:

- (a) That heat treatment has a decided effect on such magnetic properties as maximum permeability, remanence, coercive force, and hysteresis losses;
- (b) That magnetic qualities of these steels are more sensitive to changes at the higher than at the lower hardness values; and
- (c) That no significant differences can be claimed between the "N-A-X" and "STS" steels, even though they differ widely in compositions.

RECOMMENDATIONS

13. It is recommended that further work be done on these armor-plate steels. Special attention, however, should be given to the influence of mechanical impact and vibrations on the magnetic stability of the material in the various heat-treated conditions.

TABLE 1

Chemical Analysis

Composition	Steel-Type	
	"N-A-X"	"STS"
C	0.49	0.30
Mn	0.75	0.20
Ni	--	3.25
Cr	0.70	1.45
P	0.026	0.026
S	0.021	0.017
Si	0.88	0.056
Mo	0.16	0.020
Zr	0.24	--

TABLE 2

Log of Heat Treatments

Test No.*	Austenitizing		Quenching Medium	Tempering		BHN	Condition
	Temp.	Time		Temp.	Time		
3 & 4	-	-	-	-	-	300	As received
5 & 6	840°C	1 hr.	Oil	-	-	500	As quenched
7 & 8	"	"	"	500°C	2 hrs.	350	Quench-drawn
9 & 10	"	"	"	680°C	1/2 hr.	265	Quench-drawn
11 & 12	"	"	"	650°C	1 hr.	240	Quench-drawn
13 & 14	"	"	Salt bath	500°C	48 hrs.	240	Austempered
15 & 16	"	"	Oil	740°C	1 hr.	200	Quench-drawn
17 & 18	"	"	Furnace	-	-	200	Furnace cooled
19 & 20	-	-	-	-	-	245	As received
21 & 22	840°C	1 hr.	Oil	-	-	415	As quenched
23 & 24	"	"	"	450°C	1/2 hr.	315	Quench-drawn
25 & 26	"	"	"	500°C	1 hr.	280	Quench-drawn
27 & 28	"	"	"	700°C	1/2 hr.	220	Quench-drawn

*Note: Tests 3 to 18, incl., were performed on "N-A-X" specimens.

Tests 19 to 28, incl., were performed on "STS" specimens.

TABLE 3

Summary of Results

Test No.*	BHN	B _r	H _c	B _r x H _c	[BH]max.	k	μ max.	See Plate No.
3 & 4	300	8,000	-24	192,000	57,600	0.300	220	3
5 & 6	500	9,800	-46	451,000	192,000	0.426	130	4
7 & 8	350	15,400	-14	216,000	108,000	0.500	1480	5
9 & 10	265	15,200	-16	243,000	100,000	0.412	1000	6
11 & 12	240	14,600	-16	234,000	125,000	0.534	900	7
13 & 14	240	11,000	-14	154,000	80,000	0.520	620	8
15 & 16	200	13,000	-15	195,000	96,000	0.493	870	9
17 & 18	200	10,200	-14	143,000	70,000	0.493	640	10
19 & 20	245	14,200	-16	227,000	120,000	0.560	1000	11
21 & 22	415	10,200	-35	357,000	124,000	0.348	210	12
23 & 24	315	13,000	-16	208,000	99,000	0.476	1150	13
25 & 26	280	15,600	-15	234,000	100,000	0.428	2000	14
27 & 28	220	15,800	-14	221,000	76,800	0.348	1800	15

*Note: Tests 3 to 18, incl., were performed on "N-A-X" specimens.

Tests 19 to 28, incl., were performed on "STS" specimens.

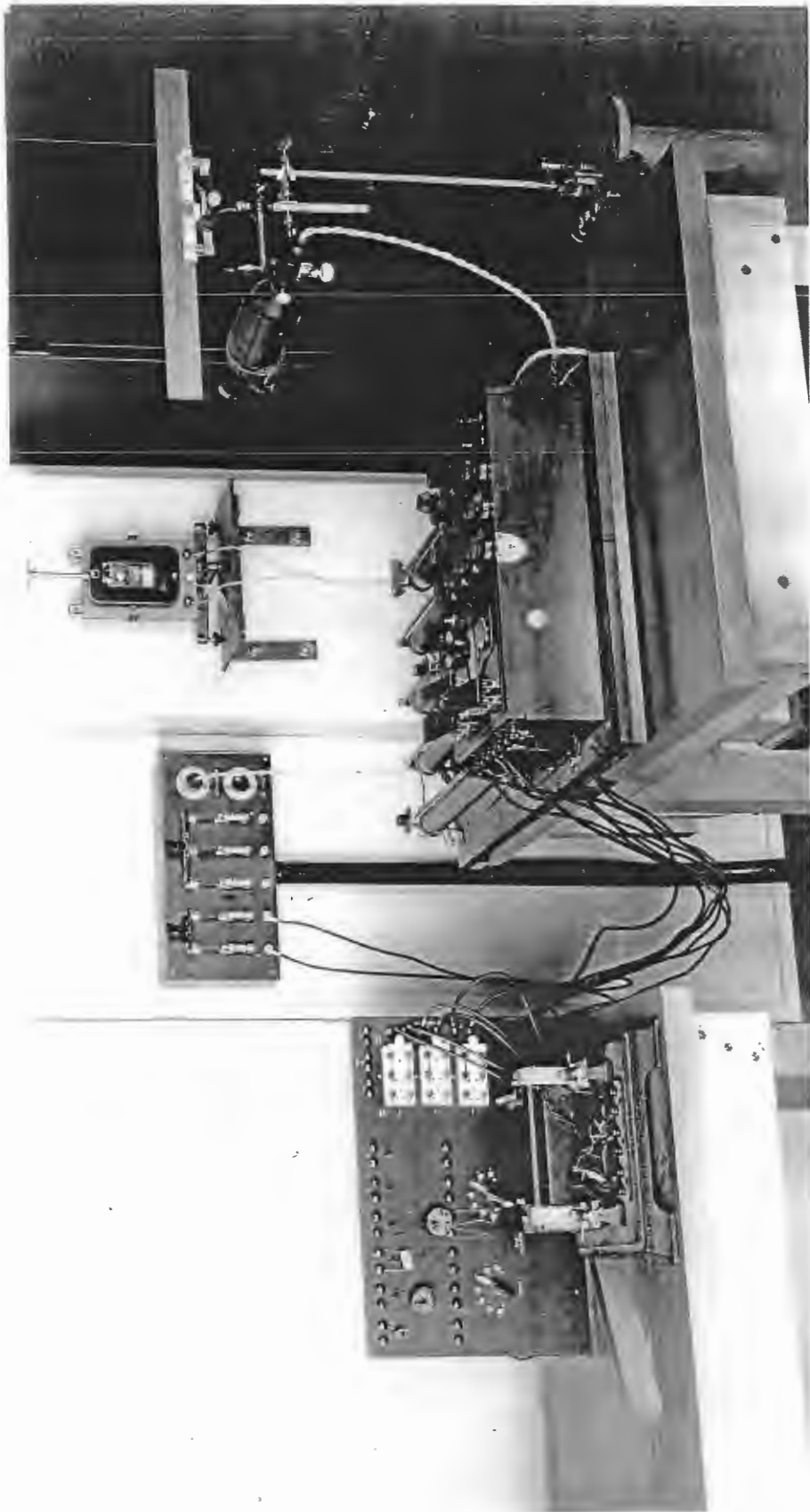
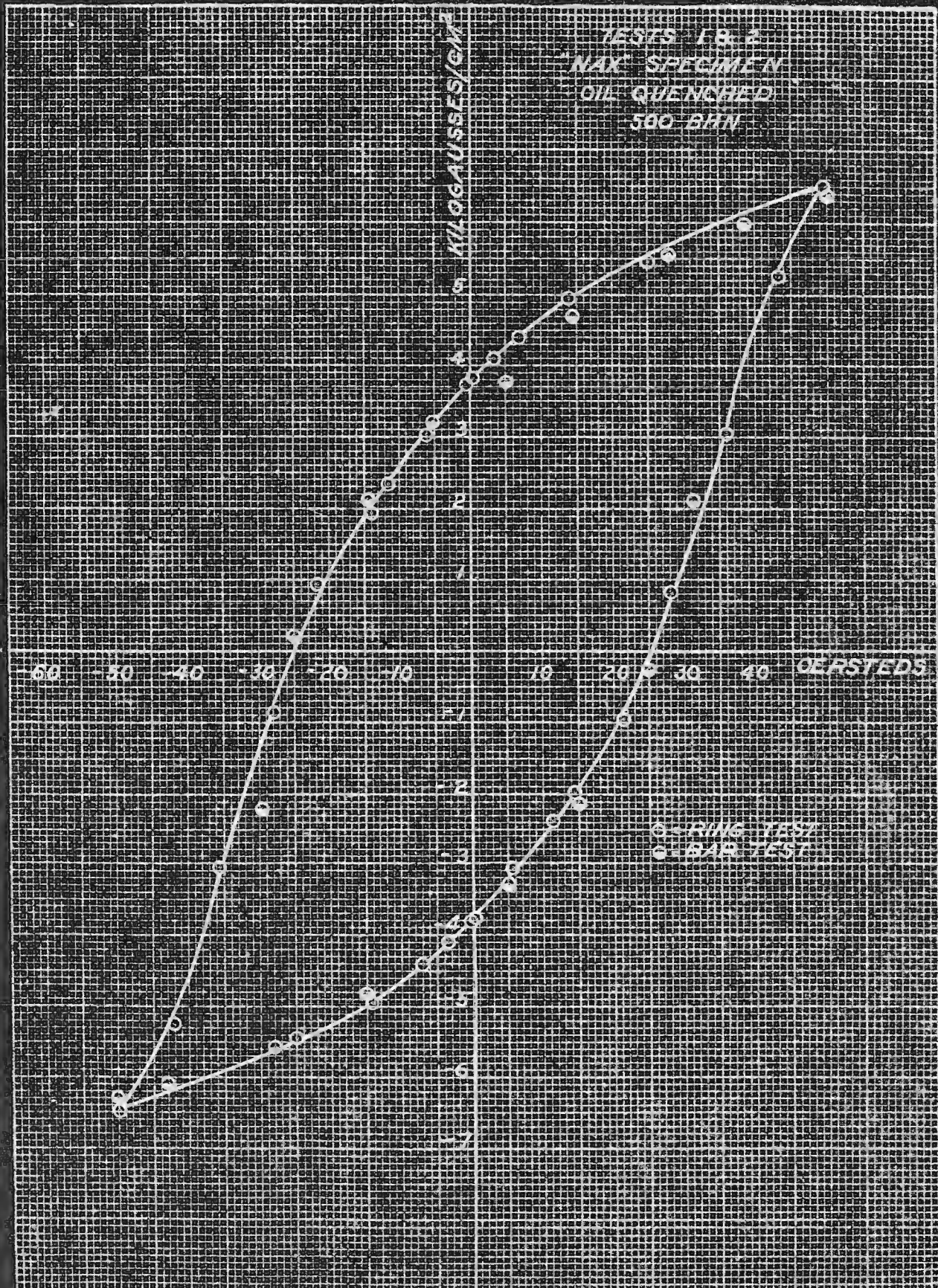


PLATE I

B

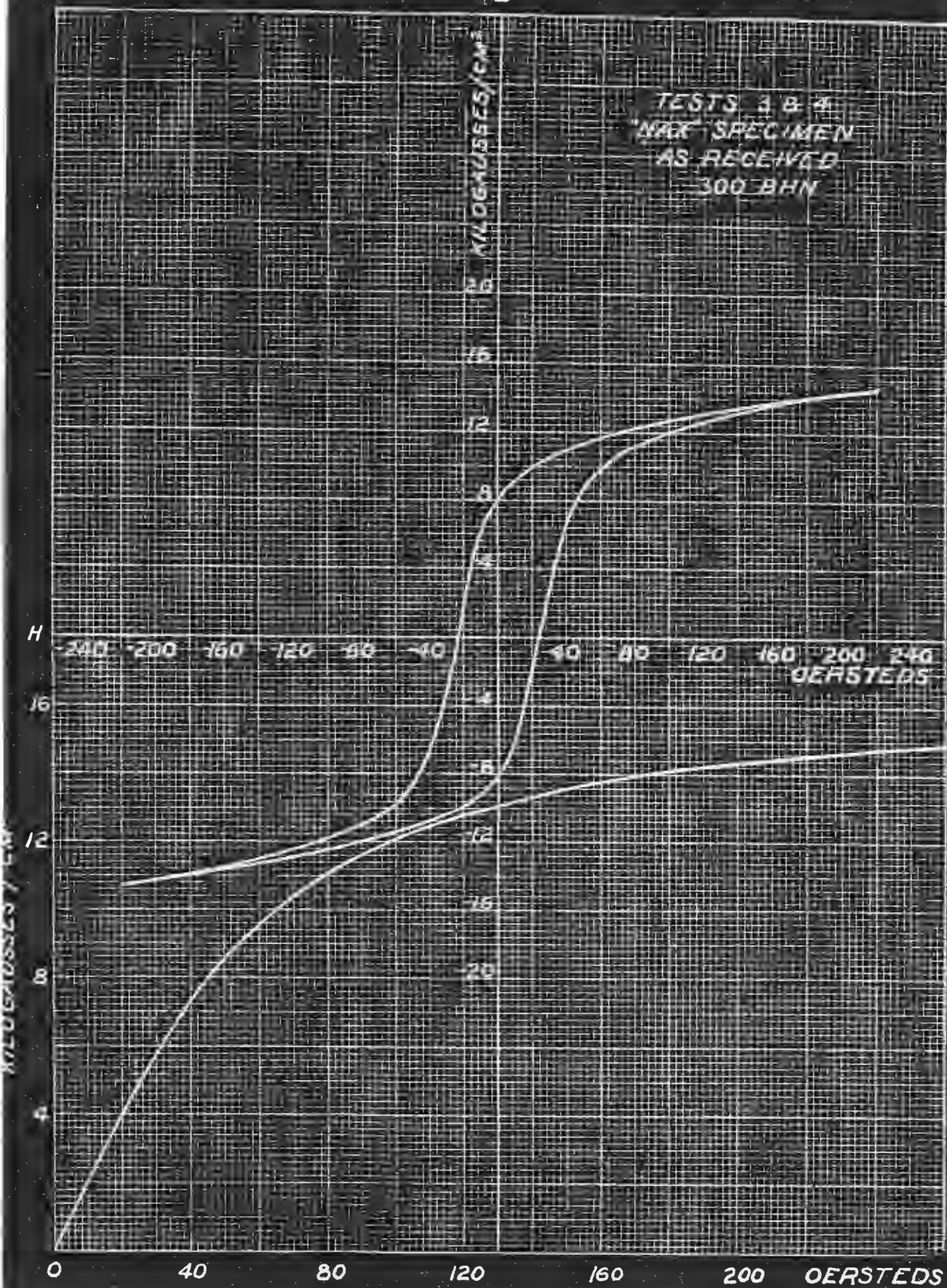
TESTS 1, 2, 3
MAX SPECIMEN
OIL QUENCHED
500 RPM

H

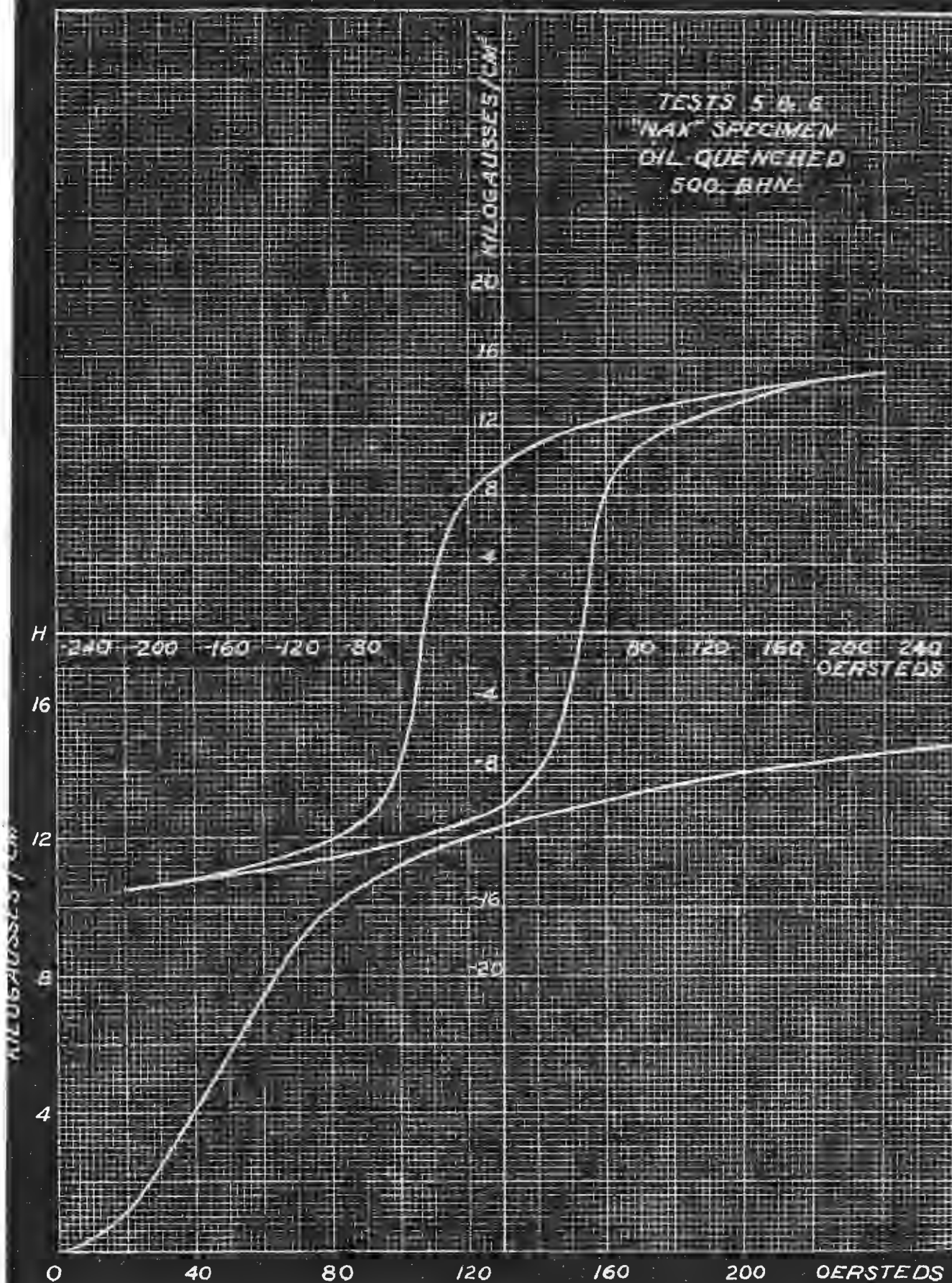


OPENING TEST
CIRCUIT TEST

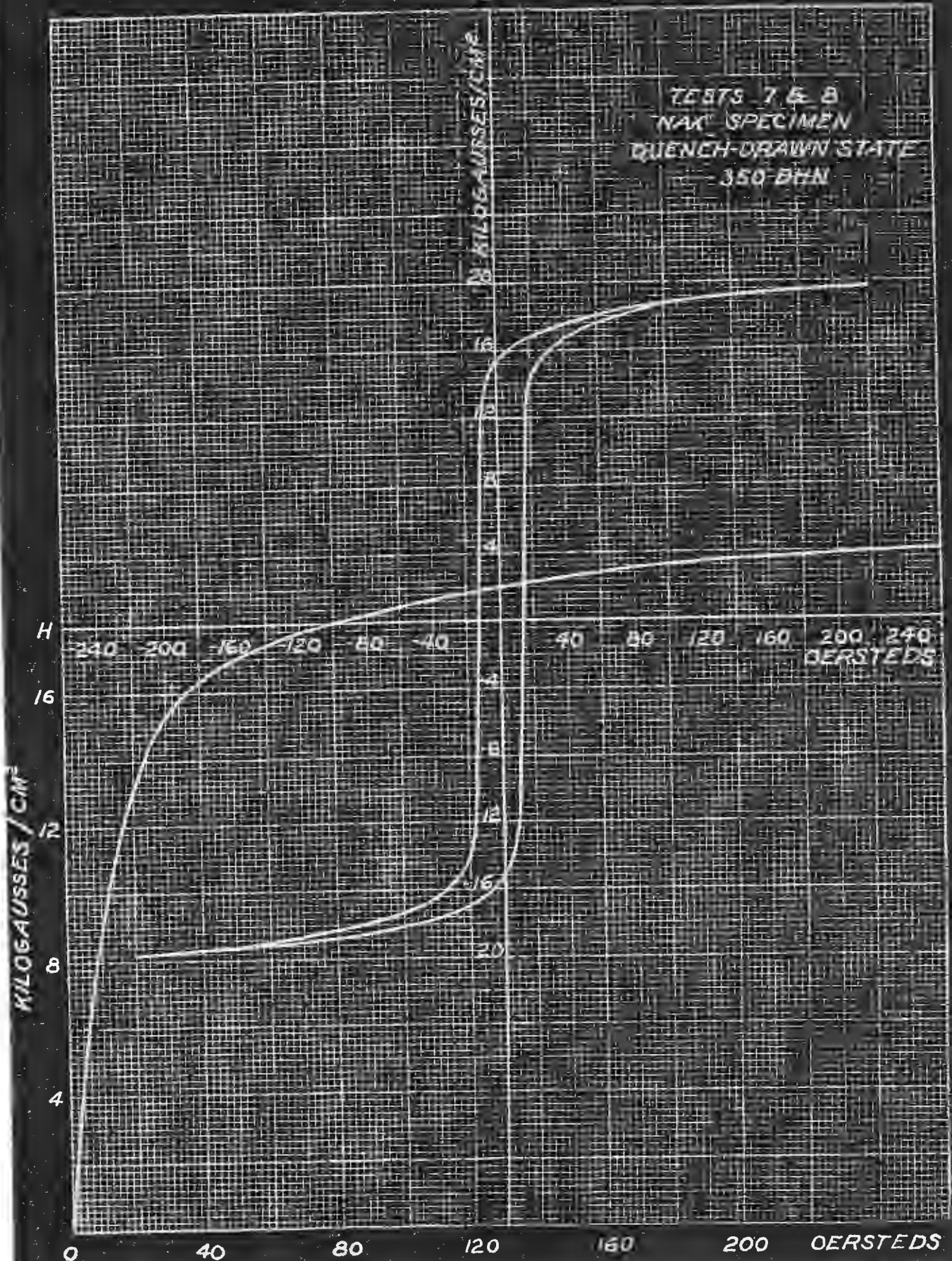
B



5

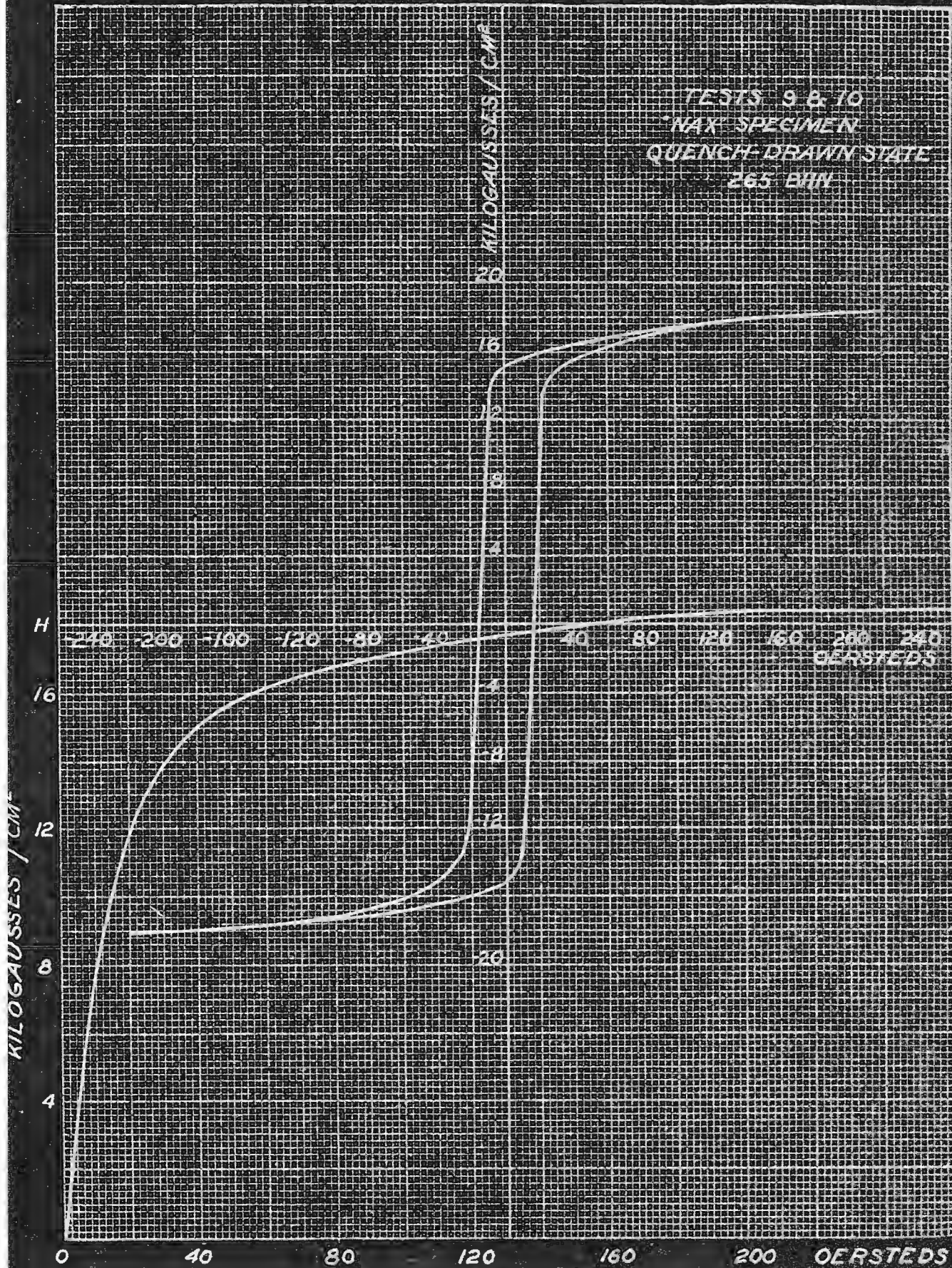


TESTS 7 & 8
"NAK" SPECIMEN
QUENCH-DRAWN STATE
350 BHN



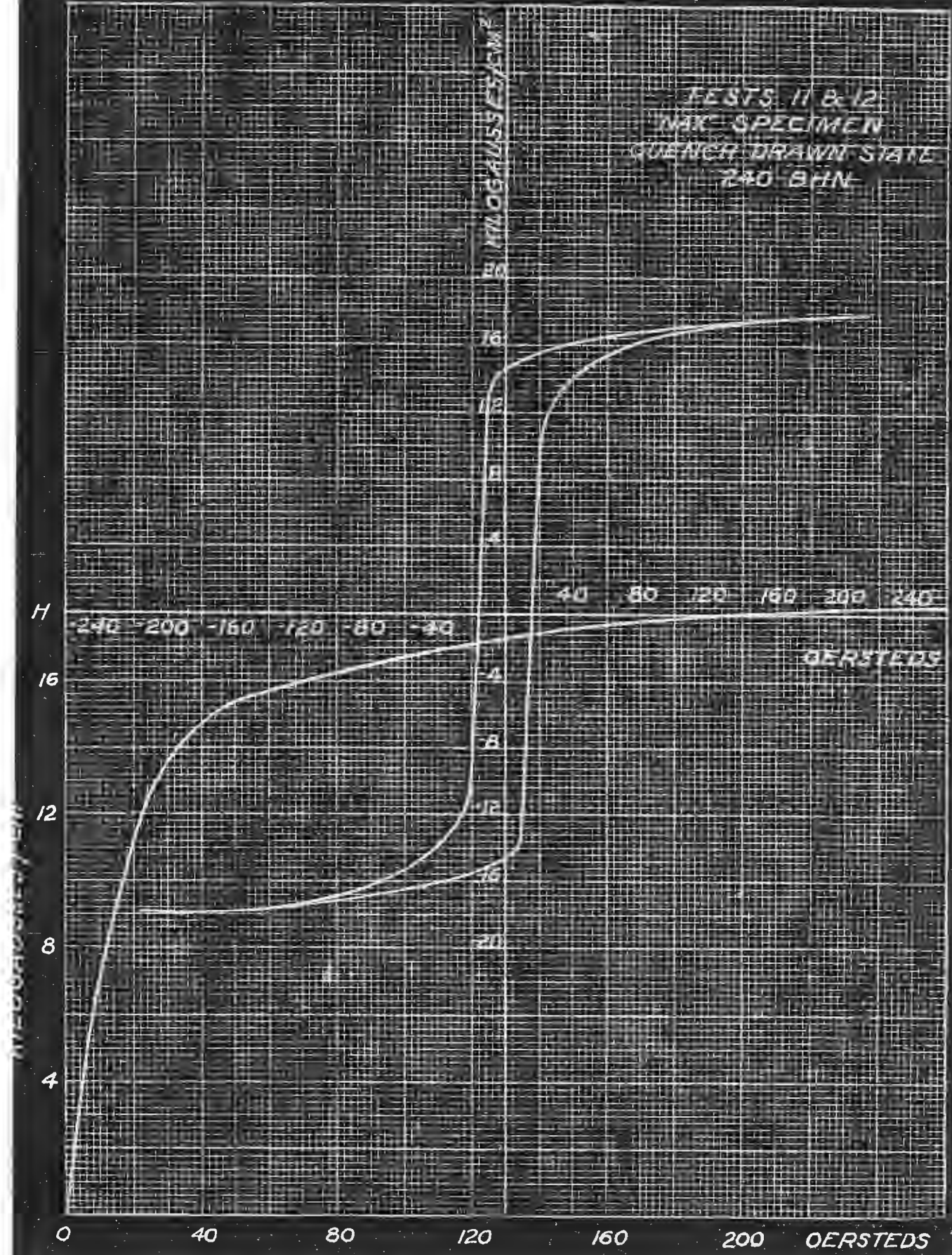
B

TESTS 9 & 10
MAX SPECIMEN
QUENCH DRAWN STATE
265 BHV



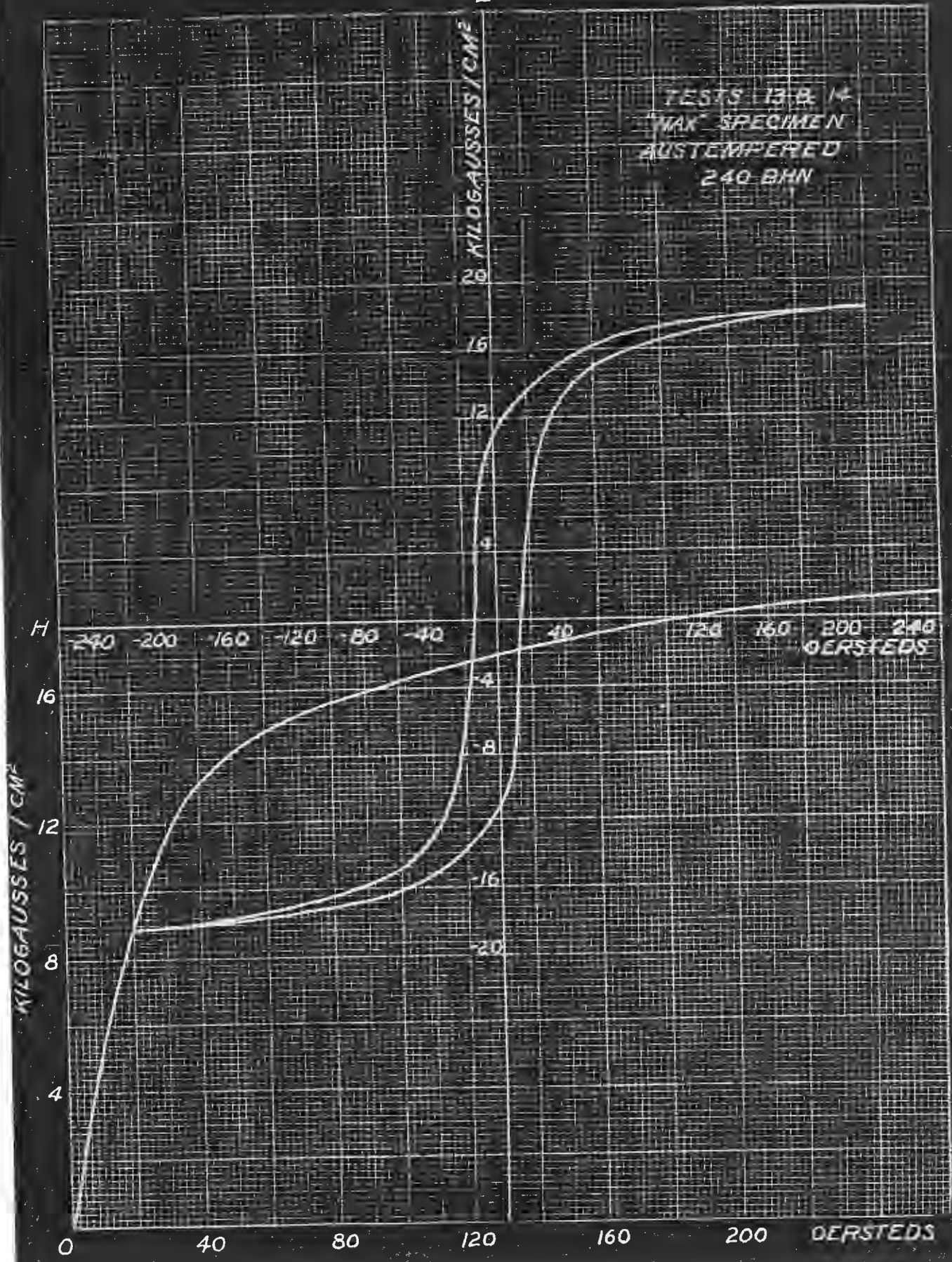
8

TESTS 11 & 12
NAK SPECIMEN
QUENCHED DRAWN STATE
240 BHN



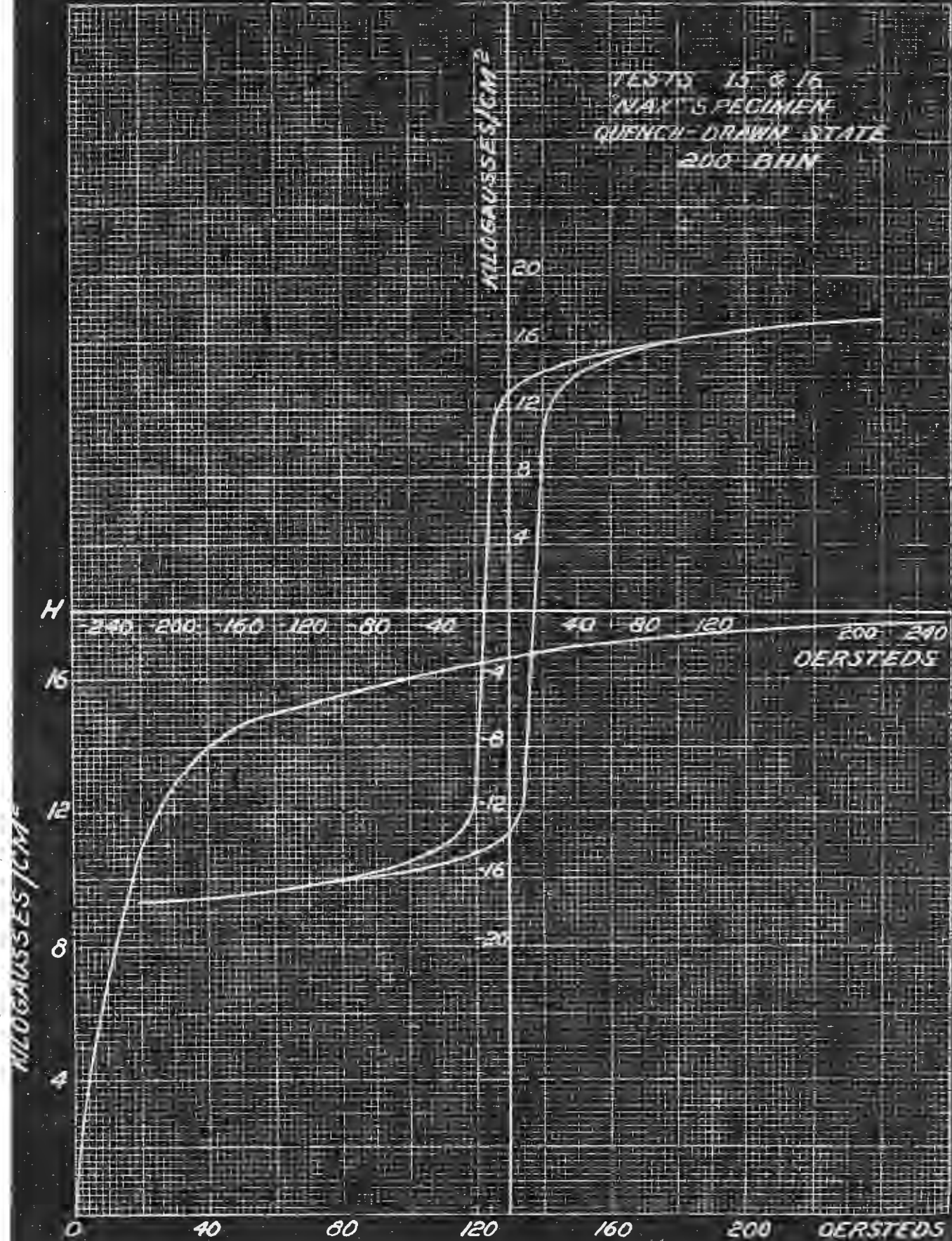
B

TESTS 13 & 14
"MAX" SPECIMEN
AUSTEMPERED
240 BHN



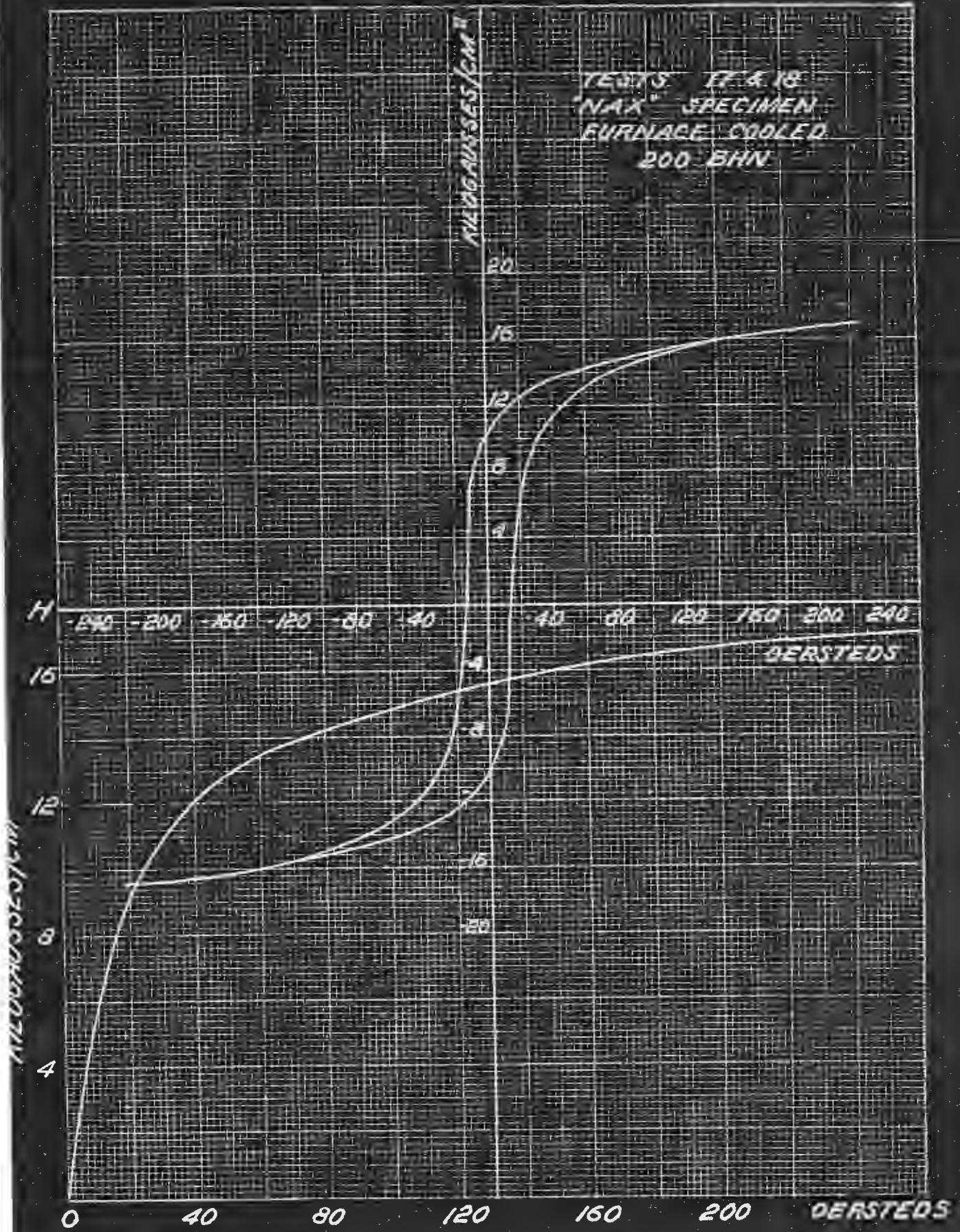
B

TESTS 15 & 16
NAY'S SPECIMEN
QUENCH-DRAWN STATE
200 BHN

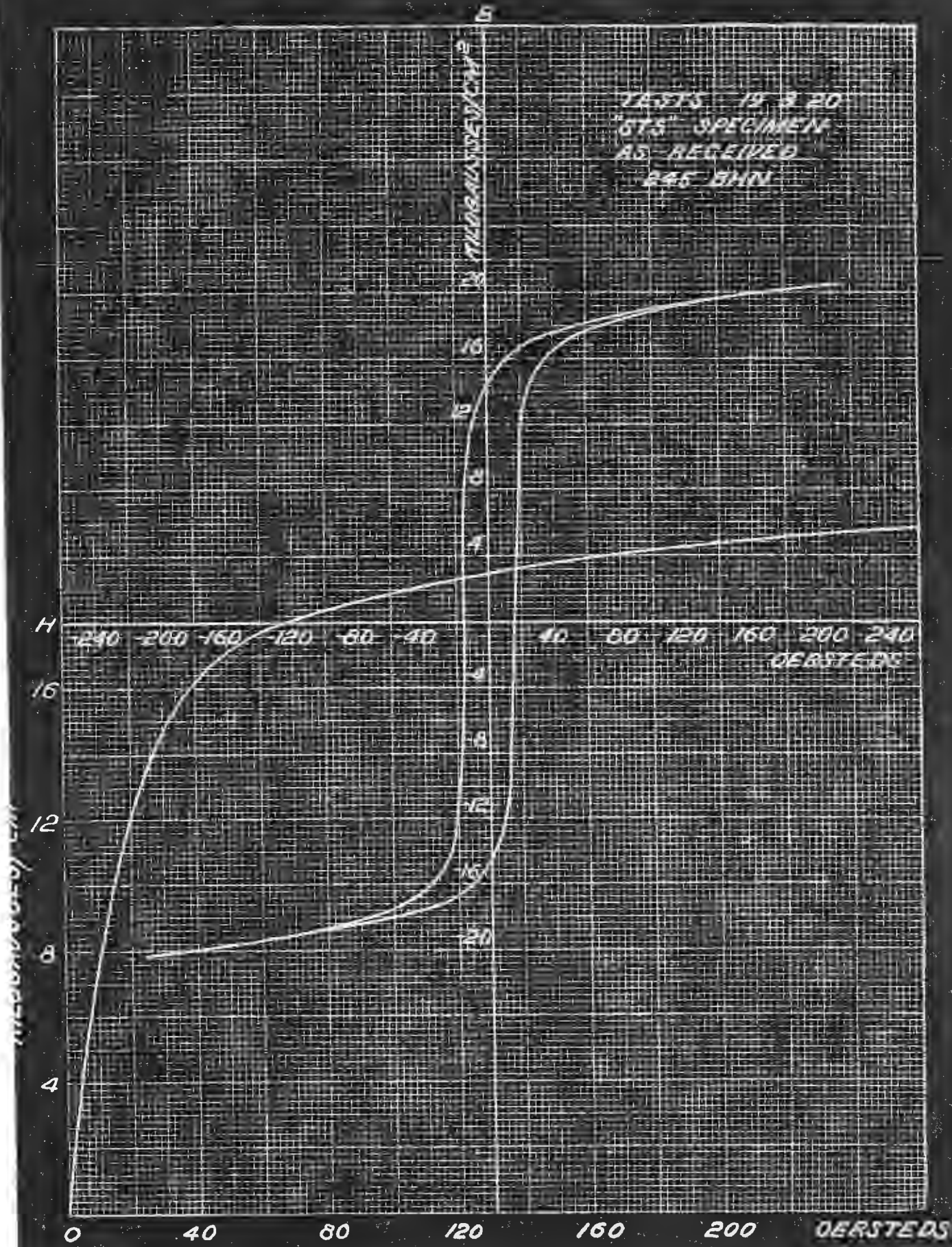


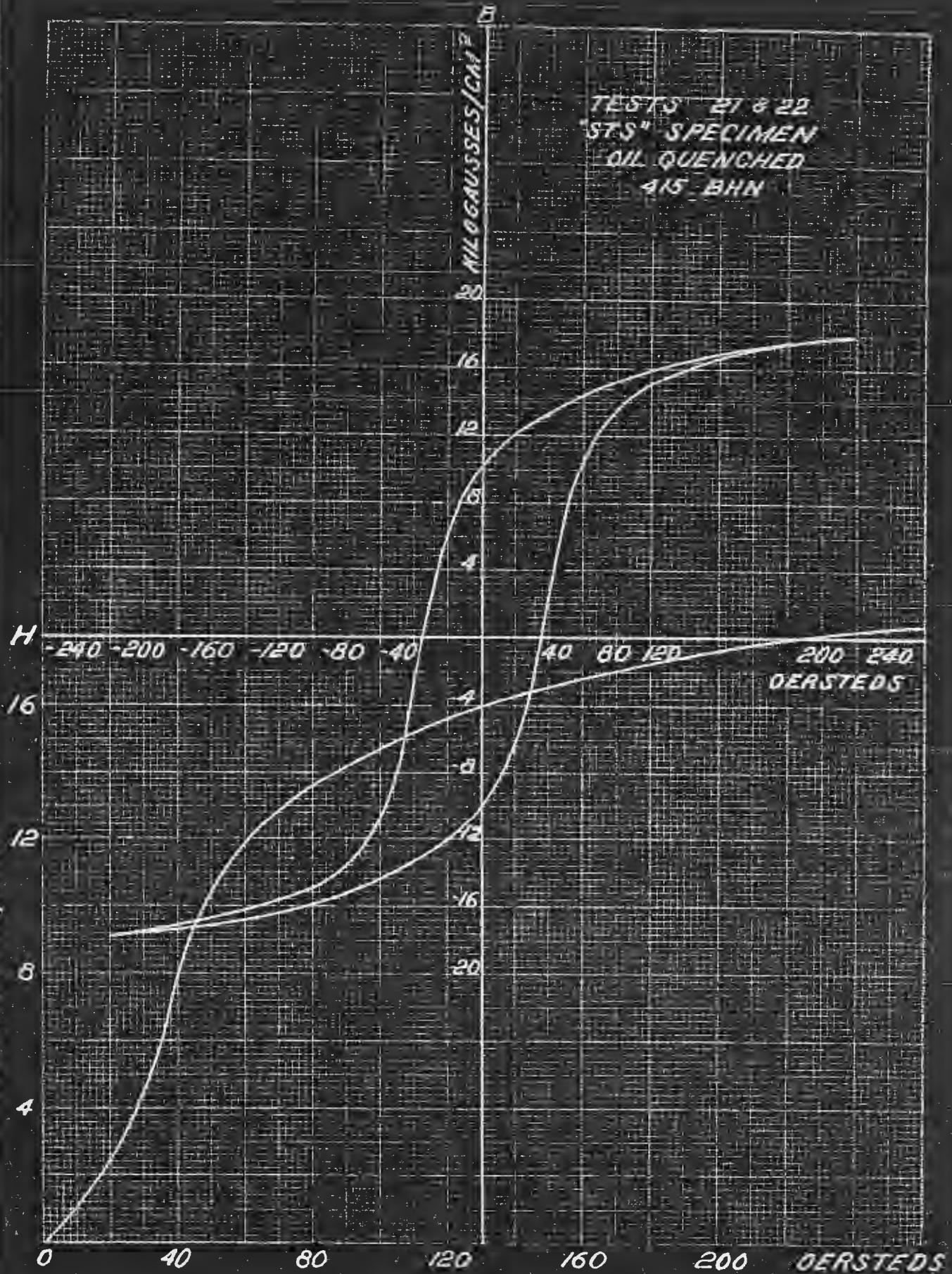
B

TESTS 17 & 18
"NAX" SPECIMEN
FURNACE COOLED
200 BHN



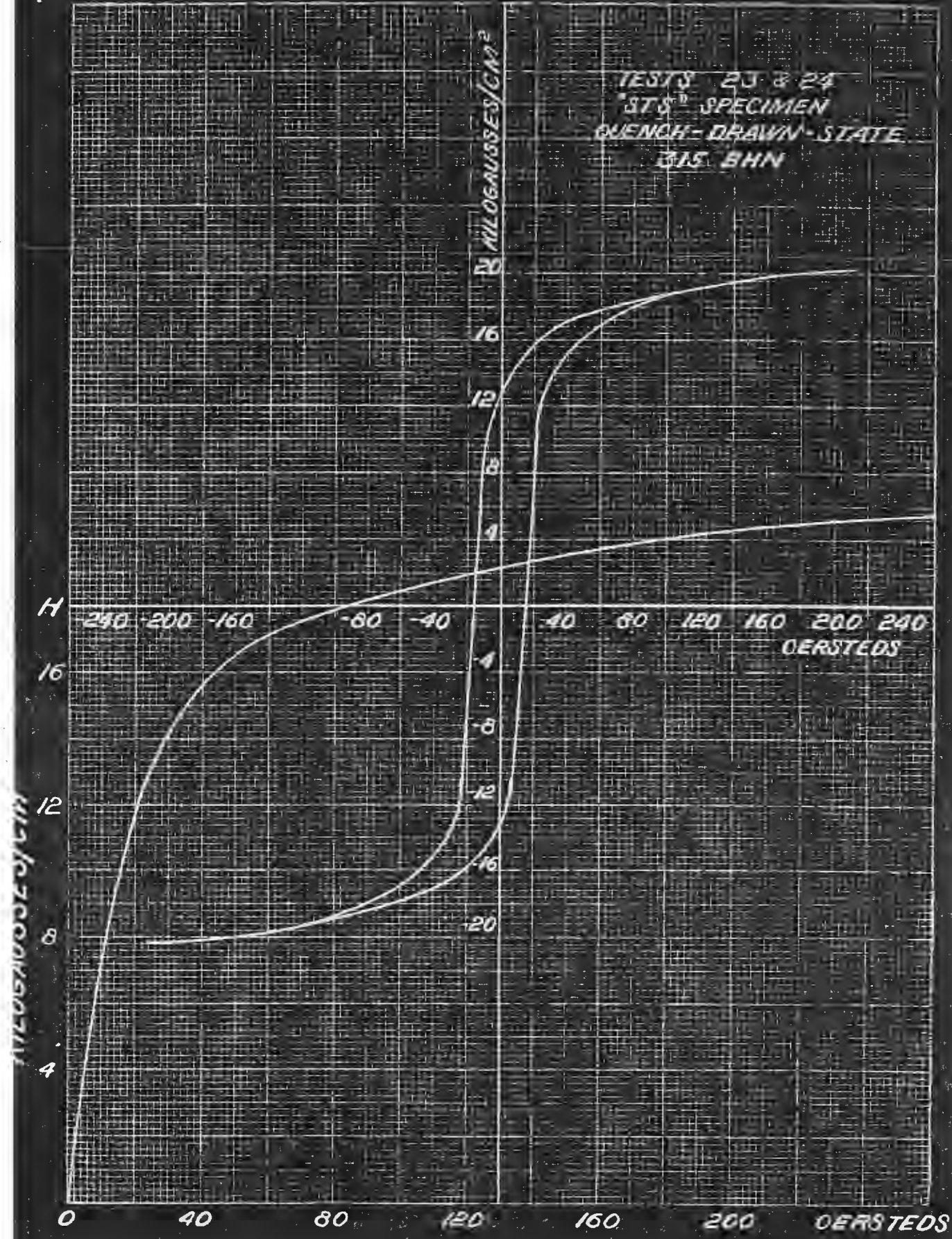
TESTS 19 & 20
"GTS" SPECIMEN
AS RECEIVED
245 BHN



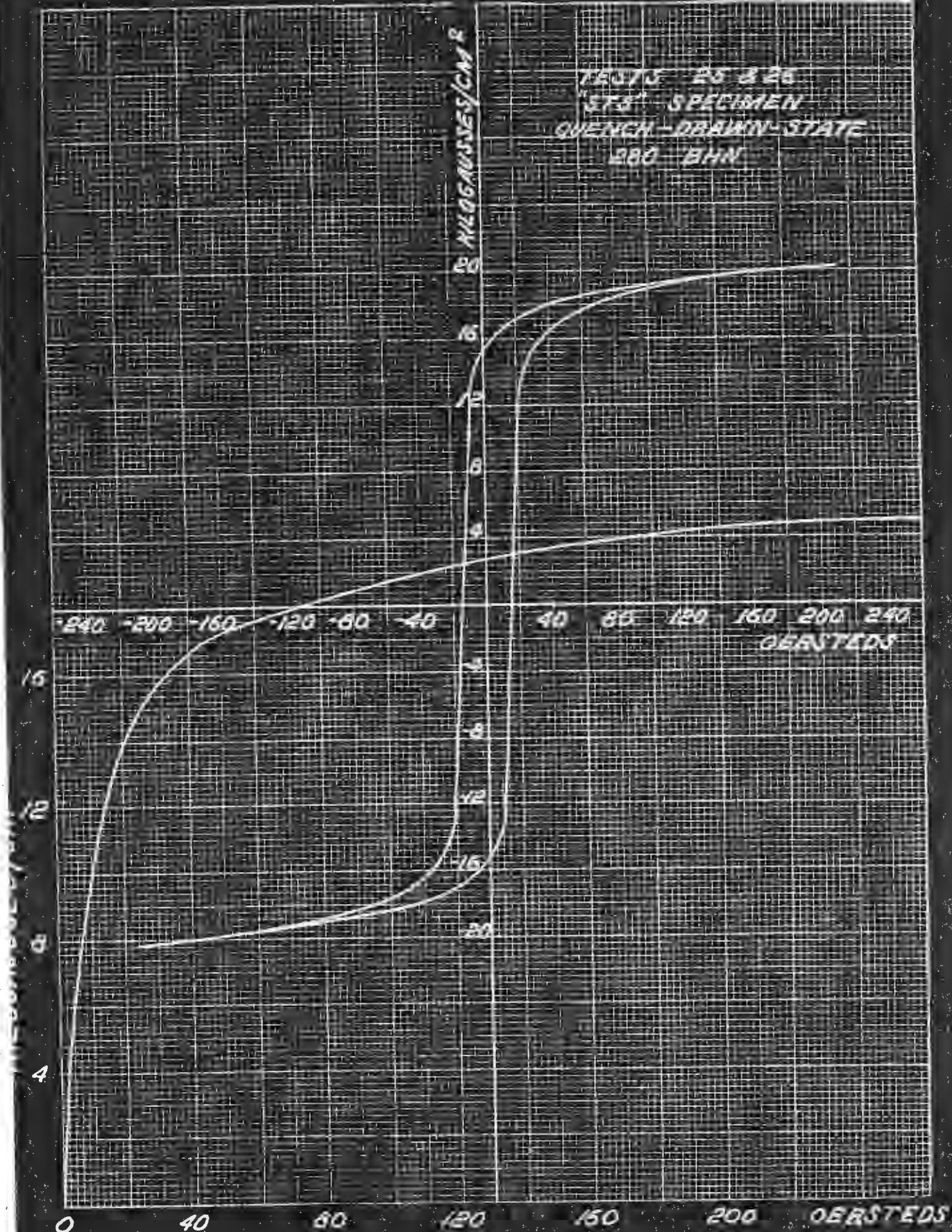


B

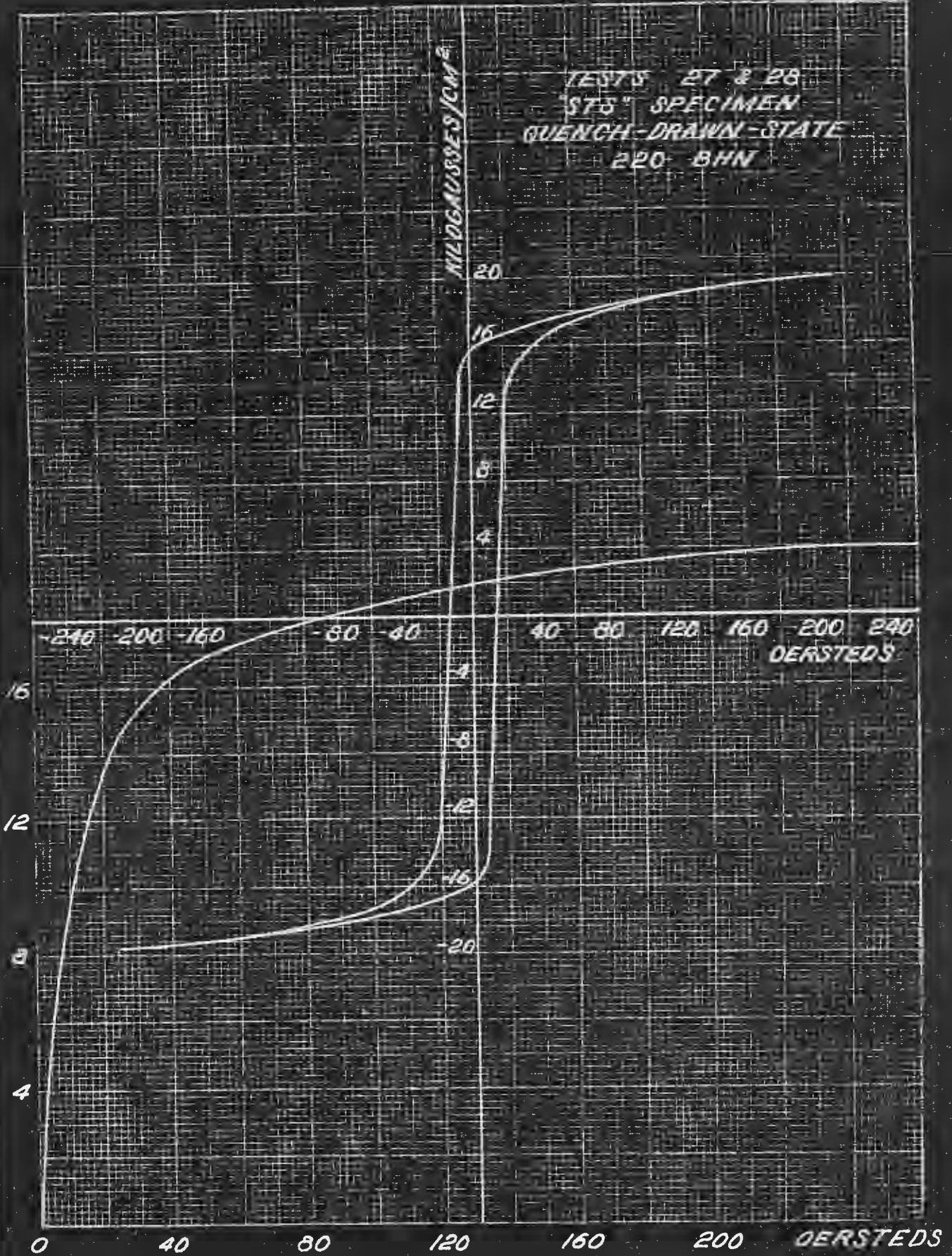
TESTS 23 & 24
ST5¹ SPECIMEN
QUENCH-DRAWN-STATE
315 BHN

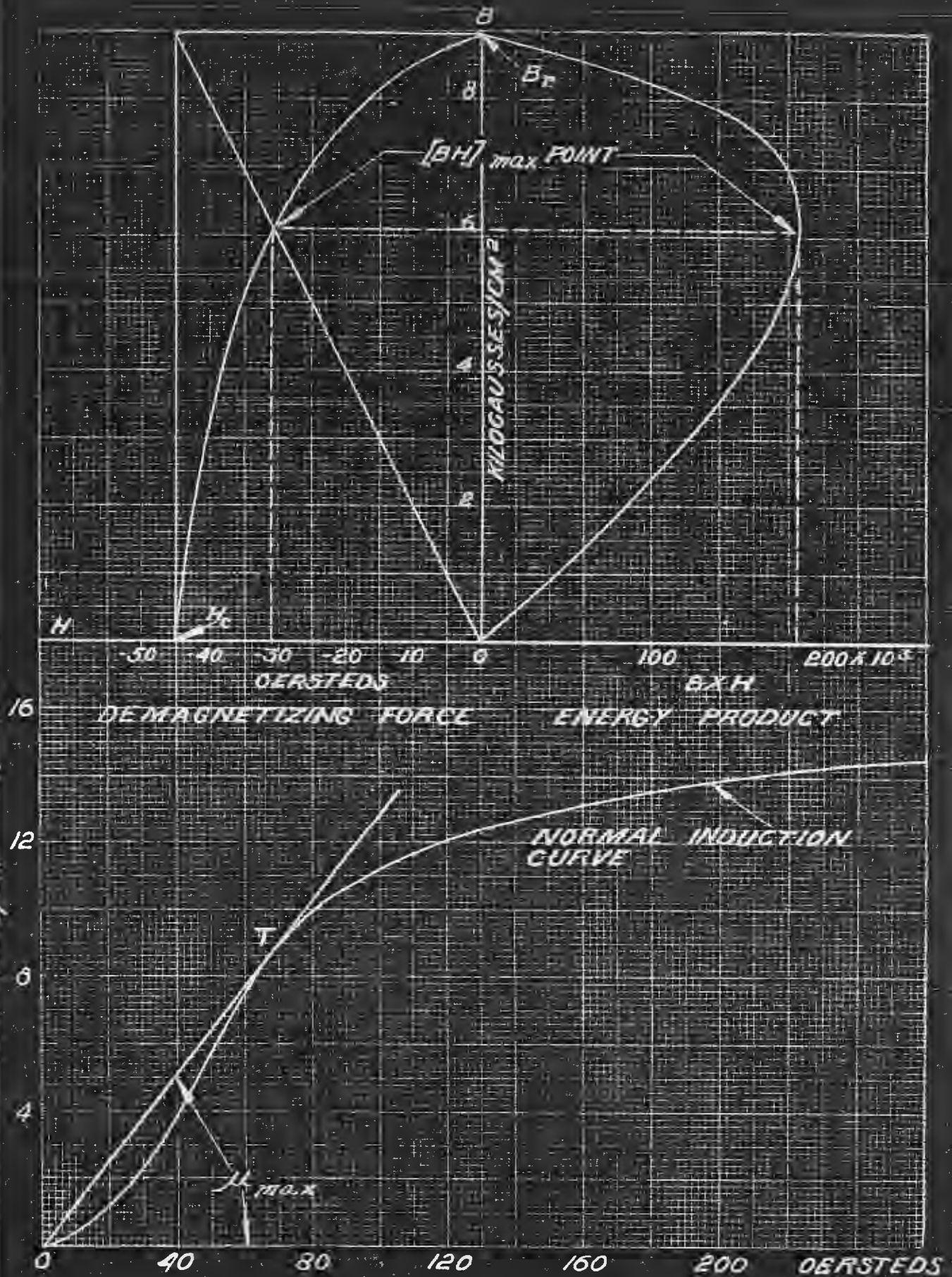


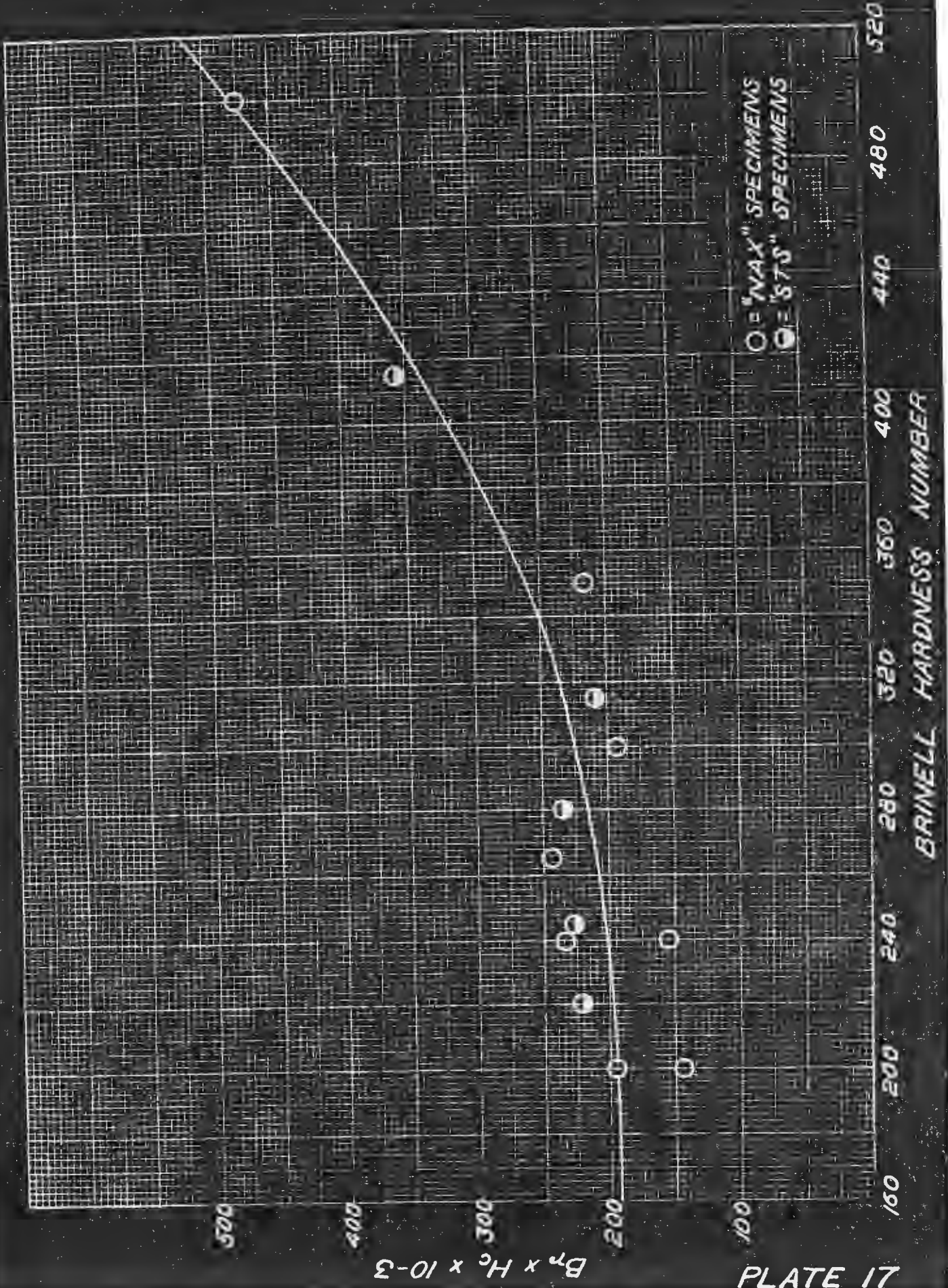
TESTS 25 & 26
'573' SPECIMEN
QUENCH-DRAWN STATE
280 BHN



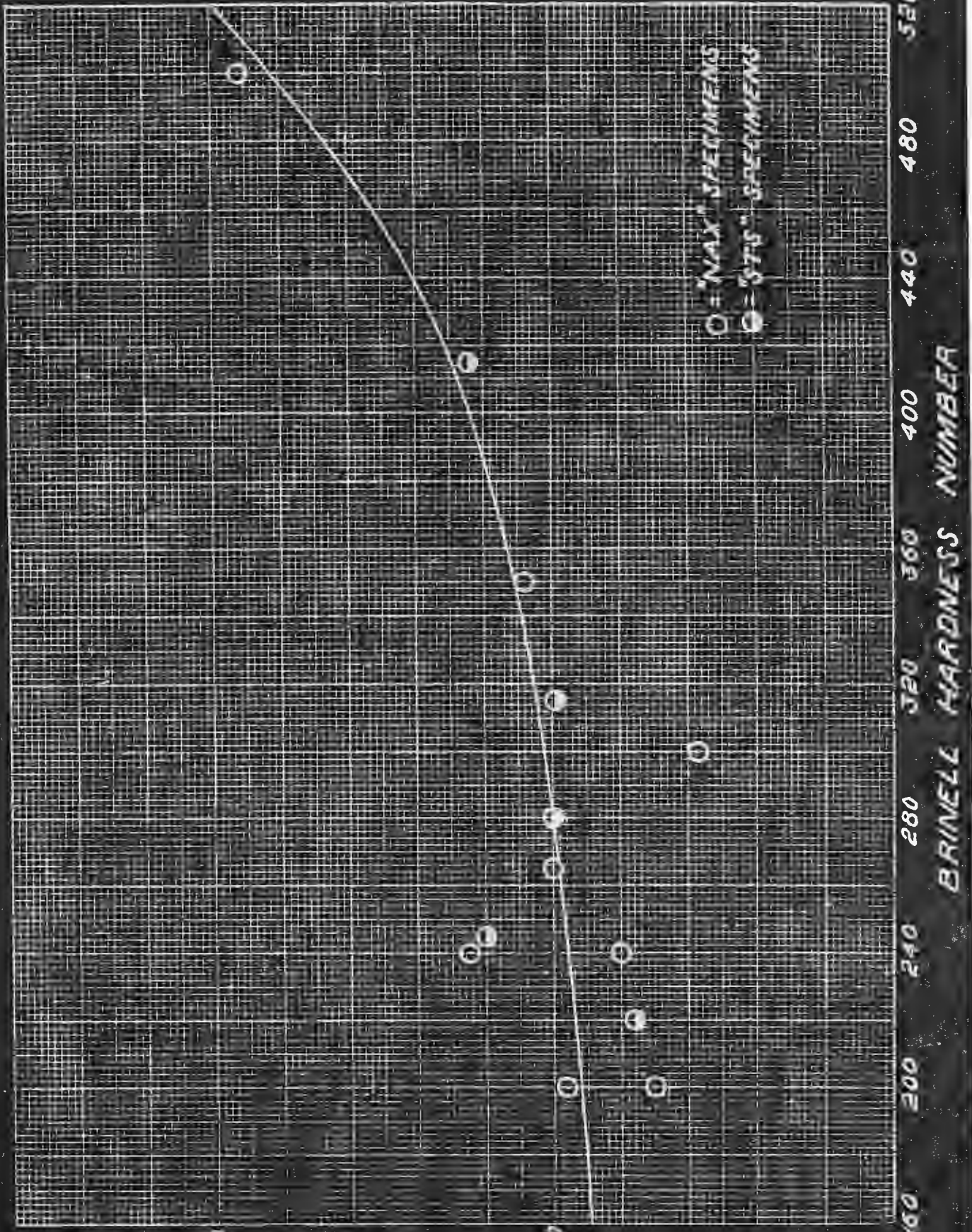
TESTS 27 & 28
"ST8" SPECIMEN
QUENCH-DRAWN-STATE
220 BHN





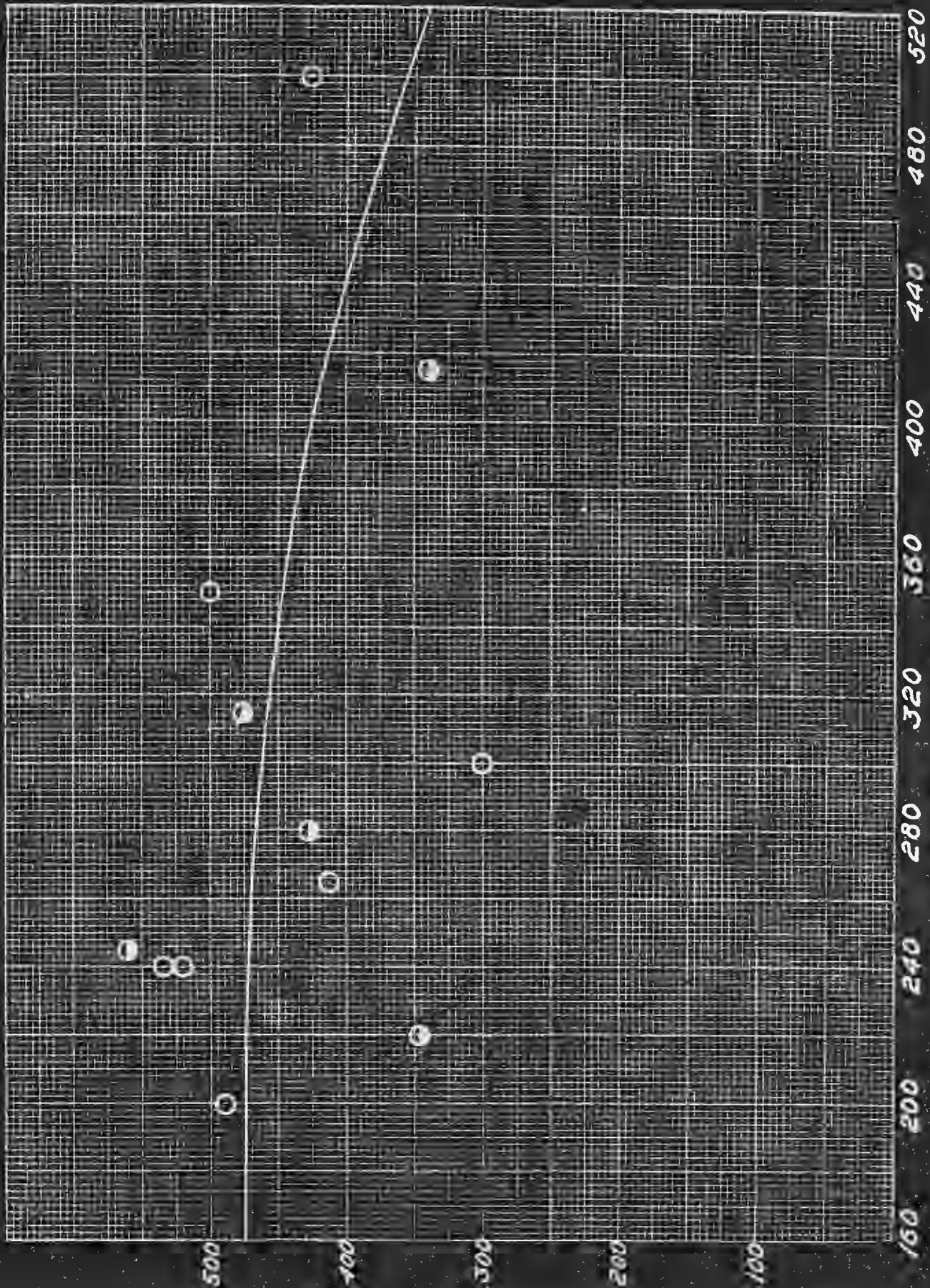


O = "NAX" SPECIMENS
● = "STJ" SPECIMENS



[σH]max x 10⁻³

PLATE 18



$K = \frac{\text{Load}}{D^2 \cdot H}$