THE UNIVERSITY OF MINNESOTA

GRADUATE SCHOOL

Report

of

Committee on Examination

This is to certify that we the undersigned, as a committee of the Graduate School, have given Ralph Lewis Dowdell final oral examination for the degree of Master of Science. We recommend that the degree of Master of Science be conferred upon the candidate.

Minneapolis, Minnesota

May 21 1921

Oscar E Harder
Chairman

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Charles A. Mann

THE UNIVERSITY OF MINNESOTA

GRADUATE SCHOOL

Report

of

Committee on Thesis

The undersigned, acting as a Committee of the Graduate School, have read the accompanying thesis submitted by Ralph Lewis Dowdell for the degree of Master of Science. They approve it as a thesis meeting the requirements of the Graduate School of the University of Minnesota, and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science.

Oscar E. Harder
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May 18 1971

STUDIES ON STEELS FOR PERMANENT MAGNETS

A THESIS

PRESENTED TO THE

FACULTY OF THE GRADUATE SCHOOL

UNIVERSITY OF MINNESOTA

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR

THE DEGREE OF MASTER OF SCIENCE

BY

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I. INTRODUCTION

1. Object.

The purpose of this investigation is to study the relation of chemical composition, heat treatment and microstructure, to the magnetic properties of different permanent magnet steels.

A large amount of research has been done by previous investigators on permanent magnets but most of the magnetic properties have been measured by instruments which give only relative values, not in C.G.S. units and not convertible into such units.

A limited amount of more scientific work has been done, notably by the U.S.Bureau of Standards, in which expensive permeameters were used, but practically all of that work has been limited to closed circuit testing so that little or no information in scientific units is available, regarding the properties of permanent magnets when tested in an open circuit.

2. Results.

The results which have been obtained in this investigation may be summarized under the following headings:

a. Thermal Analysis.--Inverse-rate curves have been determined showing the critical points of the magnet steels.

b. Microstructure.--Micrographs of both annealed and hardened magnet steels have been made.

c. Magnetic Properties.--(1) The relations between residual induction and drawing temperature have been determined. These results are in C.G.S. units and have been shown in graphs. (2) The relations between coercive force and drawing temperature up to 500°C. have been determined. The results are in C.G.S. units and have been shown in graphs. (3) The saturation values of the different magnet steels, quenched from different temperatures, have been determined and plotted. (4) A set-up has been developed which can be used to measure the coercive force and residual induction in C.G.S. units. The apparatus used is comparatively inexpensive and easily constructed.

II. MAGNET STEELS USED IN THE INVESTIGATION

The steels investigated consisted of practically all of the different permanent magnet steels made in this country except the K.S.magnet steel patented by K.Honda and S.Saito in Japan. In addition to steels which are generally used for permanent magnets, nickel steels, high chromium steels, carbon steels of different carbon contents, have been included for theoretical considerations. The chemical compositions of the various steels used in this investigation are shown in Table No. 1.

Table No. 1

Approximate Chemical Analyses of Magnet Steels.

Steel No.	C	Mn	Si	Cr	W	P	S	Ni
51	0.70	0.63	0.17	.....	....	.028	.033	....
54	0.74	0.57	0.20	.....	....	.016	.007	....
76	1.18	0.56	0.11	.....	....	.020	.021	....
68	0.53	0.36	0.40	0.57	5.17	.017	.007	....
69	0.67	0.56	0.29	0.18	5.07	.013	.018	....
73	0.67	0.61	0.31	0.20	5.43	.014	.007	....
74	0.61	0.38	0.25	none	5.31	.022	.027	....
88	0.76	0.61	0.56	0.41	5.08	.022	.011	....
67	0.72	0.56	0.35	2.17	0.19	.011	.014	....
70	0.97	0.74	0.33	2.87	....	.031	.005	....
71	0.80	0.56	0.30	2.16	....	.013	.002	....
18	0.11	0.22	0.10	15.70	....	.021	.001	0.10
15	0.35	0.45	0.23	.....	....	.019	.008	5.03
81	0.31	0.96	0.26	none	....	.013	.012	3.54
84	0.39	0.90	0.24	0.51	....	.020	trace	1.37
37	0.41	0.85	0.14	0.89	....	.013	.024	2.59

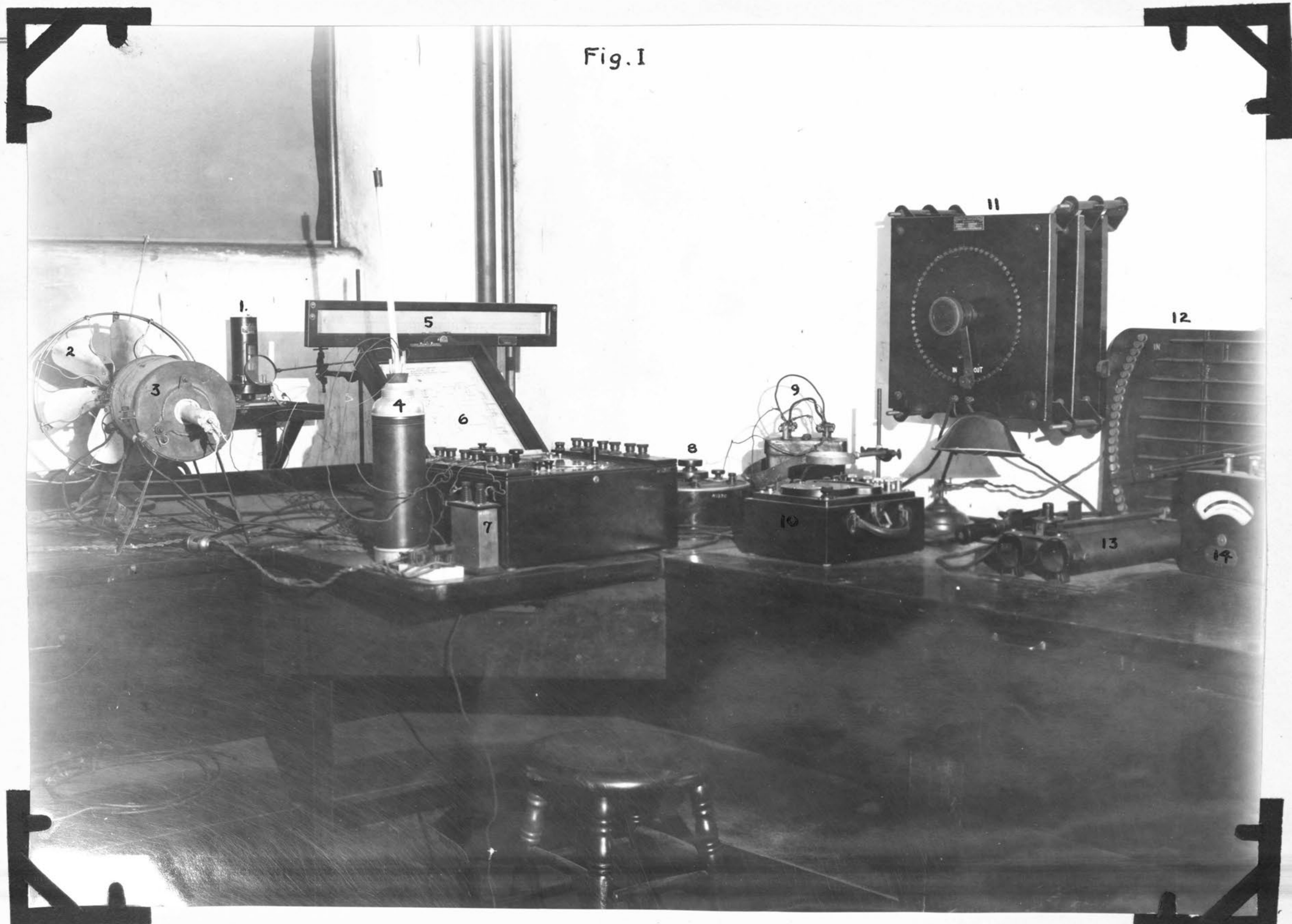


Fig.1. Set-up Used in Making Thermal Analyses.

III. THERMAL ANALYSIS

The most logical method of finding the proper heat-treating temperatures for any particular steel is by means of what is termed thermal analysis. Such a method has been used in this study and the following is a description of the apparatus, procedure, and results.

1. Apparatus.

The apparatus used in the thermal analysis investigation is shown in Figure No. 1. The pieces of apparatus indicated by the numbers on the photograph (Fig.1) are as follows:

1. Leeds & Northrup D'Arsonval type mirror galvanometer.
2. Electric fan for accelerating the rate of cooling of the electric furnace.
3. Platinum-wound electrical resistance tube furnace.
4. Thermos bottle to keep the temperature of the cold junction of the thermocouple constant. A Pt-PtRh thermocouple, with a hot junction in the furnace (3) and cold junction in (4) was used to measure the temperatures.
5. Frosted glass scale to register the galvanometer deflection.
6. Weston Potentiometer for measuring the electromotive force created by the thermocouple.
7. Standard cell (Weston type), voltage 1.0185.
8. Constant resistance on standard cell circuit.
9. Willard 6-volt, 40 amp.hours storage cell.

10. One and one-half K.W. Wattmeter on the furnace circuit, used to indicate the power on the furnace and any fluctuations that may take place on the line.

11. Five-ohm, 30 ampere resistance in series with furnace for regulating purposes.

12. Five-ohm, 30 ampere resistance for regulating the furnace.

13. Thirty-seven ohm, 10 ampere slide wire resistance for regulating the furnace. This is shunted off when the furnace is carrying high currents and switched in when needed.

14. Ampere-meter (25 ampere scale) on the furnace circuit.

2. Operation.

a. Condition of Steel.--The steels that were analyzed by the thermal method were in the annealed state. A piece of each particular steel was taken, of about 3/4" long and 1/2" in diameter. A hole 7/16" was drilled along the center line parallel to the long dimension of the pieces and about a quarter of the way through.

b. Adjustment of Apparatus.--The hot junction of the Pt-PtRh thermocouple, previously calibrated against Bureau of Standards known freezing points, is inserted in the 7/16" hole and the piece of steel, with the thermocouple in it, placed in the center of the tube furnace (3).

A small six-volt incandescent lamp is lighted behind the cover of the potentiometer (6) and is directed to the mirror of the galvanometer (1). The condensing lens of 1-meter focal length condenses the image of the diaphragm on the objective of the light tube and focusses it on the scale (5); the image appears as a circle of light with a black vertical line through the center. The galvanometer is then adjusted so that the cross-hair is on zero in the center of the scale (5).

The potentiometer is then balanced by regulating the constant resistance (8) which is in series with the storage battery (9) so that on open and closed circuit the galvanometer will remain on zero. This balance makes the e.m.f. of the storage cell equal to the e.m.f. of the standard cell (7). The standard cell is then cut out of the circuit and the storage cell e.m.f. is regulated by the potentiometer resistance until its e.m.f. is the same as the e.m.f. produced by the thermocouple. If the e.m.f.'s of the two circuits are the same, zero current will flow through the galvanometer producing a zero deflection. The potentiometer is graduated so that it reads directly in millivolts.

c. Rate of Heating and Cooling.--The specimen is heated in the furnace to some temperature below the critical points and held for about fifteen minutes to insure uniformity. The resistances on the furnace circuit (11 and 12) are then decreased at small intervals so that the specimen will heat at a constant rate. The rate of heating and cooling for all of the steels was about 2°C. in thirty seconds, except the last cooling curve on graph No. 1. As can be seen from the curve, this cooling rate was about 2°C. in fifteen seconds.

d. Method of Taking Data.--Now as the specimen heats, the millivolts created by the thermocouple will increase. Readings were taken every .02 millivolt by setting the instrument .02 Mv. higher than the correct reading and recording the time taken to go the .02 Mv. increment; then setting the potentiometer .02 Mv. higher and again recording the time it takes for the galvanometer to come back to zero. The cooling curves were taken in the reverse manner.

The time intervals were measured by alternating two stop-watches[10] so that one man could operate the set-up. By this method one stop-watch measures one interval of time and the other watch the succeeding interval so the operator does not have to record accumulative time and make subtractions after each reading.

e. Method of Plotting Data.--The inverse-rate method has been used in plotting all heating and cooling curves. Graphs 1 to 6 inclusive will show how the millivolts are plotted against the intervals of time. This particular method of plotting is usually used for convenience and also because the graphs will show the rate of heating or cooling, which is a very important item in the thermal analysis of alloy steels. Speaking in mathematical terms, the inverse-rate curve is plotted with temperature as ordinate and the derivative of time with respect to temperature as abscissa ($dt/d\theta$). The arrows designate a heating or a cooling curve.

3. Nomenclature of Critical Points.

The nomenclature adopted here is the same as that of Swinden[6] and others --

Ac denotes an arrest on heating.

Ar denotes an arrest on cooling.

Number 1 denotes the pearlite transformation indicated by the reaction $\gamma = \alpha + Fe_3C$.

Number 2 denotes the magnetic transformation from α- into β-iron and vice versa.

Number 3 denotes the reaction where the γ solid solution forms and breaks down.

The combinations of numbers indicate the reactions in the orders of the numbers at practically the same time.

4. Results of Thermal Analysis.

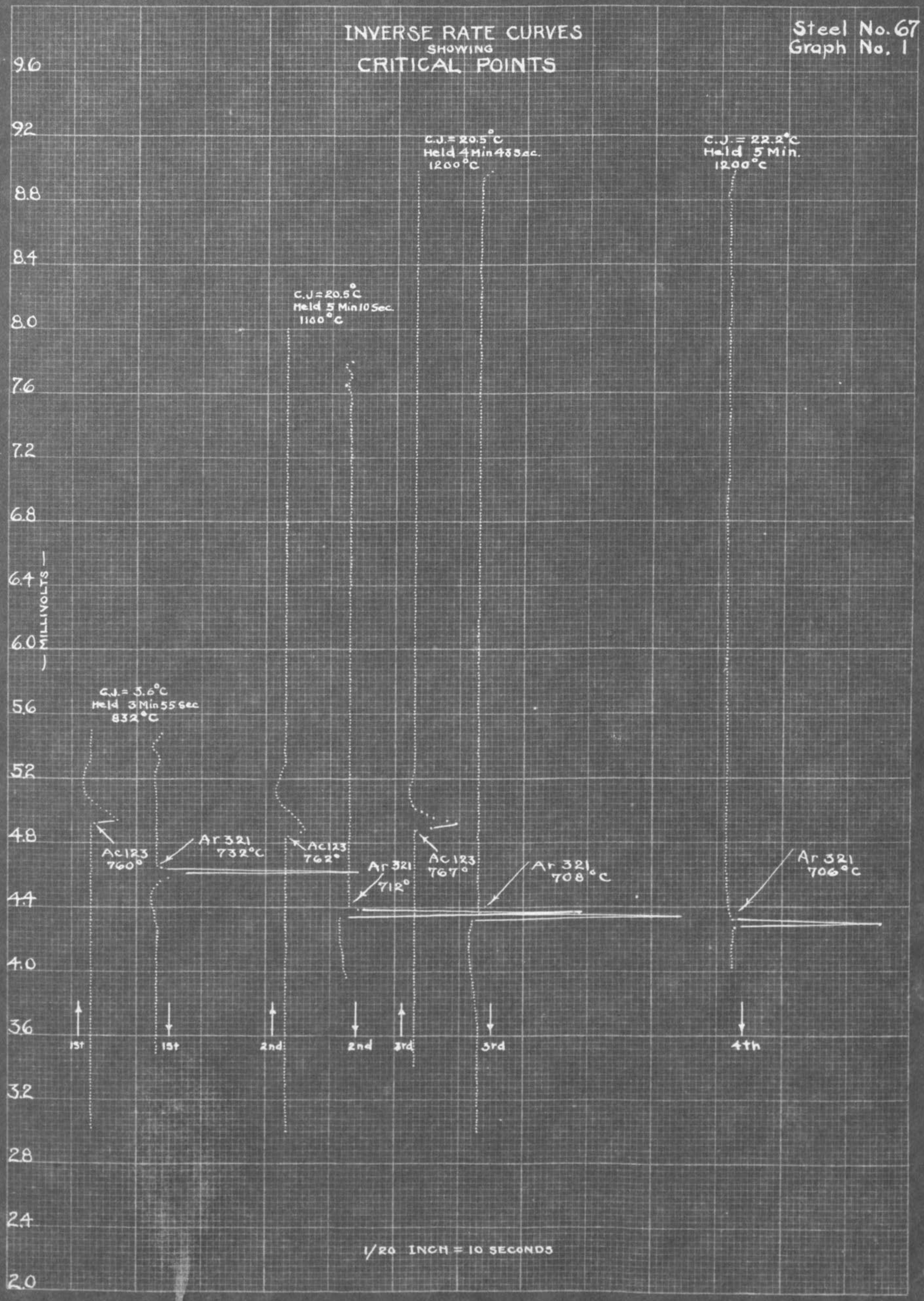
The temperatures of the different heat effects accompany the curves of the different steels and can be obtained by consulting graphs 1 to 6 inclusive.

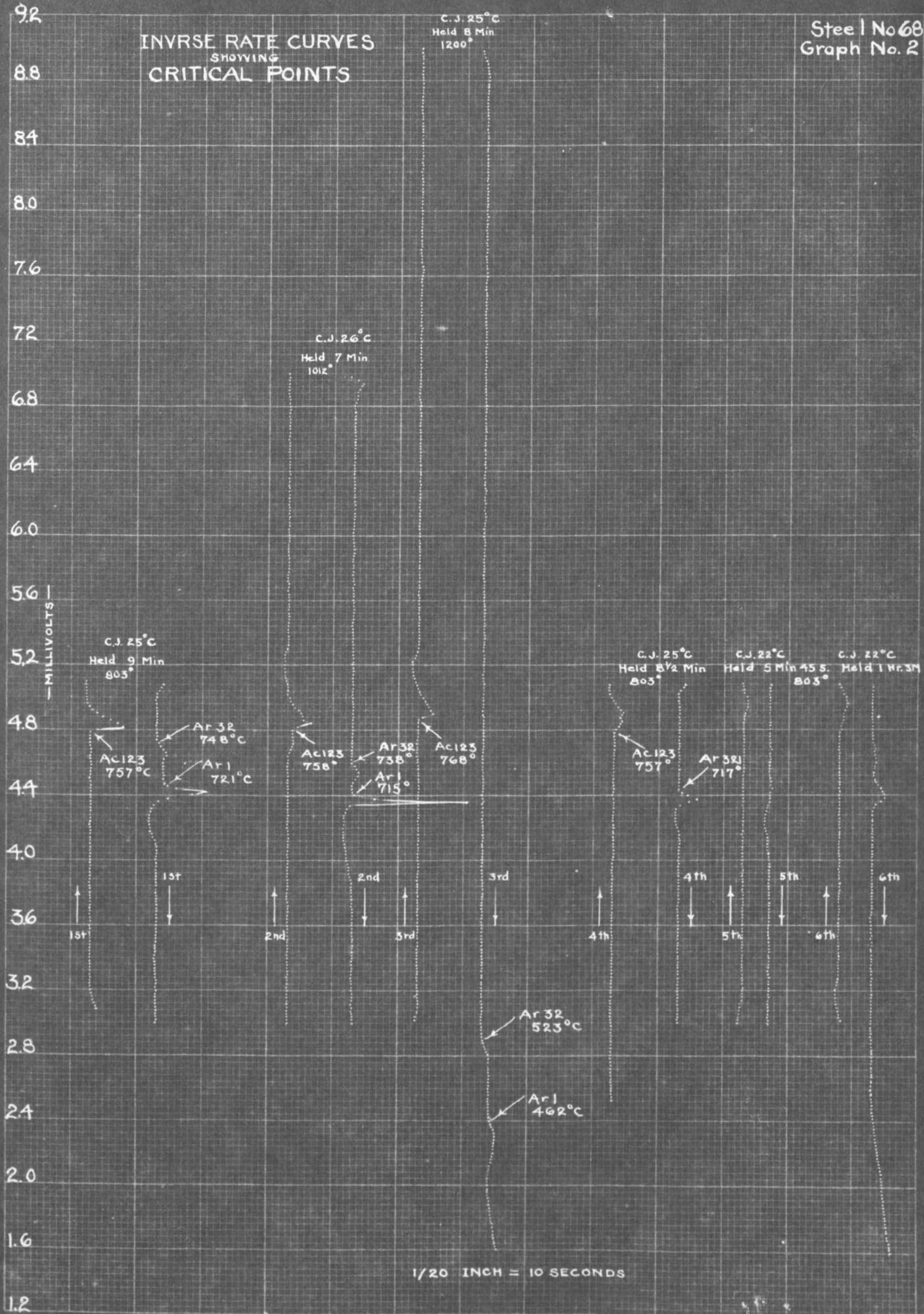
Graph No.1 of Chrome steel No.67, shows the critical points in practically the same place on cooling from different initial temperatures at the same rate. The seventh cooling curve on the graph shows a slightly lower Ar_{321} due to the increased rate of cooling.

Graphs No. 2, No. 3, No. 3A, No. 4, and No. 5 of tungsten steels show the influence of a high initial temperatture on the position of the critical points for the same rate of cooling. After reheating any of these steels above the upper critical and below the lowering temperature, the points appear as normal except as regards Ar_{32} which disappears. This phenomenon was found by Swinden also.[6] As this paper is dealing mainly with the magnetic properties of these steels, these phenomena will not be discussed further.

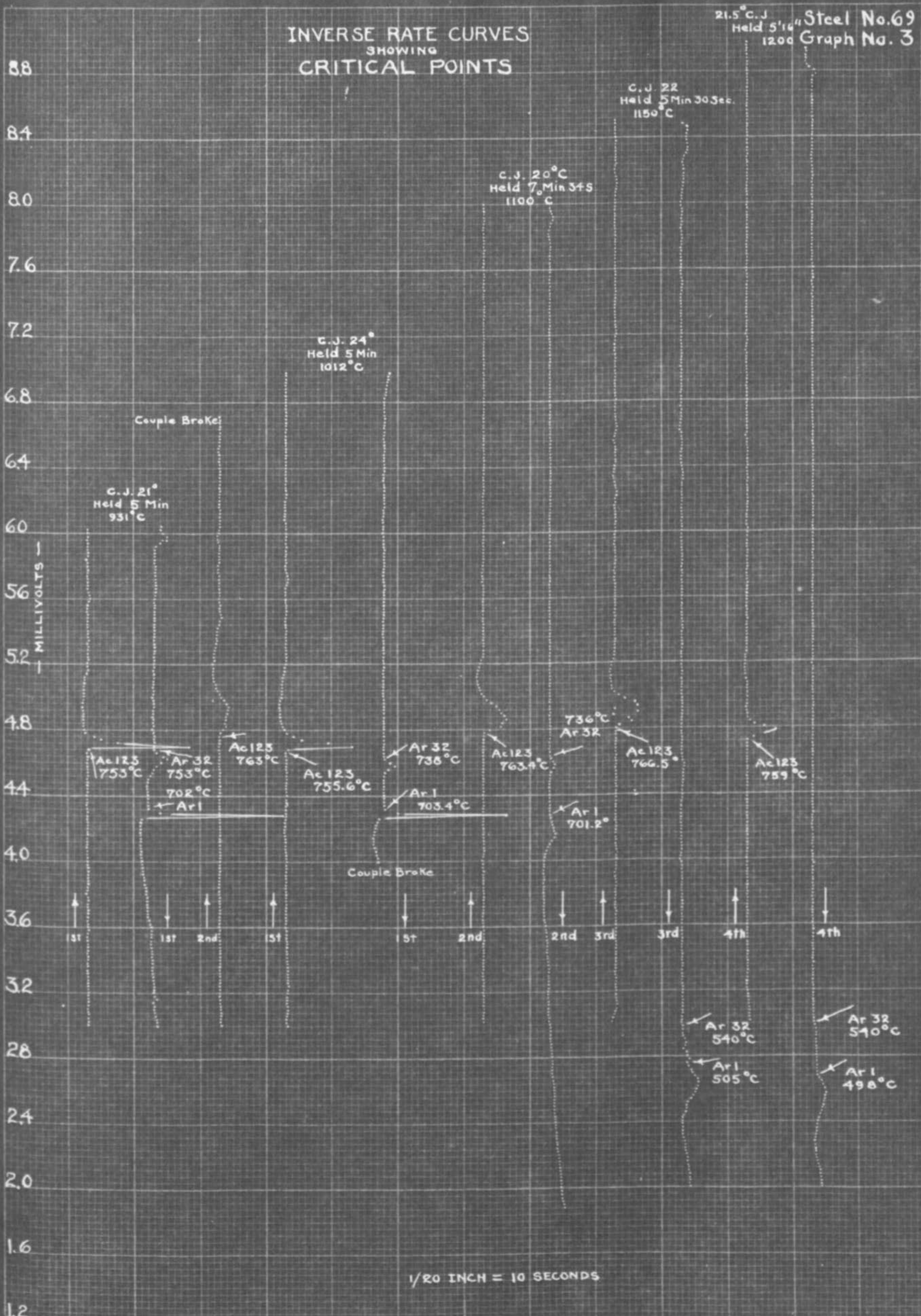
Graph No. 6 shows the critical points of some of the miscellaneous steels whose points do not have any peculiar positions, except perhaps steel No. 18 (Stainless steel, 14% Cr). In this steel the Ac_2 is below the Ac_{13} and the Ar_3 is above the Ar_2. The magnitude of the heat evolution indicates that it also includes Ar_1. This is due to the fact that chromium raises the pearlite transformation while the magnetic transformation remains the same.

The results of the thermal analyses furnished satisfactory data for heat treating as can be shown by the operations which follow and by the photomicrographs.

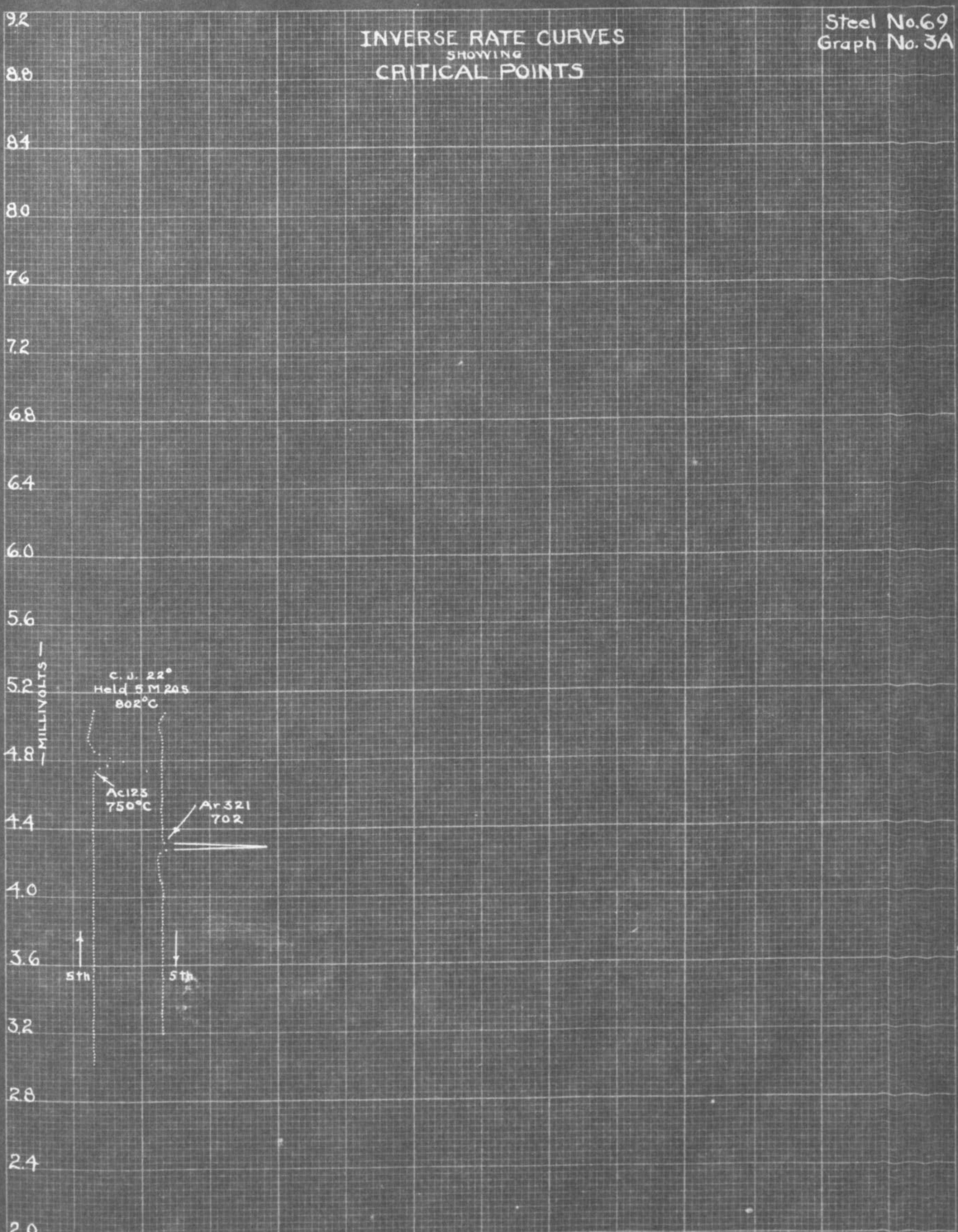

INVERSE RATE CURVES
SHOWING
CRITICAL POINTS
Steel No. 67
Graph No. 1
MILLIVOLTS
9.6
9.2
8.8
8.4
8.0
7.6
7.2
6.8
6.4
6.0
5.6
5.2
4.8
4.4
4.0
3.6
3.2
2.8
2.4
2.0
C.J. = 3.6°C
Held 3 Min 55 Sec
832°C
C.J. = 20.5°C
Held 5 Min 10 Sec.
1100°C
C.J. = 20.5°C
Held 4 Min 43 Sec.
1200°C
C.J. = 22.2°C
Held 5 Min.
1200°C
Ac123
760°
Ar 321
732°C
Ac123
762°
Ar 321
712°
Ac123
767°
Ar 321
708°C
Ar 321
706°C
1st
1st
2nd
2nd
3rd
3rd
4th
1/20 INCH = 10 SECONDS

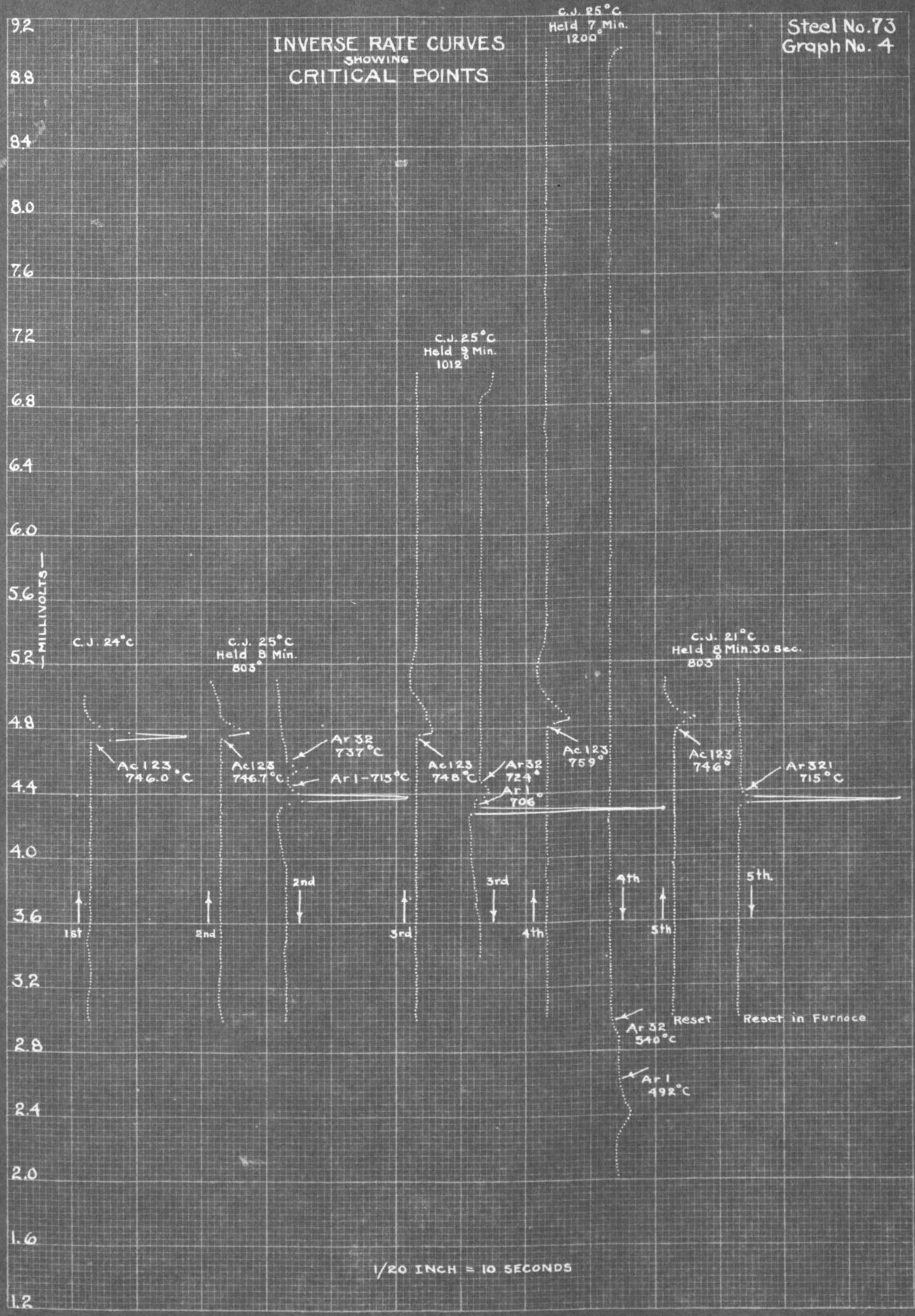


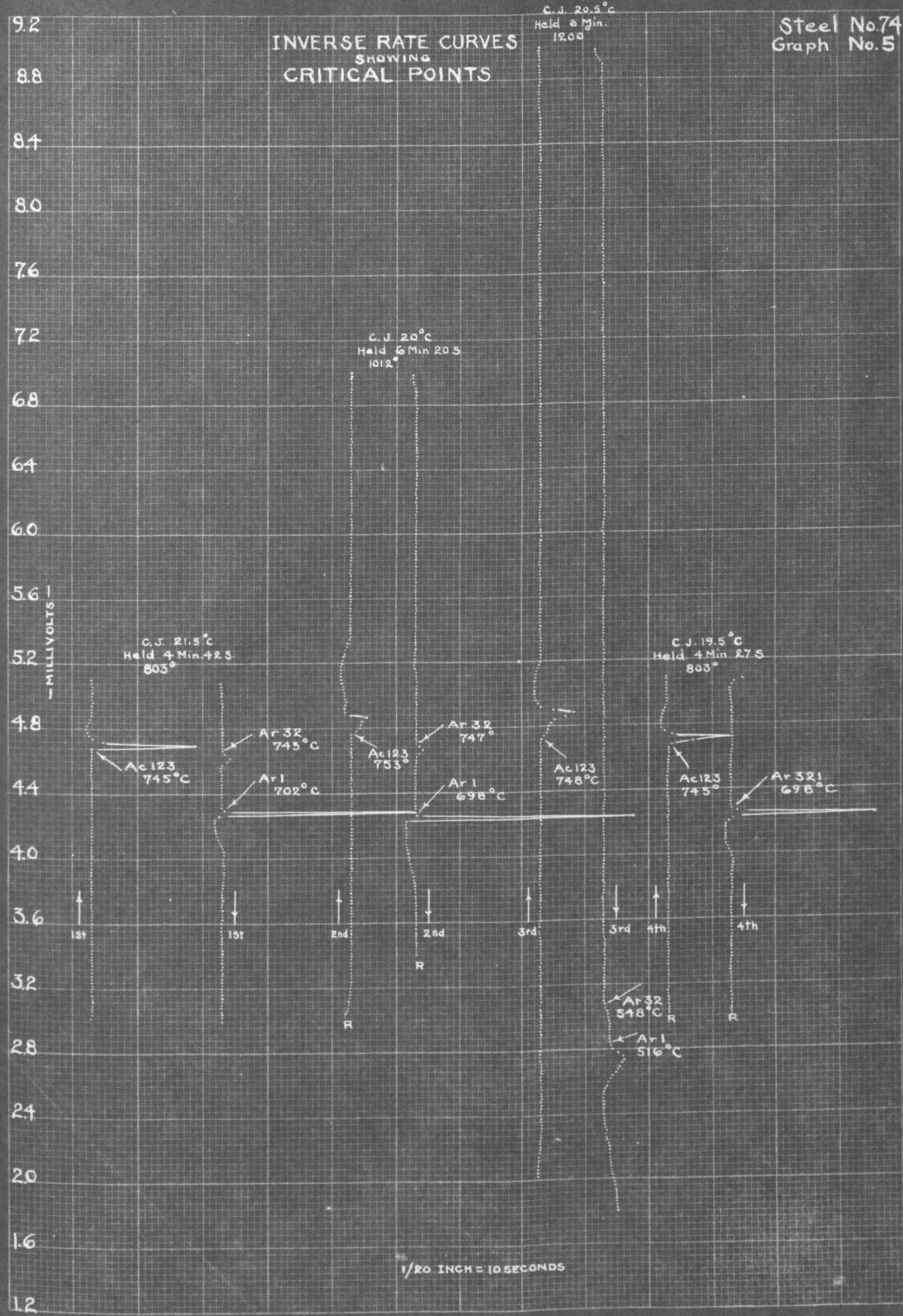
INVRSE RATE CURVES
SHOWING
CRITICAL POINTS
Steel No 68
Graph No. 2
9.2
8.8
8.4
8.0
7.6
7.2
6.8
6.4
6.0
5.6
5.2
4.8
4.4
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
MILLIVOLTS
C.J. 25°C
Held 9 Min
803°
Ac123
757°C
Ar 32
748°C
Ar 1
721°C
C.J. 26°C
Held 7 Min
1012°
Ac123
758°
Ar 32
738°
Ar 1
715°
C.J. 25°C
Held 8 Min
1200°
Ac123
768°
Ar 32
523°C
Ar 1
462°C
C.J. 25°C
Held 8½ Min
803°
Ac123
757°
Ar 321
717°
C.J. 22°C
Held 5 Min 45 S.
803°
C.J. 22°C
Held 1 Hr. 3 M
1st
2nd
3rd
4th
5th
6th
1/20 INCH = 10 SECONDS



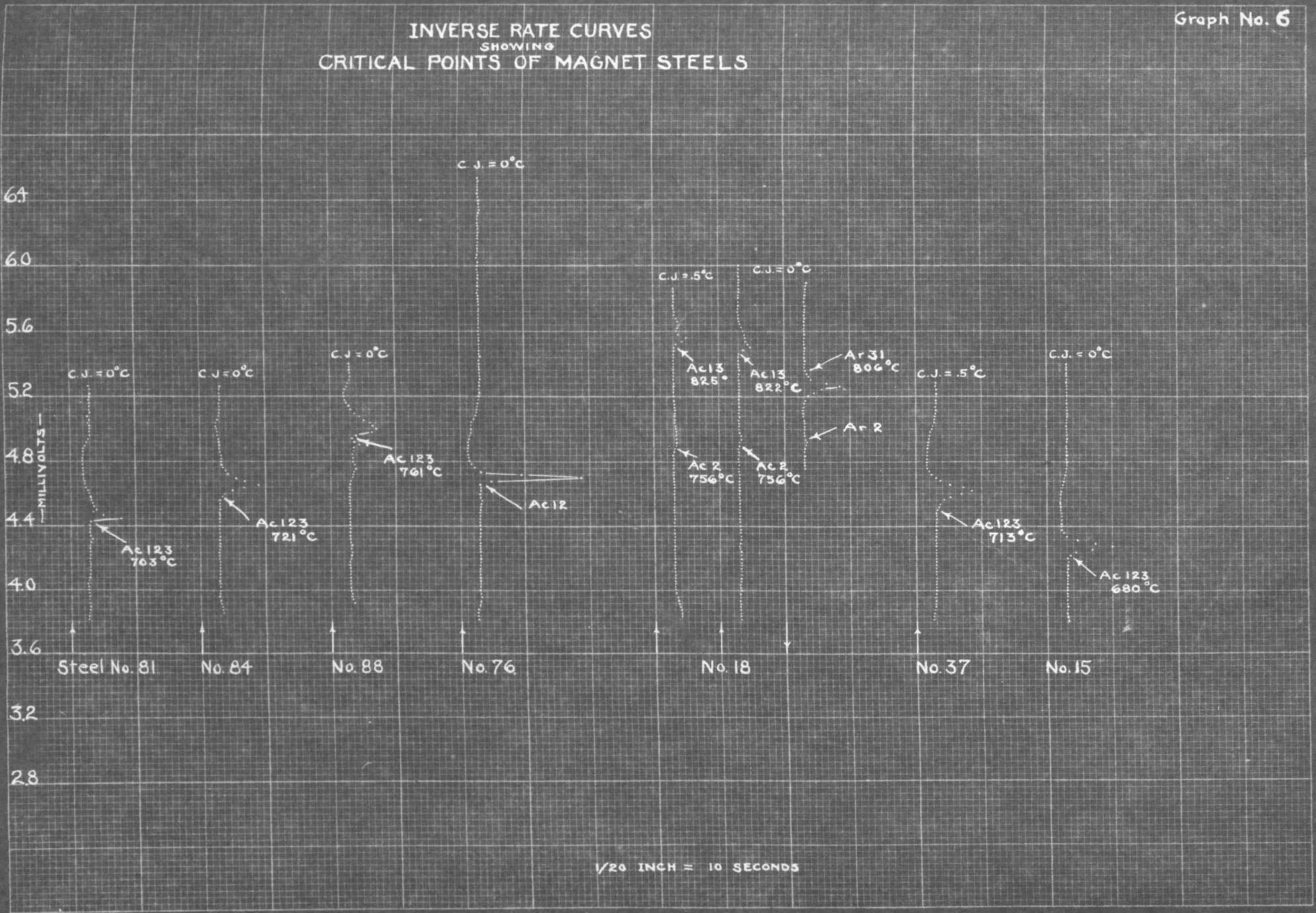
INVERSE RATE CURVES
SHOWING
CRITICAL POINTS
Steel No.69
Graph No. 3
21.5°C.J
Held 5'14"
1200
C.J. 22
Held 5 Min 30 Sec.
1150°C
C.J. 20°C
Held 7 Min 34 S
1100 C
C.J. 24°
Held 5 Min
1012°C
Couple Broke
C.J. 21°
Held 5 Min
931°C
MILLIVOLTS
Ac123
753°C
Ar 32
753°C
702°C
Ar1
Ac123
763°C
Ac 123
755.6°C
Ar 32
738°C
Ar 1
703.4°C
Couple Broke
Ac123
763.4°C
736°C
Ar 32
Ar 1
701.2°
Ac 123
766.5°
Ac123
759°C
Ar 32
540°C
Ar 1
505°C
Ar 32
540°C
Ar 1
498°C
1st
1st
2nd
1st
1st
2nd
2nd
3rd
3rd
4th
4th
8.8
8.4
8.0
7.6
7.2
6.8
6.4
6.0
5.6
5.2
4.8
4.4
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
1/20 INCH = 10 SECONDS


Steel No. 69
Graph No. 3A
INVERSE RATE CURVES
SHOWING
CRITICAL POINTS
9.2
8.8
8.4
8.0
7.6
7.2
6.8
6.4
6.0
5.6
5.2
4.8
4.4
4.0
3.6
3.2
2.8
2.4
2.0
1.6
— MILLIVOLTS —
C. J. 22°
Held 5 M 20 S
802°C
Ac123
750°C
Ar 321
702
5th
5th
1/20 INCH = 10 SECONDS


INVERSE RATE CURVES
SHOWING
CRITICAL POINTS
Steel No. 73
Graph No. 4
MILLIVOLTS
9.2
8.8
8.4
8.0
7.6
7.2
6.8
6.4
6.0
5.6
5.2
4.8
4.4
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
C.J. 24°C
C.J. 25°C
Held 8 Min.
803°
C.J. 25°C
Held 8 Min.
1012°
C.J. 25°C
Held 7 Min.
1200°
C.J. 21°C
Held 8 Min. 30 Sec.
803°
Ac 123
746.0 °C
Ac123
746.7°C
Ar 32
737°C
Ar 1 - 715°C
Ac123
748°C
Ar 32
724°
Ar 1
706°
Ac 123
759°
Ac 123
746°
Ar 321
715°C
Ar 32
540°C
Ar 1
492°C
1st
2nd
2nd
3rd
3rd
4th
4th
5th
5th
Reset
Reset in Furnace
1/20 INCH = 10 SECONDS



Steel No.74
Graph No.5
INVERSE RATE CURVES
SHOWING
CRITICAL POINTS
9.2
8.8
8.4
8.0
7.6
7.2
6.8
6.4
6.0
5.6
5.2
4.8
4.4
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
— MILLIVOLTS —
C.J. 21.5°C
Held 4 Min.42 S.
803°
Ac123
745°C
Ar 32
743°C
Ar 1
702°C
C.J. 20°C
Held 6 Min 20 S
1012°
Ac123
753°
Ar 32
747°
Ar 1
698°C
C.J. 20.5°C
Held 6 Min.
1200
Ac123
748°C
Ar 32
548°C
Ar 1
516°C
C.J. 19.5°C
Held 4 Min 27 S
803°
Ac123
745°
Ar 321
698°C
1st
1st
2nd
2nd
3rd
3rd
4th
4th
R
R
R
R
R
1/20 INCH = 10 SECONDS


Graph No. 6
INVERSE RATE CURVES
SHOWING
CRITICAL POINTS OF MAGNET STEELS
6.4
6.0
5.6
5.2
4.8
4.4
4.0
3.6
3.2
2.8
—MILLIVOLTS—
C.J. = 0°C
Ac 123 703°C
Steel No. 81
C.J = 0°C
Ac 123 721°C
No. 84
C.J = 0°C
Ac 123 761°C
No. 88
C.J. = 0°C
Ac 12
No. 76
C.J. = .5°C
Ac 13 825°
Ac 2 756°C
C.J. = 0°C
Ac 13 822°C
Ac 2 756°C
Ar 31 806°C
Ar 2
No. 18
C.J. = .5°C
Ac 123 713°C
No. 37
C.J. = 0°C
Ac 123 680°C
No. 15
1/20 INCH = 10 SECONDS

IV. TEST BARS USED IN MAGNETIC TESTING

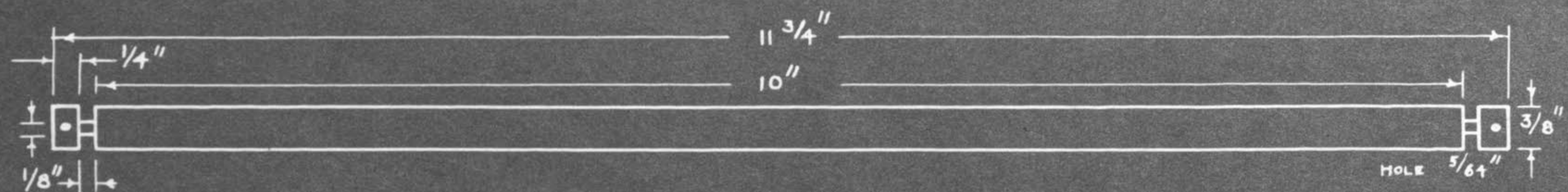
The steel stock as received was about 3/4" in diameter. After the annealing operation (See page 21) it was turned down to the size and shape shown in Fig. 2.

It is generally accepted that the greater the ratio between the length and width the more permanent the magnet will be. The ratio used was

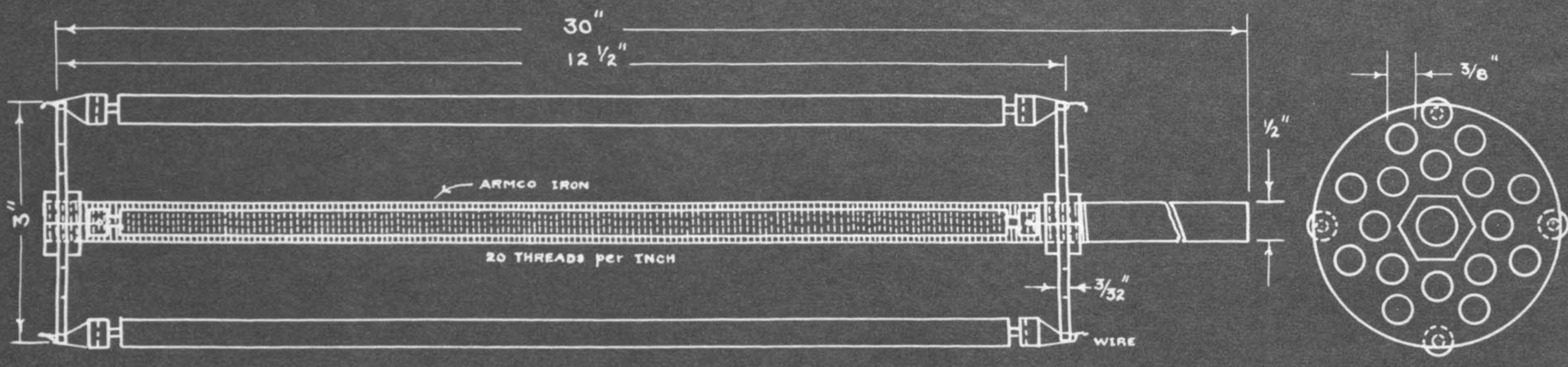
$$\frac{10''}{3/8''} = 26.7$$

This was considered the largest ratio that could be successfully heat treated and tested.

The peculiar end pieces on the bars were for the purpose of having a specimen for microscopic examination and hardness testing. One other purpose which they served was in the operation of quenching. Instead of letting the tongs touch the bars and thereby causing soft spots, the bars were wired to a holder with the aid of these ends and quenched more uniformly.



MAGNET TEST BAR
Fig. No. 2



HARDENING APPARATUS
Fig. No. 3

V. HEAT TREATMENT

1. Annealing.

The annealing operations were carried on in a gas-fired assay muffle. Most of the steels as received were 3/4" round and only partly annealed. Practically all alloy steels are hard to work on a lathe unless they are put into the granular pearlitic state, so this was done in order to facilitate machining operations on the bars.

The annealing temperatures, the method of cooling, and the scleroscope hardness of the annealed steels, are shown in the following tabulated data:

Table No. 2

Annealed Steels

Steel Number	Annealing Temp. in °C for 1 hour.	Method of cooling.	Scleroscope hardness.
54	790	Furnace	36.2
76	790	"	....
68	790	"	41.8
69	790	"	45.0
73	790	"	43.2
74	790	"	44.4
67	790	"	40.2
70	790	"	41.2
71	790	"	40.0
51	750	"	40.4
37	750	"	40.4
15	750	"	37.0
84	750	"	41.0
81	750	"	33.8
18	850	"	36.4
88	850	Sil-o-cell	40.0

2. Hardening Operation.

The heating operation before quenching was done in the lead pot of a Stewart standard furnace. The combustion chamber of this furnace was made higher in order to accommodate a large graphite crucible. The crucible was made by turning out a 6" diameter graphite electrode, so that it had an inside diameter of 3 1/2" and a depth of about 13 1/2".

The specimens were wired to a holder made of Armco iron and lowered into the graphite crucible containing the molten lead. The temperature of the lead bath was a low red heat when the bars were put in. The temperature of the bath was then brought up to the desired temperature, depending on the critical points of the particular steels involved, and held at temperature 15 minutes. The temperature of the lead pot was obtained by the same thermocouple used in obtaining the critical points. Four bars were generally quenched at one time by this method. When the bars were ready to quench the holder, with bars attached, was pulled from the lead. About one second was taken up in brushing off adhering lead from the bars, which were then quenched vertically in a large receptacle containing water which was kept below 30°C. The holder was given a spinning motion by rotating between the hands until the bars had cooled down to the temperature of the water.

Table No. 3 shows the quenching temperature and scleroscope hardness of the bars as hardened.

Table No. 4 shows the dimensions before and after hardening.

Table No. 3.

Quenching Temperature and Scleroscope Hardness
<u>of Permanent Magnet Steels</u>

Bar Numbers	Ac_3	Quenching Temp.	Quenching Medium	Average Scleroscope Hardness.	
51-1-2-3-4	750°C.	760°C.	Tap water	85.2	
54-1-2-3-4	735	745	" "	86.8	
76-1-2-3-4	800	810	" "	89.0	
68-1-2-3-4	760	770	Tap water	89.2	
69-1-2-3-4	760	770	" "	92.4	
73-1-2-3-4	750	760	" "	87.6	
74-1	750	760	" "	83.8	
74-2	750	850	" "	88.2	
74-3	750	950	" "	91.6	
74-4	750	600#	" "	92.0	cracked
67-1-2-3-4	765	775	Tap water	88.4	
70-1-2-3-4	765	865	" "	96.6	
71-1-2-3-4	765	775	" "	93.8	
15-1-2-3-4	680	690	Tap water	75.8	
18-2	825	835	" "	67.0	
18-1-3	825	925	" "	67.8	
37-1-2-3-4	715	725	" "	78.6	
81-1-2-3-4	705	715	" "	70.0	
84-1-2-3-4	721	731	" "	73.8	
88-1-2	761	771	" "	76.0	

Heat to 1150°C.; air cool to 600°C.

Table No. 4.

The Dimensions of Bars Before and After Hardening

A = diameter in inches of the end to strike the water first.
B = diameter in inches of the middle of the bar.
C = diameter in inches of the end to strike the water last.

Bar Number	Before Hardening A	B	C	After Hardening A	B	C
51-1	.3660	.3730	.3715	.3665	.3735	.3720
51-2	.3750	.3770	.3760	.3765	.3775	.3775
51-3	.3770	.3780	.3760	.3790	.3780	.3765
51-4	.3655	.3765	.3760	.3780	.3780	.3750
54-1	.3755	.3770	.3765	.3770	.3775	.3775
54-2	.3760	.3750	.3745	.3760	.3760	.3760
54-3	.3780	.3780	.3785	.3795	.3780	.3800
54-4	.3740	.3750	.3740	.3740	.3760	.3765
76-1	.3720	.3770	.3750	.3760	.3760	.3765
76-2	.3780	.3750	.3750	.3785	.3770	.3770
76-3	.3750	.3770	.3750	.3850	.3765	.3760
76-4	.3660	.3780	.3790	.3710	.3790	.3800
68-1	.3745	.3745	.3745	.3750	.3750	.3750
69-1	.3740	.3750	.3750	.3745	.3745	.3750
69-2	.3750	.3740	.3750	.3750	.3745	.3750
69-3	.3730	.3750	.3750	.3770	.3750	.3750
69-4	.3750	.3750	.3750	.3745	.3745	.3755
73-1	.3710	.3750	.3710	.3710	.3745	.3740
73-2	.3750	.3760	.3750	.3740	.3760	.3765
73-3	.3730	.3750	.3750	.3700	.3710	.3715
73-4	.3710	.3720	.3710	.3730	.3735	.3745
74-1	.3730	.3740	.3770	.3725	.3735	.3725
74-2	.3750	.3730	.3760	.3745	.3735	.3760
74-3	.3760	.3760	.3770	.3765	.3755	.3775
74-4	.3770	.3760	.3760	.3760	.3760	.3760
67-1	.3730	.3745	.3715	.3735	.3750	.3720
67-2	.3750	.3770	.3760	.3760	.3780	.3775
67-3	.3770	.3775	.3760	.3775	.3780	.3770
67-4	.3755	.3765	.3750	.3770	.3775	.3755

Table No. 4 (Continued)

Bar Number	Before Hardening A	B	C	After Hardening A	B	C
70-1	.3780	.3770	.3770	.3780	.3775	.3755
70-2	.3780	.3770	.3770	.3780	.3770	.3770
70-3	.3750	.3770	.3760	.3750	.3770	.3760
70-4	.3760	.3760	.3750	.3775	.3770	.3765
71-1	.3755	.3760	.3760	.3755	.3760	.3760
71-2	.3750	.3760	.3750	.3755	.3742	.3750
71-3	.3755	.3760	.3765	.3755	.3760	.3770
71-4	.3770	.3770	.3760	.3770	.3772	.3765
15-1	.3730	.3750	.3740	.3730	.3750	.3735
15-2	.3730	.3730	.3730	.3725	.3755	.3720
15-3	.3750	.3770	.3740	.3740	.3770	.3785
15-4	.3730	.3720	.3700	.3715	.3730	.3715
18-1	.3600	.3770	.3720	.3600	.3755	.3715
18-2	.3630	.3610	.3670	.3630	.3630	.3630
18-3	.3685	.3710	.3700	.3665	.3735	.3735
37-1	.3750	.3760	.3750	.3750	.3750	.3750
37-2	.3750	.3790	.3740	.3755	.3775	.3755
37-3	.3730	.3760	.3750	.3725	.3755	.3725
37-4	.3710	.3740	.3730	.3720	.3740	.3730
81-1	.3740	.3740	.3720	.3735	.3745	.3730
81-2	.3730	.3750	.3730	.3745	.3755	.3745
81-3	.3745	.3755	.3745	.3750	.3755	.3750
81-4	.3725	.3740	.3730	.3735	.3750	.3735
84-1	.3720	.3735	.3725	.3725	.3745	.3735
84-2	.3740	.3770	.3760	.3745	.3773	.3760
84-3	.3730	.3740	.3725	.3745	.3745	.3730
84-4	.3750	.3770	.3750	.3755	.3780	.3750
88-1	.3775	.3760	.3770	.3785	.3766	.3785
88-2	.3770	.3750	.3750	.3800	.3755	.3750

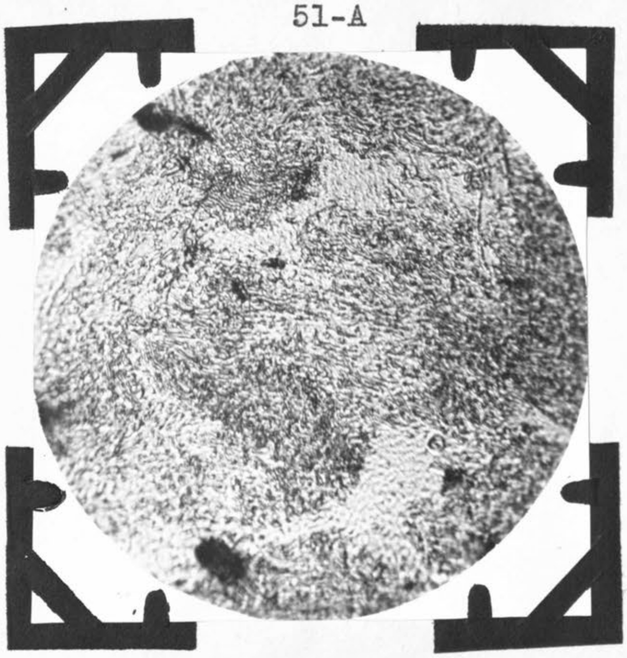
3. Drawing.

The drawings at low temperatures (up to 200°C.), after the hardening operation on the magnets, were made in a copper drying oven heated on a hotplate. A copper sheet was bent in the form of a channel; holes were drilled in each wing so that the 17 bars could be supported in a horizontal position and drawn at the same time. For drawing temperatures from 200°C. to 600°C. an electric oven was used.

4. Microstructures of Annealed and Hardened Steels.

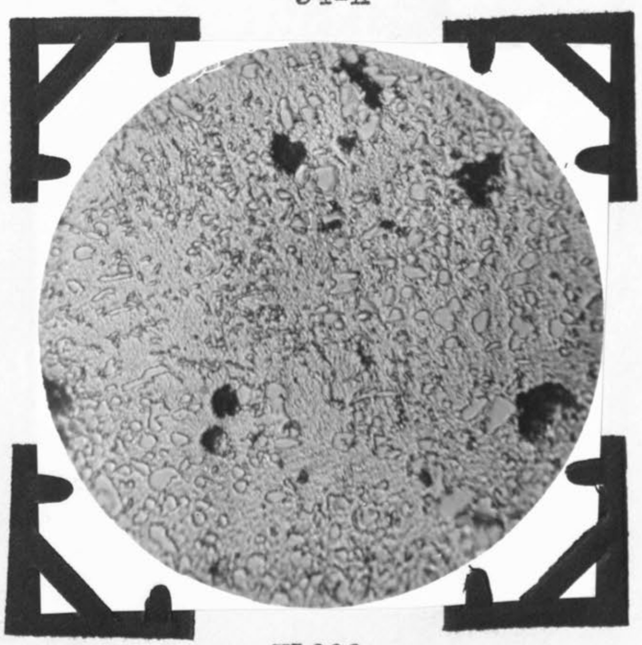
The microstructures of the steels are shown in the photomicrographs which follow. The annealed steels are designated by an "A" suffixed to the steel number. The hardened steels are designated by their steel number with a numerical suffix to show the heat treatment as given in Table No. 3.

51-A



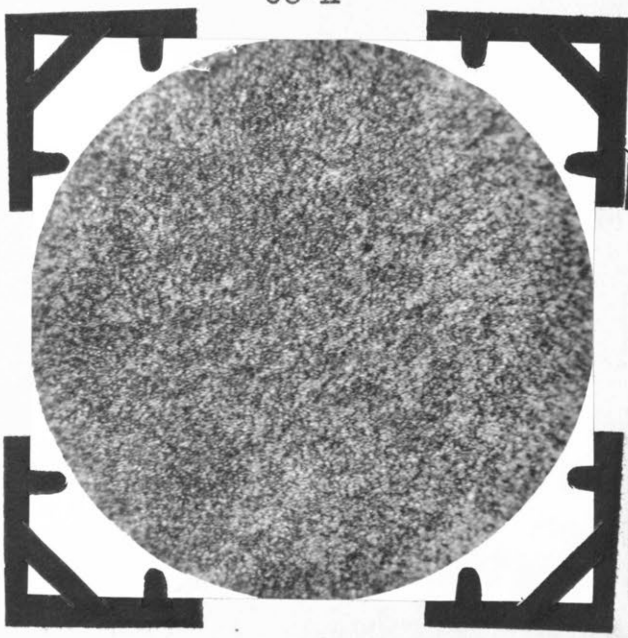
X1000
Dark, lamellar pearlite; light, ferrite
Picric acid in alcohol.

54-A



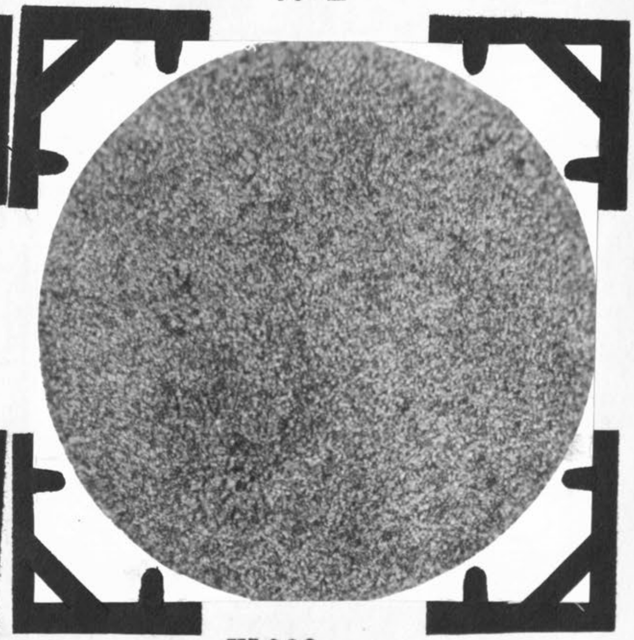
X1000
Granular pearlite.
Picric acid in alcohol.

68-A



X1000
Sorbite

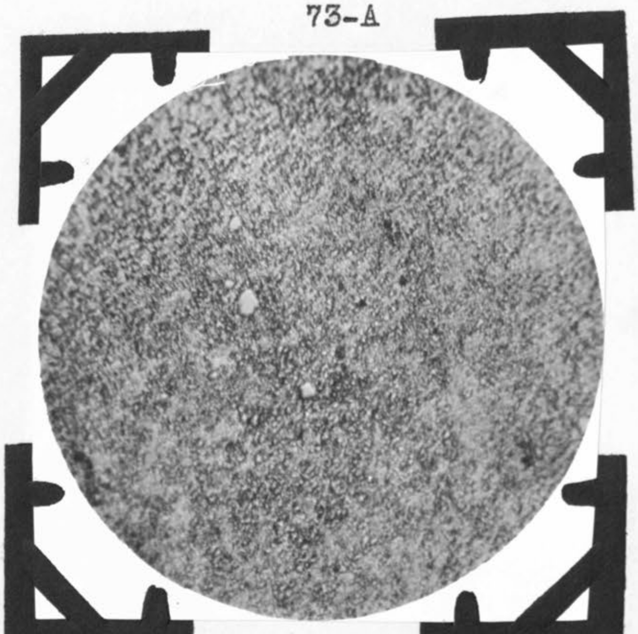
69-A



X1000
Sorbite.

Picric acid in alcohol.

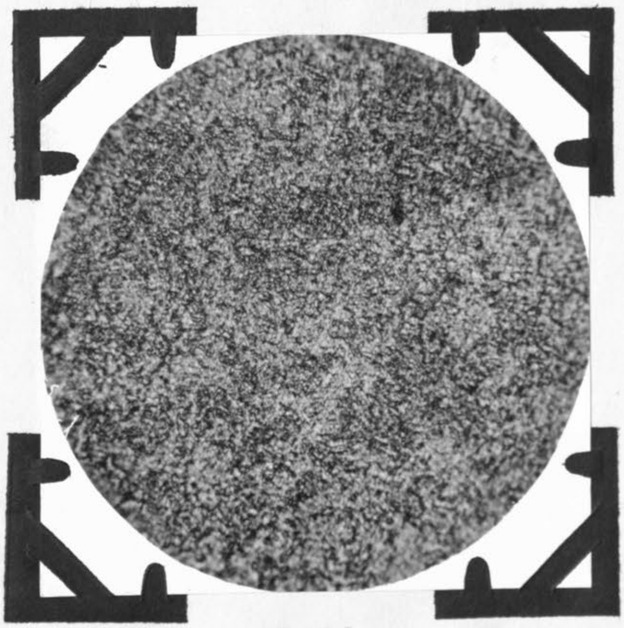
73-A



X1000
Granular pearlite.
Picric acid in alcohol.

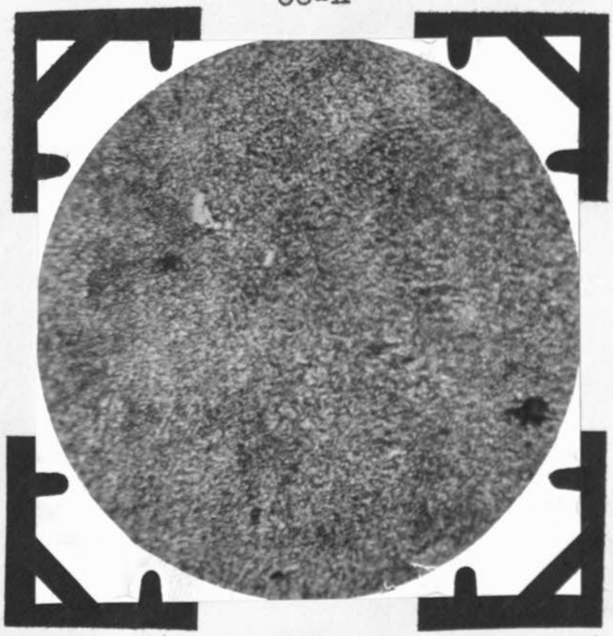
10-20 5M

74-A



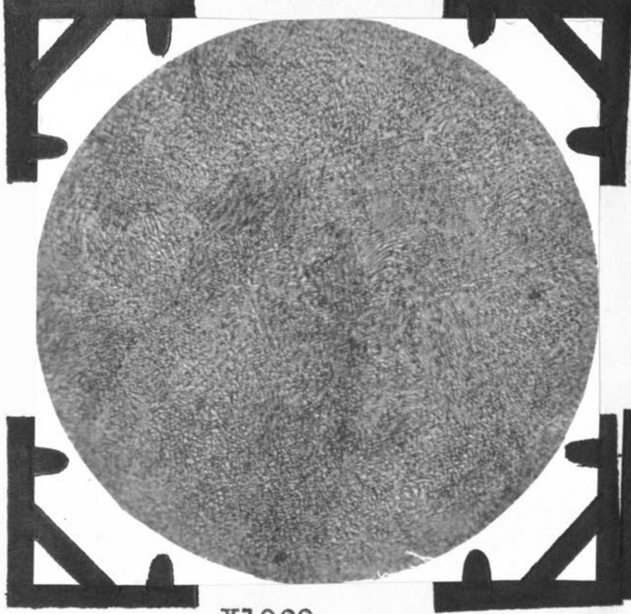
X1000
Dark areas are sorbite; light areas are largely ferrite.
Picric acid in alcohol.

88-A



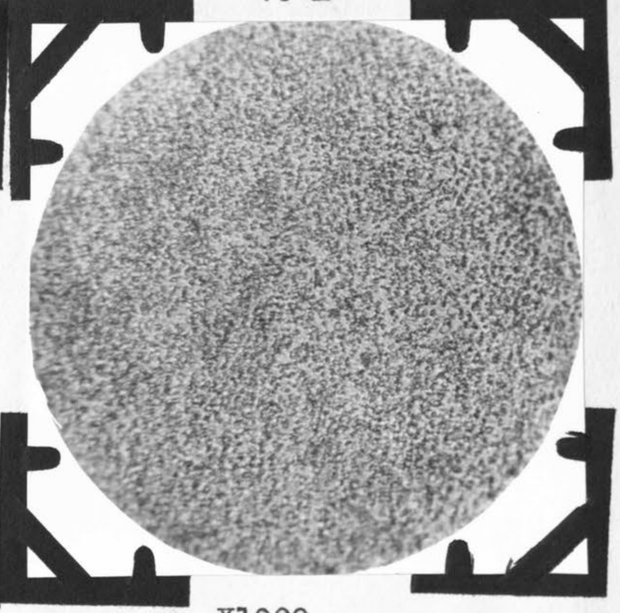
X1000
Practically all sorbitic.
Picric acid in alcohol.

67-A



X1000
Sorbitic pearlite.

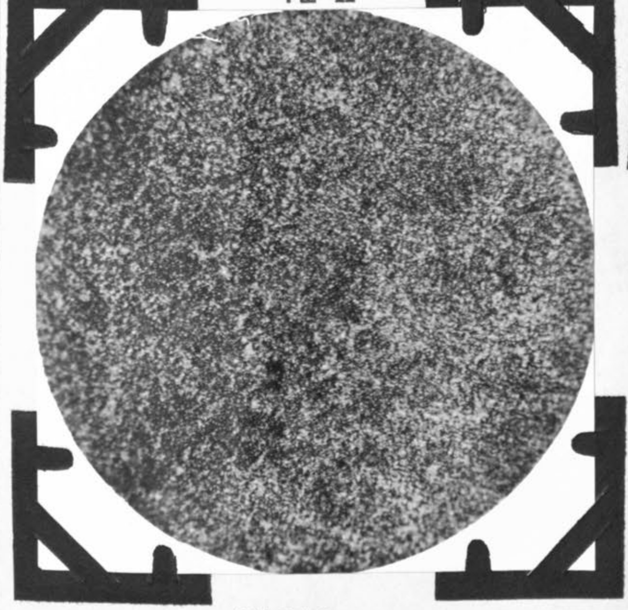
70-A



X1000
Granular pearlite.

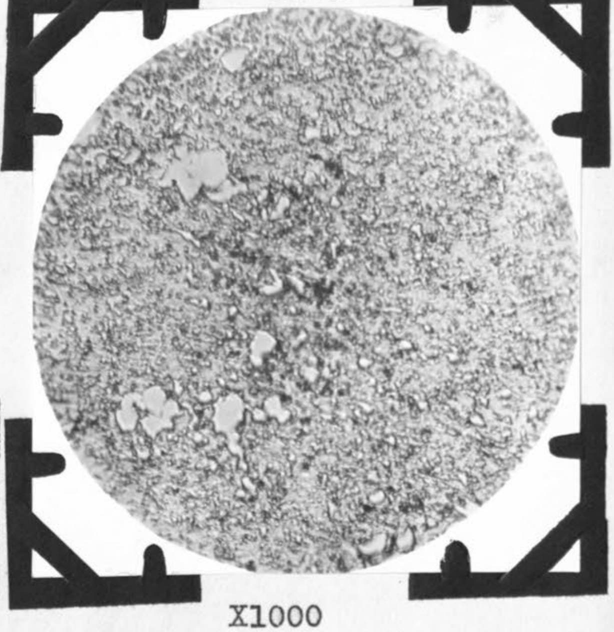
Picric acid in alcohol.

71-A



X1000
Sorbite and granular pearlite.
Picric acid in alc.

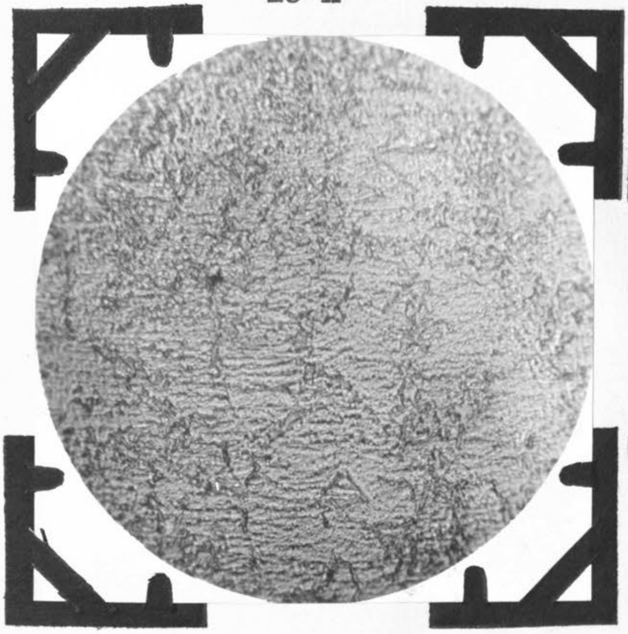
18-A



X1000
Granular pearlite.
Conc. HCl.

10-20 5M

15-A



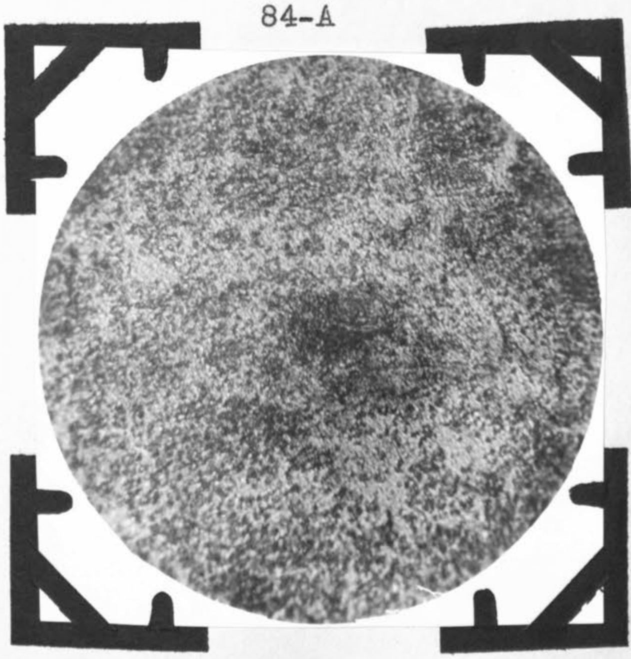
X1000
Granular pearlite.

81-A

X1000
Ferrite groundmass with sorbite and cementite islands.

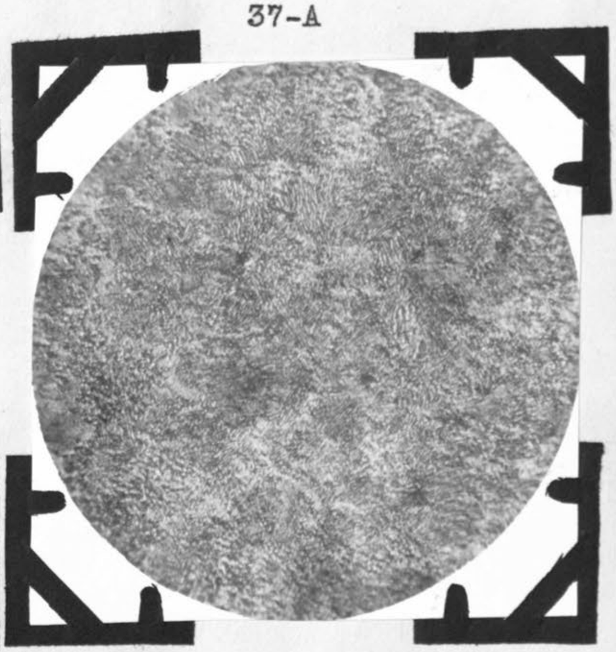
Picric acid in alcohol.

84-A



X1000
Dark areas are sorbite;
Light areas are ferrite.

37-A

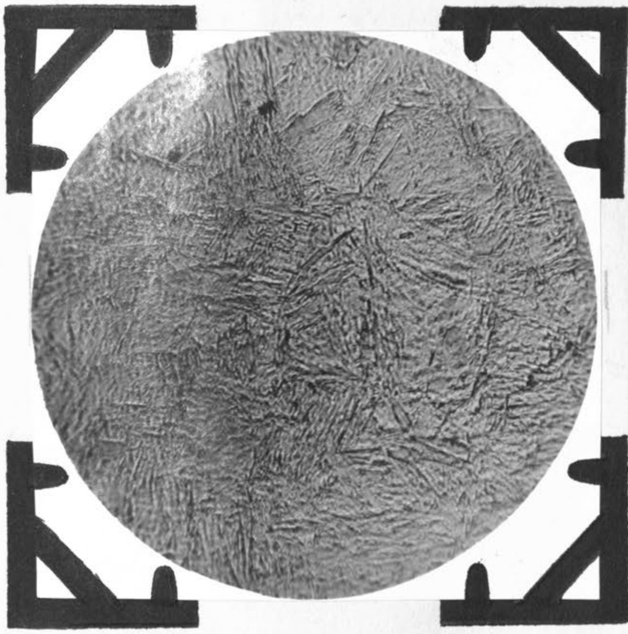


X1000
Sorbitic pearlite.

Picric acid in alcohol.

10-20 5M

51-1



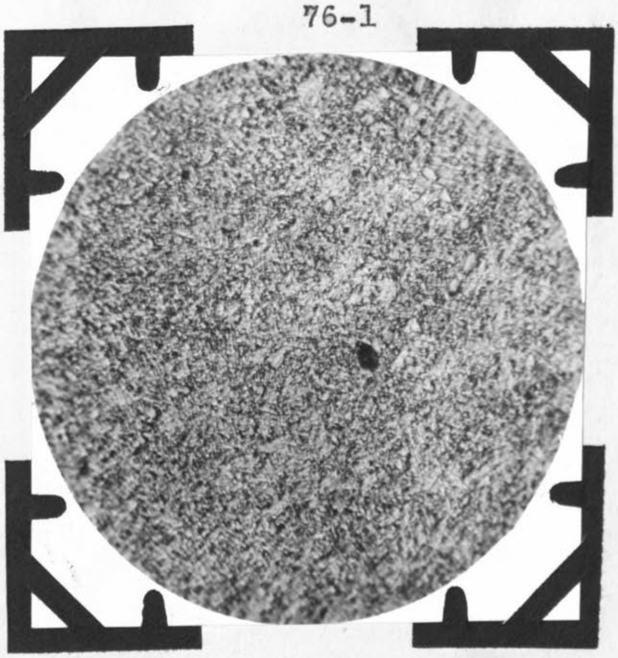
X1000
Martensite

54-1

X1000
Martensite; stringers of cementite.

Picric acid in alcohol.

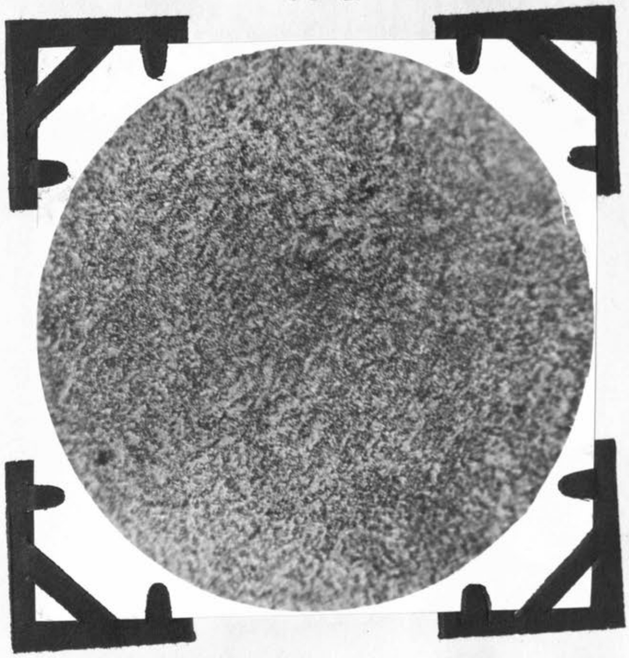
76-1



X1000
Martensite with a few carbide particles.
Picric acid in alcohol.

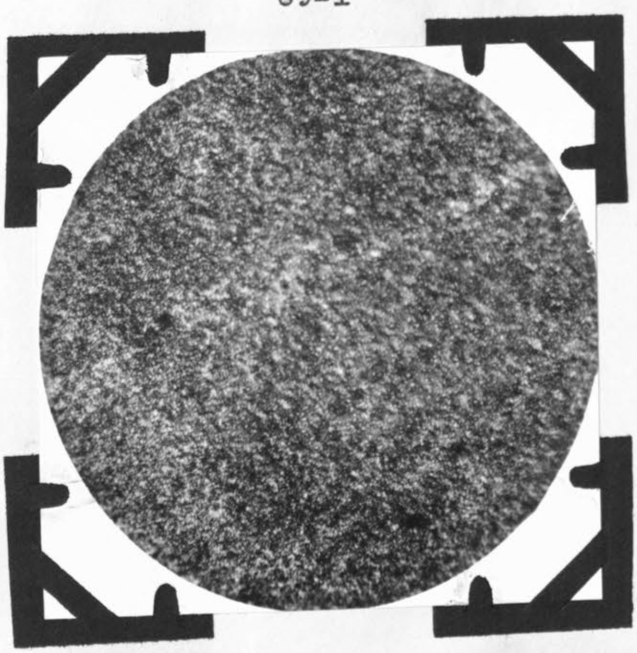
10-20 5M

68-1



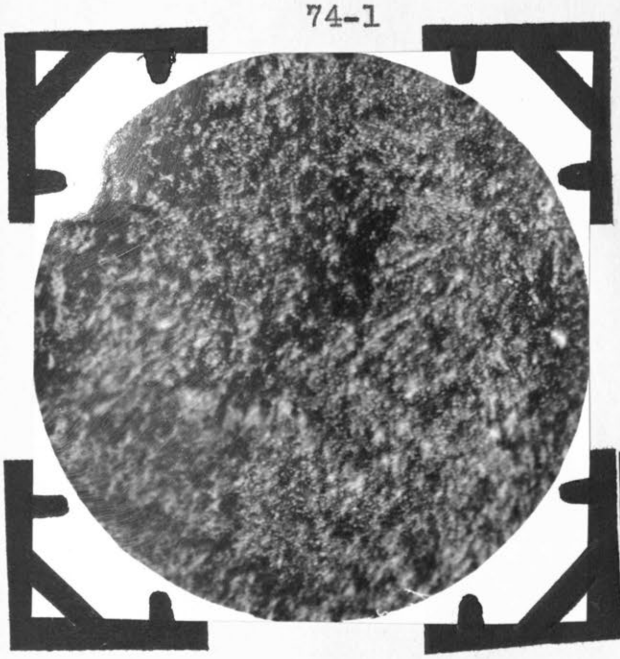
X1000
Light is martensite; small amount of troostite forming which etches dark.
Picric acid in alcohol.

69-1



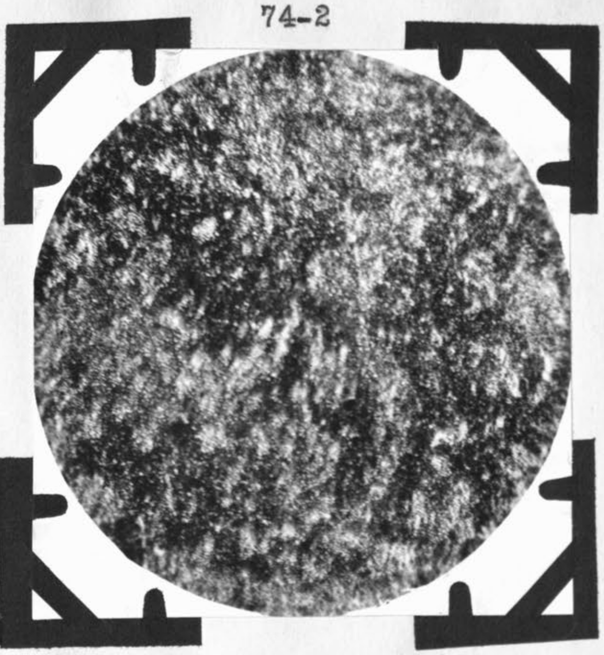
X1000
Light is martensite; dark areas are troostite beginning to form.
Picric acid in alcohol.

74-1



X1000
Light areas are martensite;
Dark areas are troostite.

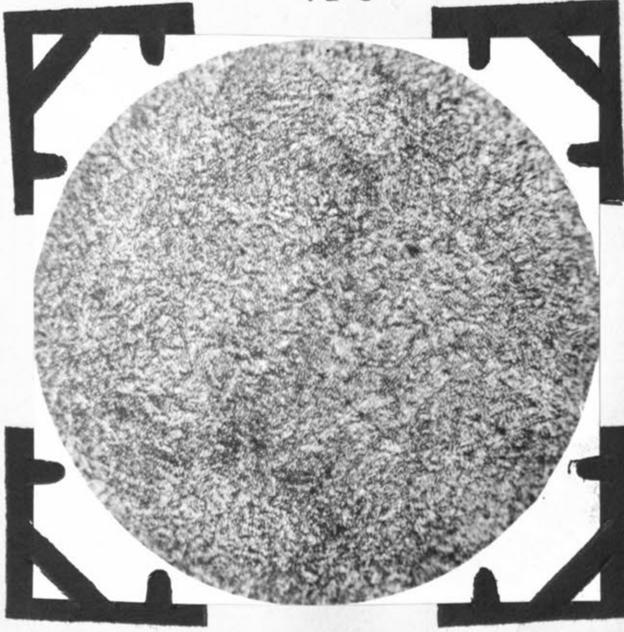
74-2



X1000
Light areas are martensite;
Dark areas are troostite.

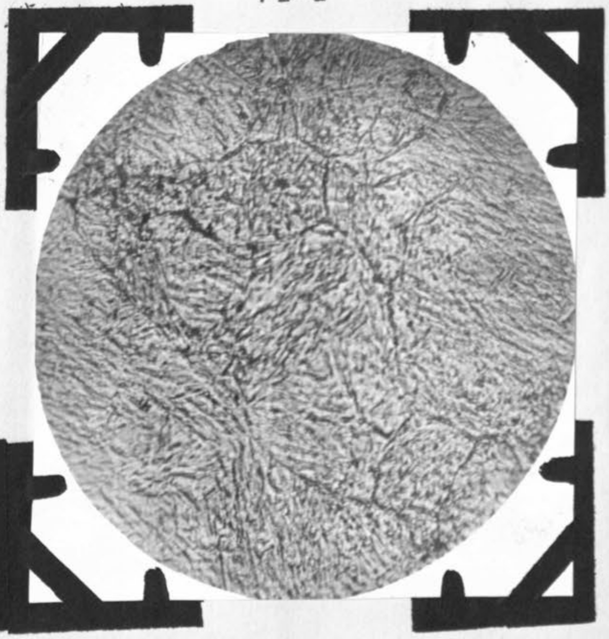
Picric acid in alcohol.

74-3



X1000
Martensite

74-4

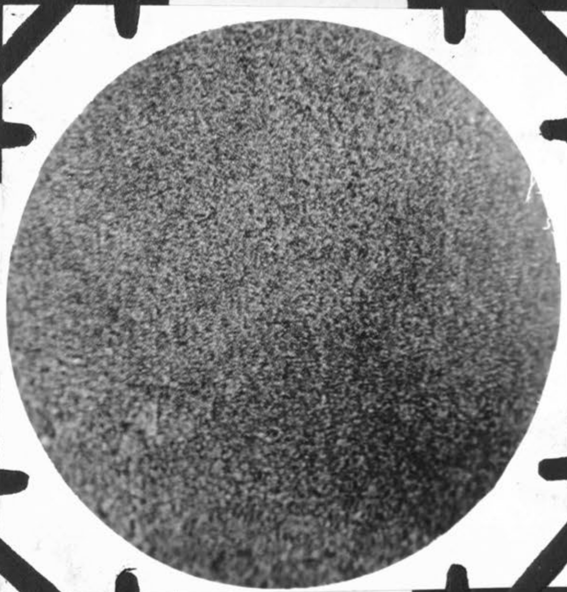


X1000
Martensite.

Picric acid in alcohol

10-20 5M

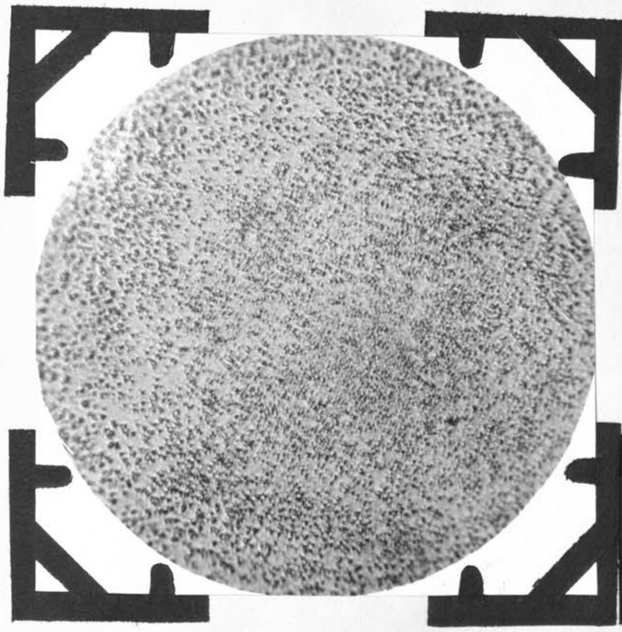
88-2



X1000
Light areas of martensite (groundmass); dark areas are the beginning of the formation of troostite.
Picric acid in alcohol.

10-20 5M

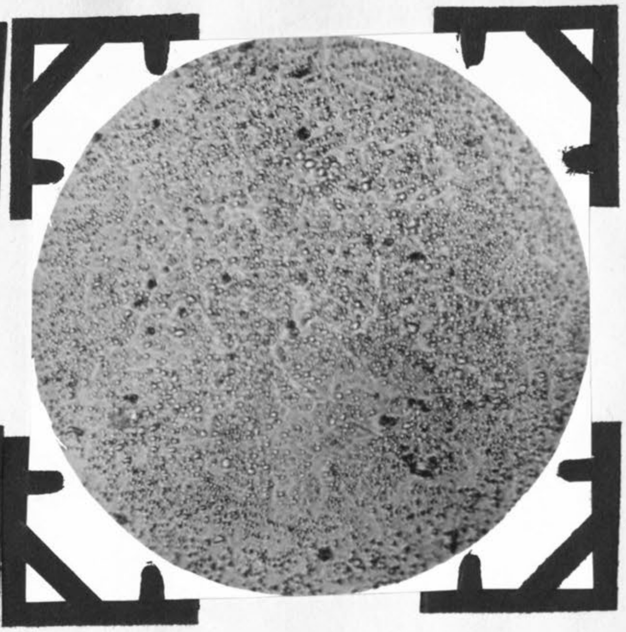
67-1



X1000

Martensite with fine particles of cementite not in solution.

70-1

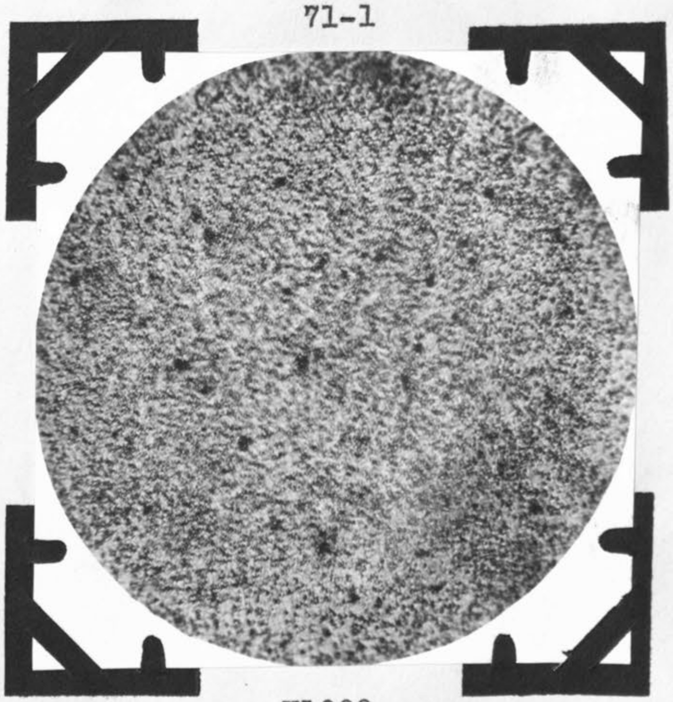


X1000

Light groundmass is martensite; islands of cementite.

Picric acid in alcohol.

71-1



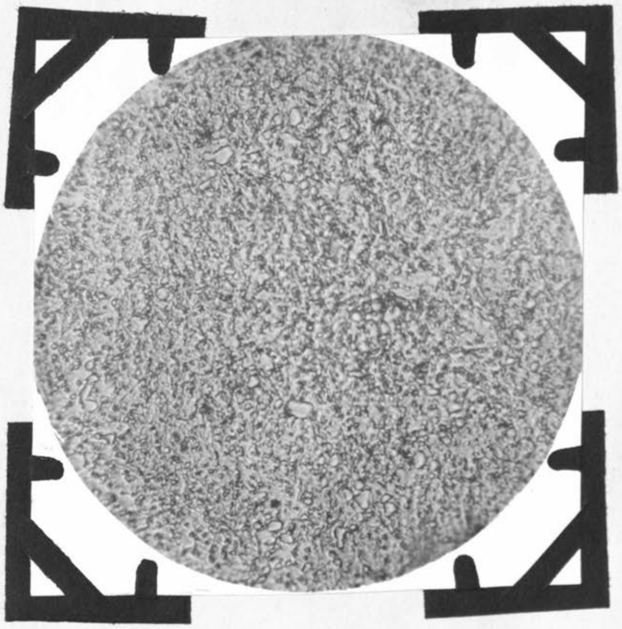
X1000

Light groundmass is martensite; islands of cementite.

Picric acid in alcohol.

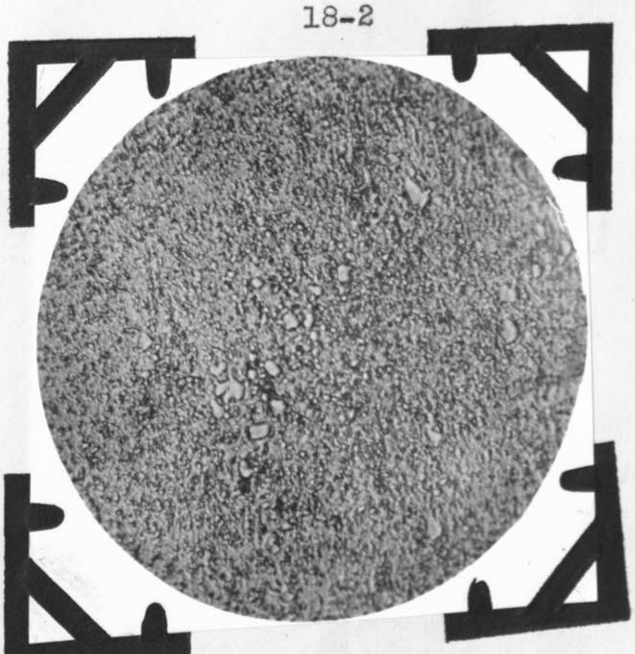
10-20 5M

18-1



X1000
Light groundmass is austenite; islands of cementite.
Concentrated HCl

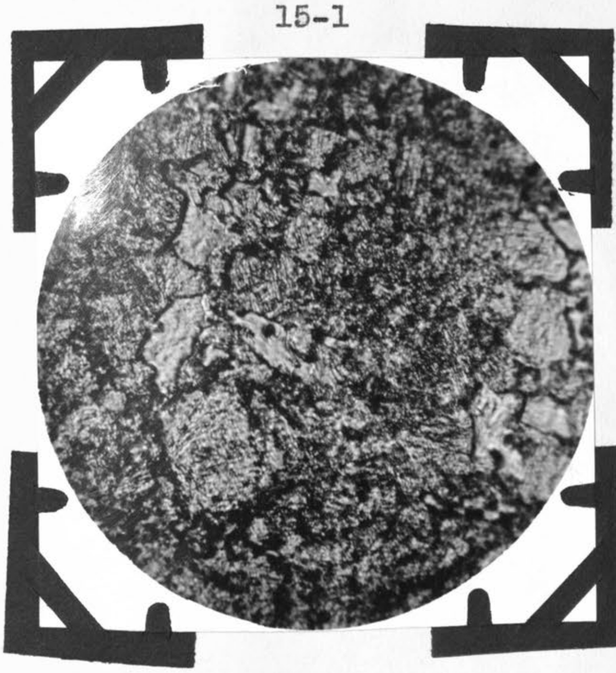
18-2



X1000
Light areas of austenite (groundmass); islands of cementite.
Concentrated HCl

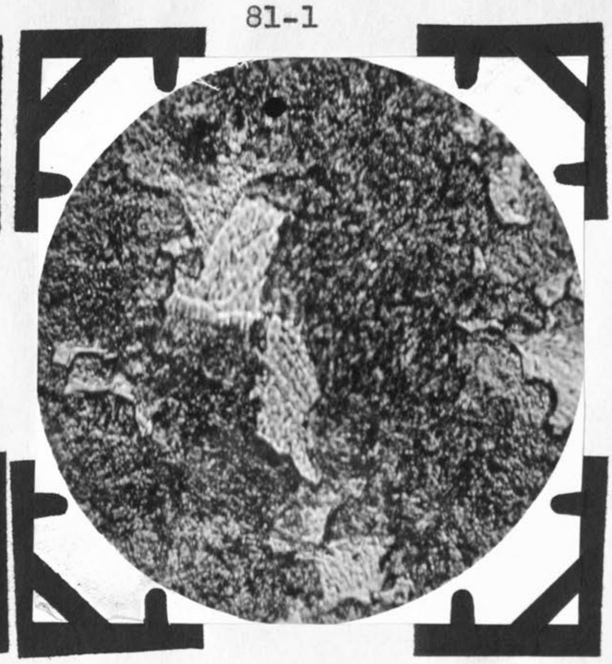
10-20 5M

15-1



X1000
Light areas are martensite;
Dark areas are beginning of formation of troostite.

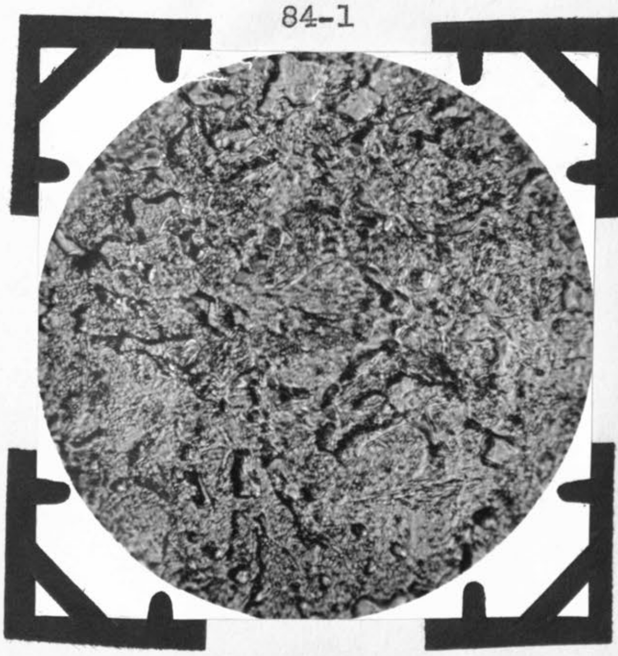
81-1



X1000
Light areas of martensite;
Dark areas are troostite.

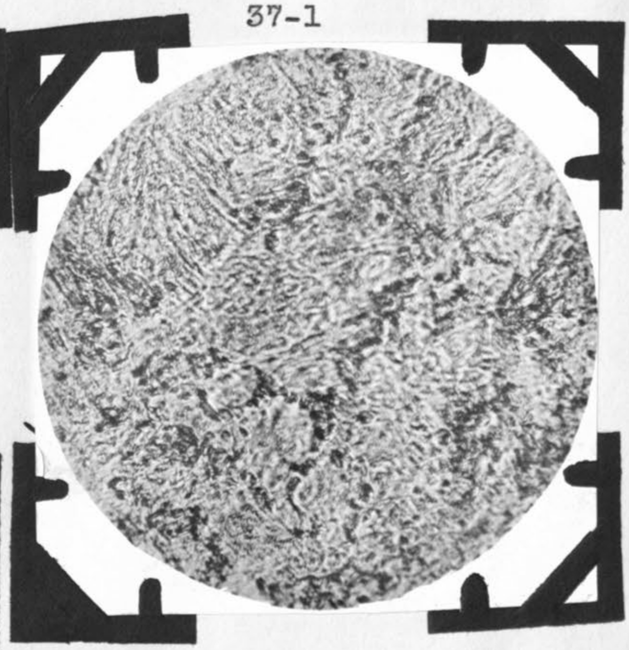
Picric acid in alcohol.

84-1



X1000
Nickeliferous martensite.

37-1



X1000
Light areas are martensite;
Dark areas are troostite.

Picric acid in alcohol.

VI. MAGNETIC TESTING

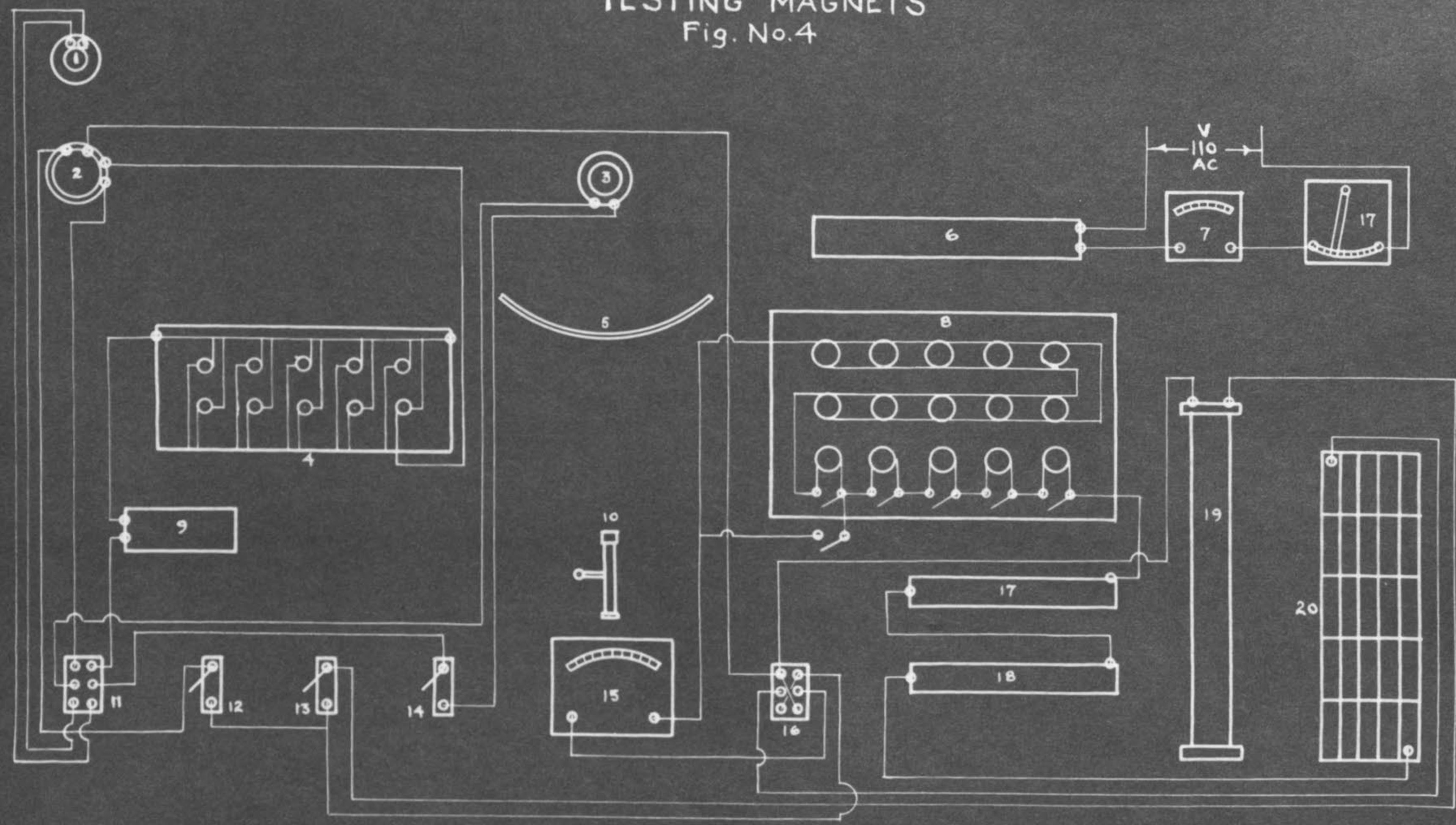
1. Apparatus.

Figure 4 shows the apparatus used for testing the magnet bars and also the wiring diagram. Figure 5 is a photograph of the set-up as used in testing. The numbers on Fig. 4 and Fig. 5 are the same so that either figure can be referred to in the following discussion.

It should be pointed out that this particular type of testing would be classified as open-circuit testing. As stated in the introduction, most work which has been done on permanent magnets has been closed circuit testing, by which is meant that the lines of force pass from one pole of the magnet to the other through a metallic medium or conductor instead of passing through the air.

a. Mutual Inductance.--The mutual inductance (2) was made from a fiber tube 4" outside diameter, 3 1/2" inside diameter, and 31 1/5" long. This tube was inserted in a lathe and a screw thread 20 turns per inch was cut the entire length. Six hundred twenty-four turns of No. 18, double cotton covered copper wire were wound in a single layer on this tube. The wire was further protected by a heavy coating of shallac on the finished coil. This winding constitutes the primary of the mutual inductance.

WIRING DIAGRAM OF APPARATUS
for
TESTING MAGNETS
Fig. No. 4



1 TEST COIL FOR COERCIVE FORCE
2 MUTUAL INDUCTANCE
3 BALISTIC GALVANOMETER
4 TEST COILS FOR MAGNETIC FLUX
5 GALV. SCALE
6 SOLENOID FOR DEMAGNETIZING
7 A.C. AMPERE-METER
8 LAMP-BANK RESISTANCE
9 1000 Ω RESISTANCE
10 TELESCOPE
11 DOUBLE THROW SWITCH
12 KNIFE SWITCH
13 " "
14 " "
15 D.C. AMPERE-METER
16 REVERSING SWITCH
17 SLIDE-WIRE RES. CAP. 3 AMP. 25 Ω
18 " " " " 3 " 45 Ω
19 MAGNETIZING SOLENOID
20 STORAGE BATTERIES OR 110 V-D.C.

Fig.5. Set-up Used in Magnetic Testing.

10-20 5M

The field strength (H = gausses) of a solenoid in C.G.S. units is given by the equation:

$$H = \frac{4 \pi N i}{10 L}$$

when i is in amperes and L is in centimeters. The primary winding was put on in its particular way so that there would be 8 turns per centimeter,[66] in order to simplify calculations. To obtain the field strength with such a winding it is only necessary to multiply the current in amperes in the solenoid by 10 which gives the flux within the solenoid, or H = 10 i.

Around the middle of the primary winding was wound 785 turns of No. 30 double cotton covered copper wire of 100 turns per layer, constituting the secondary winding of the mutual inductance.

b. Movable Test Coil.--A movable test coil (No.1 on the figures) was made by winding 100 turns of No.30 enameled copper wire on a wooden spool. A circular piece of wood was glued to the bottom of the spool so that it would act as a guide in slipping in and out of the fiber tube of the mutual inductance in the coercive force determinations.

c. Test Coil Box Used to Measure Magnetic Flux.--Apparatus No.4 was made by taking ten high grade glass tubes with 1/16" walls, 5/8" outside diameter and 10 1/2" long. Around the middle of these ten tubes were wound 1, 2, 5, 10, 20, 40, 50, 60, 80, and 100 turns, respectively, of No. 60 enameled copper wire with the leads connected to individual taps so that any one of the tubes could be put into the circuit for the flux measurements. The windings were held in place on the glass rods by rubber cement which when dried made practically a rubber insulation. Rubber stoppers were cut so that they would slip over the ends of these tubes, acting as spreaders. These tubes were then mounted in vertical positions in a wooden box. Horizontal slides were made at the bottom of each tube so that the operator could trip the magnet, which had been placed within the tube, with the coil at its center. On tripping, the magnet fell through the test coil on to three heavy layers of felt which took up the impact largely, thus protecting the magnet against a loss of flux.

d. Demagnetizing Solenoid.--The demagnetizing solenoid (No. 6) consisted of 2000 turns of No. 15 double cotton covered copper wire wound on a brass spool.

e. Ampere-Meter.--The ampere-meter (No.15) used to measure the field strength of the different parts of the apparatus was a D.C. Weston ampere-meter of 10 ampere capacity graduated in tenths of an ampere. This was standardized by Professor Springer of the Electrical Engineering Department of the University of Minnesota and found to be as accurate as their standard instrument.

f. Magnetizing Solenoid.--The magnetizing solenoid (No. 19) was made from a fiber tube of 1" outside diameter, 3/4" inside diameter, and 23.6" (60 cm.) long.

This tube was inserted into a lathe and 10 layers of No. 17 enameled copper wire were wound as close together as possible just making 482 turns per layer or practically 8 turns per centimeter. The magnetic field in gausses in this solenoid will then be H = 100 i, on account of there being ten layers.

An infinitely long solenoid would have the same field strength at its center that it would have at either end. An equation for the field strength for any point along the center line of a solenoid is given as [67]

$$H = \frac{2 \pi N i (\cos \alpha + \cos \alpha')}{10 L}$$

H = field strength in gausses
N = total number of turns
i = amperes
α = angle subtended between center line of solenoid at the point where the field is to be determined, and a line from that point to the inside circumference of the end of the solenoid winding.
α' = the angle subtended at the opposite end of the solenoid.

If the point is in the center of the solenoid the $(\cos \alpha + \cos \alpha') = 2 \cos \alpha$ with the cos of α approaching 1 at infinity or making the equation

$$H = \frac{4 \pi N i}{10 L}$$

In calculating the required length of the magnetizing solenoid so that at a point 5" from the center there would be a negligible error (the magnet being 10" long or 5" on each side of the center), it was found that the field was .05% less than at the center for a solenoid 60 cm. long. The fields at the center and ends of the magnet can therefore be considered the same.

2. Definition of Terms Used in Magnetic Testing.

Symbol.

Mutual Inductance.--The mutual inductance is the value of the e.m.f. in the secondary circuit when the primary circuit is changed by a unit amount per second. The unit is the Henry. — M

Coercive Force.--The coercive force is the reversed magnetizing force necessary to bring the residual induction in a bar down to zero. The unit is the Gauss. — $-H_c$

Residual Induction.--The residual induction is the number of lines of force per unit area that remains when the magnetizing force is removed. The unit is the Gauss. $B_r = \frac{\phi \text{ Flux}}{\text{Area}}$ — B_r

Magnetizing Force.--The magnetizing force is the magnets motive force in a solenoid per unit length. The unit is the Gauss. — H

Symbol

<u>Flux</u>.--Flux is the total number of lines of force through a magnetic circuit. ϕ

<u>Coulomb</u>.--The coulomb is the quantity of electricity transferred by a current of one ampere per second. Equivalent to 1/10 C.G.S.unit. Q

<u>Henry</u>.--The Henry is the unit of induction, equivalent to 10^9 C.G.S. units; it is the induction in a current when the e.m.f. induced in the circuit is one volt, and when the inducing current varies at the rate of one ampere/second. H

<u>Gauss</u>.--The gauss is the unit of field strength which acts on a unit pole with a force of one dyne. One gauss = one gilbert per centimeter.

3. Procedure in Testing Magnets.

a. Electrical Energy.--The electrical energy used for magnetizing was obtained, in the earlier part of the work, from a number of storage batteries connected in series, but later from a 15 Kw. motor-generator set developing direct current at 110 volts. The latter, however, was found to be more satisfactory than a storage battery arrangement but not as constant.

b. Calibration of Ballistic Galvanometer.--The ballistic galvanometer was calibrated before each set of tests. One ampere was broken on the primary of the mutual inductance and the secondary deflection noted.

c. Determination of Residual Induction.--The bars tested were all magnetized and reversed ten times before testing. After magnetizing they were tested for residual induction by dropping them through the 100-turn test coil (4) and noting the deflection of the ballistic galvanometer.

In the derivation of the formula, it is assumed without proof that a unit magnet pole has 4π lines of force proceeding from it, the surface of a sphere being 4π. The strength of a magnetic field is then equal to $4\pi N i$ in C.G.S. units or dynes.

Now on the mutual inductance,

Let N = number of turns per centimeter,
S = total number of turns on secondary,
r = radius of secondary in centimeters,
A = area of cross section of secondary in sq.cm.,

The magnetic flux (ϕ) through the secondary of the mutual inductance is

$$\phi = FA \quad \text{or force times the area.}$$

$$\phi = FA = 4\pi N i A = 4\pi^2 N r^2 i$$

The number of linkings $N = \phi S = 4\pi^2 r^2 i S$

$$M = \frac{N}{i} \quad \text{or } N = M i$$

The value of the current flowing through a resistance R under an e.m.f. is given by Ohms law,

$$i = \frac{E}{R}, \quad (a)$$

Remembering that the current $i = \frac{dQ}{dt}$ (b)

and that $E = \frac{dN}{dt}$ (c).

Now combining (a), (b) and (c),

$$\frac{dQ}{dt} = \frac{\frac{dN}{dt}}{R} = Q = \frac{N}{R}$$

$$Q = \frac{N}{R} = \frac{M i}{R} = \frac{4\pi^2 N r^2 S i}{R} \quad \text{in C.G.S. units.}$$

However in practice i is in amperes and R is in ohms.

1 ampere = 10^{-1} C.G.S. units.

1 ohm = 10^{9} C.G.S. units.

When the magnet is dropped in the test coil giving the deflection d_1, we have,

Equation (a), $$Q_1 = \frac{N}{R\,10^8} = \frac{B\,A\,S'}{R\,10^8} \text{ coulombs} = G\,d_1$$

N = total number of linkings.

B = the induction density.

A = the cross section of the bar in sq.cm.

S' = number of wire turns on test coil.

R = total secondary circuit resistance.

When the primary of the mutual inductance is broken we have,

Equation (b),

$$Q_2 = \frac{4\pi\,N\,i\,a\,S}{R\,10^9} \text{ coulombs} = G\,d_2$$

N = number of primary turns per cm.

a = area of secondary coil.

S = total number of turns on secondary coil.

Solving equations (a) and (b) for G and equating we have,

$$\frac{B_r\,A\,S'}{d_1\,R\,10^8} = \frac{4\pi\,N\,i\,a\,S}{d_2\,R\,10^9}$$

Now solving for B_r,

$$B_r = \frac{4\pi\,N\,i\,a\,S\,d_1\,R\,10^8}{d_2\,R\,10^9\,A\,S'}$$

Taking out the constant K we have,

$$K = \frac{4 \pi N i a S}{10 S' d_2}$$ or galvanometer constant,

$$B_r = \frac{K d_1}{A}$$

All of the residual inductions in the following tables were figured from the last two equations by substituting the following numbers for the letters.

a = area of primary coil = 81.071 sq.cm.

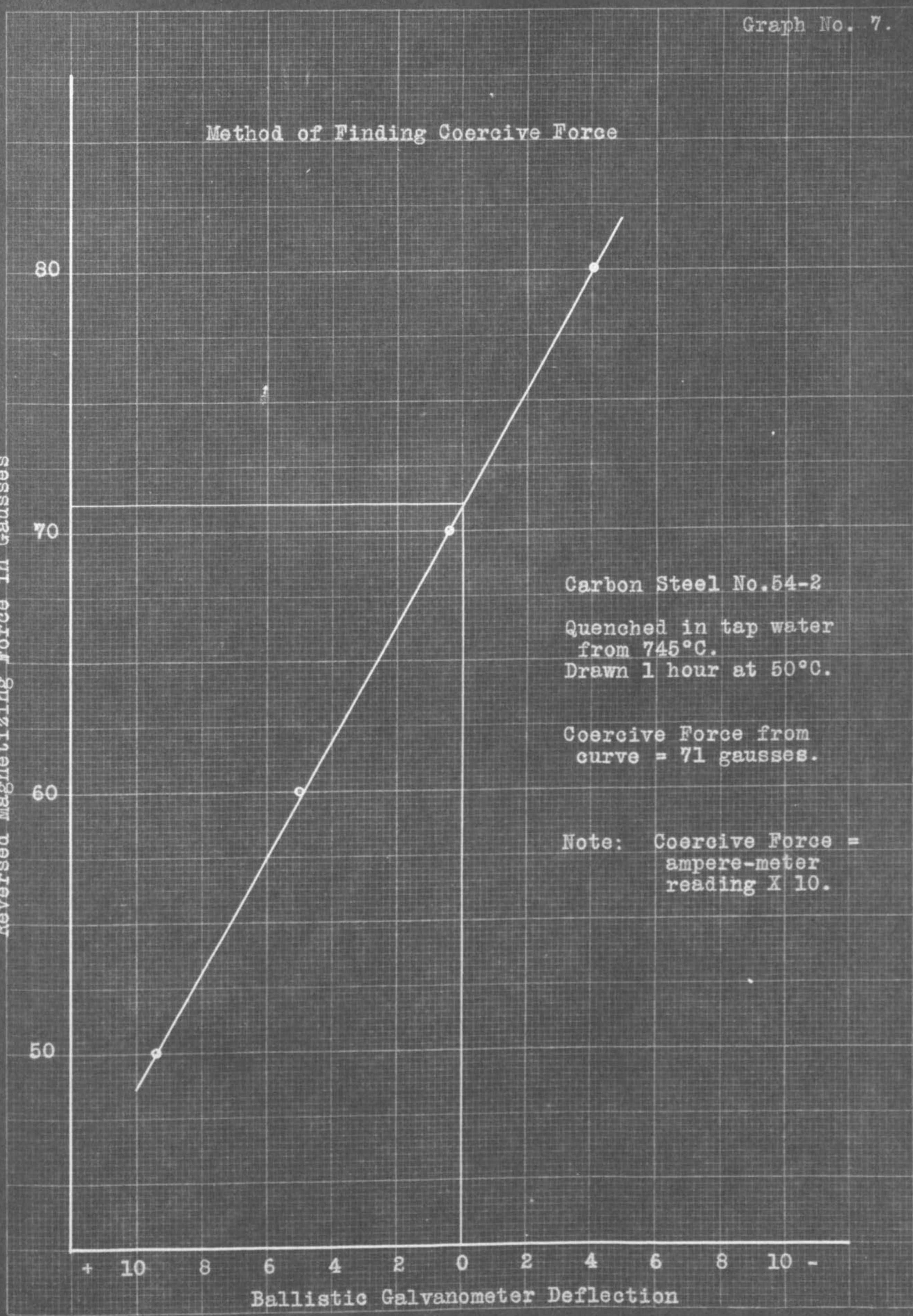
N = 8 primary turns per centimeter.

i = current in amperes.

S = 785 turns on secondary.

S' = 100 turns on test coil.

d. Determination of Coercive Force.--The bars were then tested for coercive force by lowering them into a holder at the center of the mutual inductance primary, the center of the bar being in the center of the solenoid. The movable coil (1) was then lowered so that the coil came around the middle of the magnet. An increment of a reversed magnetic force was then applied and broken; the movable coil was then pulled out by a string, cutting the lines of force in the magnet and producing a ballistic deflection.[11] When the magneto motive force applied is too strong the bar will be magnetized in the reverse



Graph No. 7.
Method of Finding Coercive Force
80
70
60
50
Reversed Magnetizing Force in Gausses
Carbon Steel No.54-2
Quenched in tap water from 745°C.
Drawn 1 hour at 50°C.
Coercive Force from curve = 71 gausses.
Note: Coercive Force = ampere-meter reading X 10.
+ 10
8
6
4
2
0
2
4
6
8
10 -
Ballistic Galvanometer Deflection

direction and the ballistic galvanometer will deflect in the reverse direction. These increments of field strength were taken so that the magneto motive force could be plotted and the point obtained by extrapolation where the induction in the bar was zero. Graph No. 7 shows how this was done. If the bar is remagnetized and the proper coercive field made and broken on the solenoid, the bar will be found to have a zero deflection and zero induction when the movable coil is jerked out.

When the magnets are to be demagnetized for future operation, it can be done more easily and faster by putting them through an alternating current solenoid with a field stronger than that which was used for magnetizing. Before each drawing operation the bars were completely demagnetized.

4. Results of Magnetic Testing.

The results of the saturation determinations for each particular steel are shown in Table 5. These results are also in graphical form.

Graph No. 8 shows the saturation for carbon steels.

Graph No. 9 shows the saturation for chromium steels.

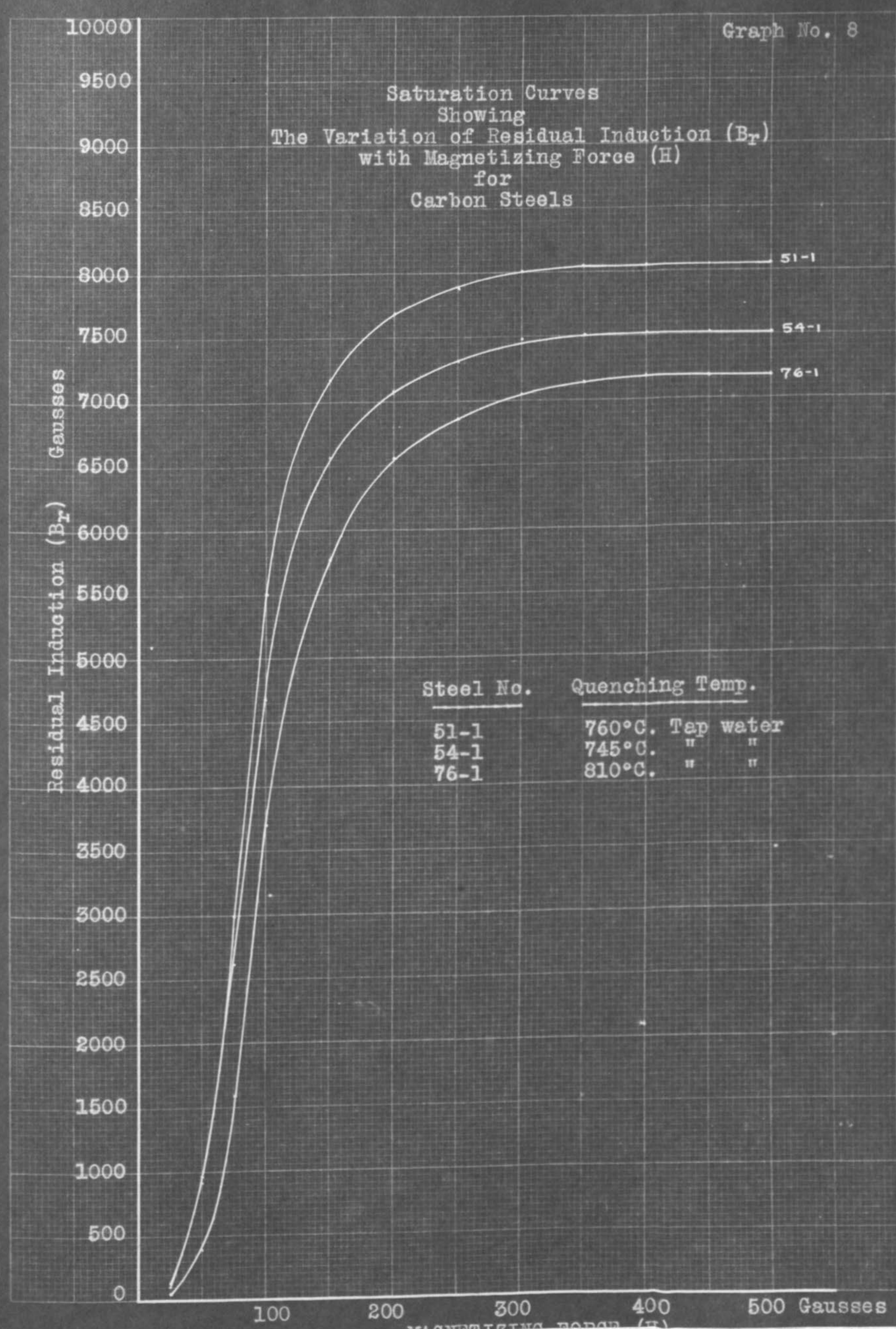
Graph No. 10 shows the saturation for chrome-nickel steels.

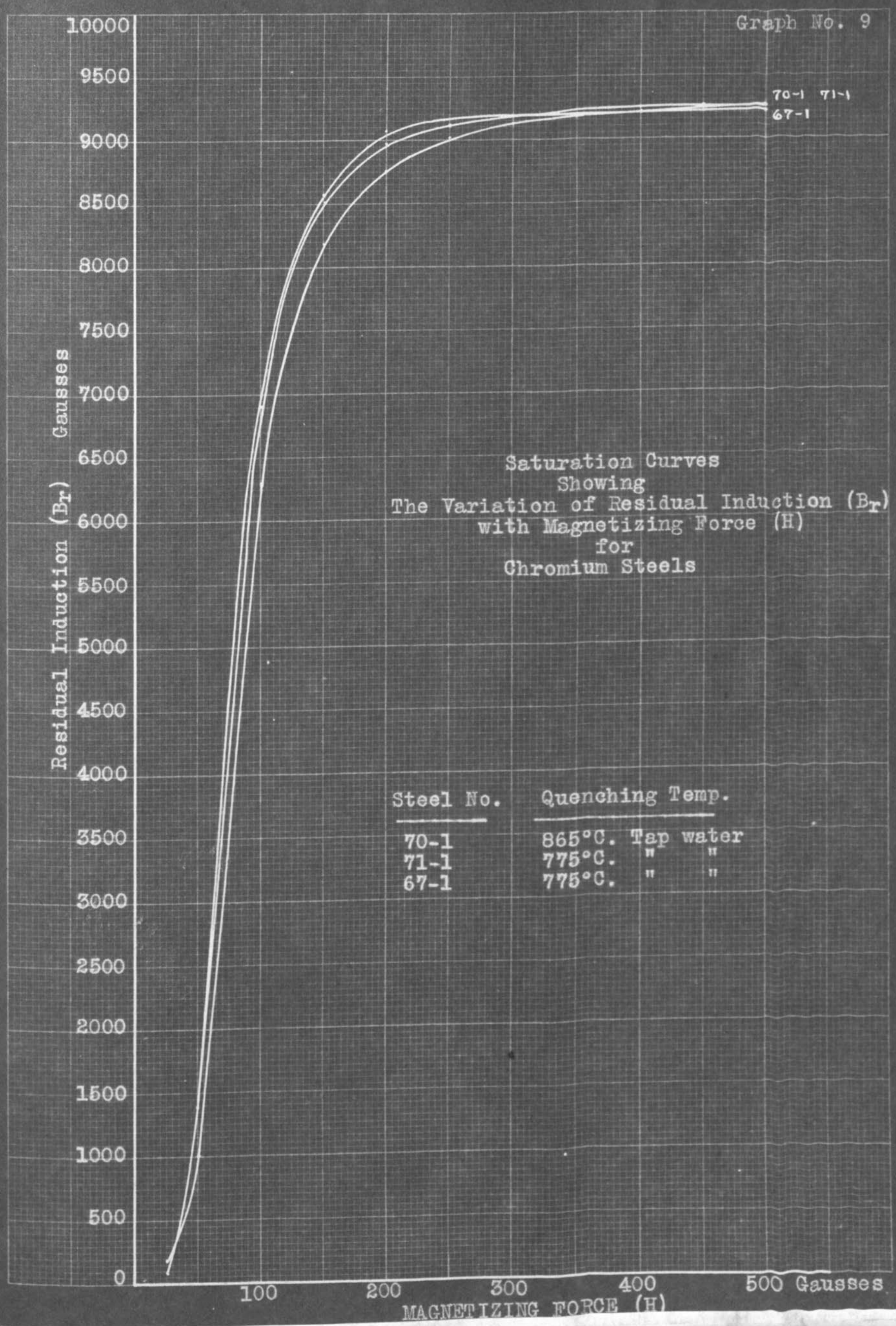
Graph No. 11 shows the saturation for tungsten steels.

Graph No. 12 shows the variation of the saturation with quenching temperature on an average tungsten and a high chrome steel.

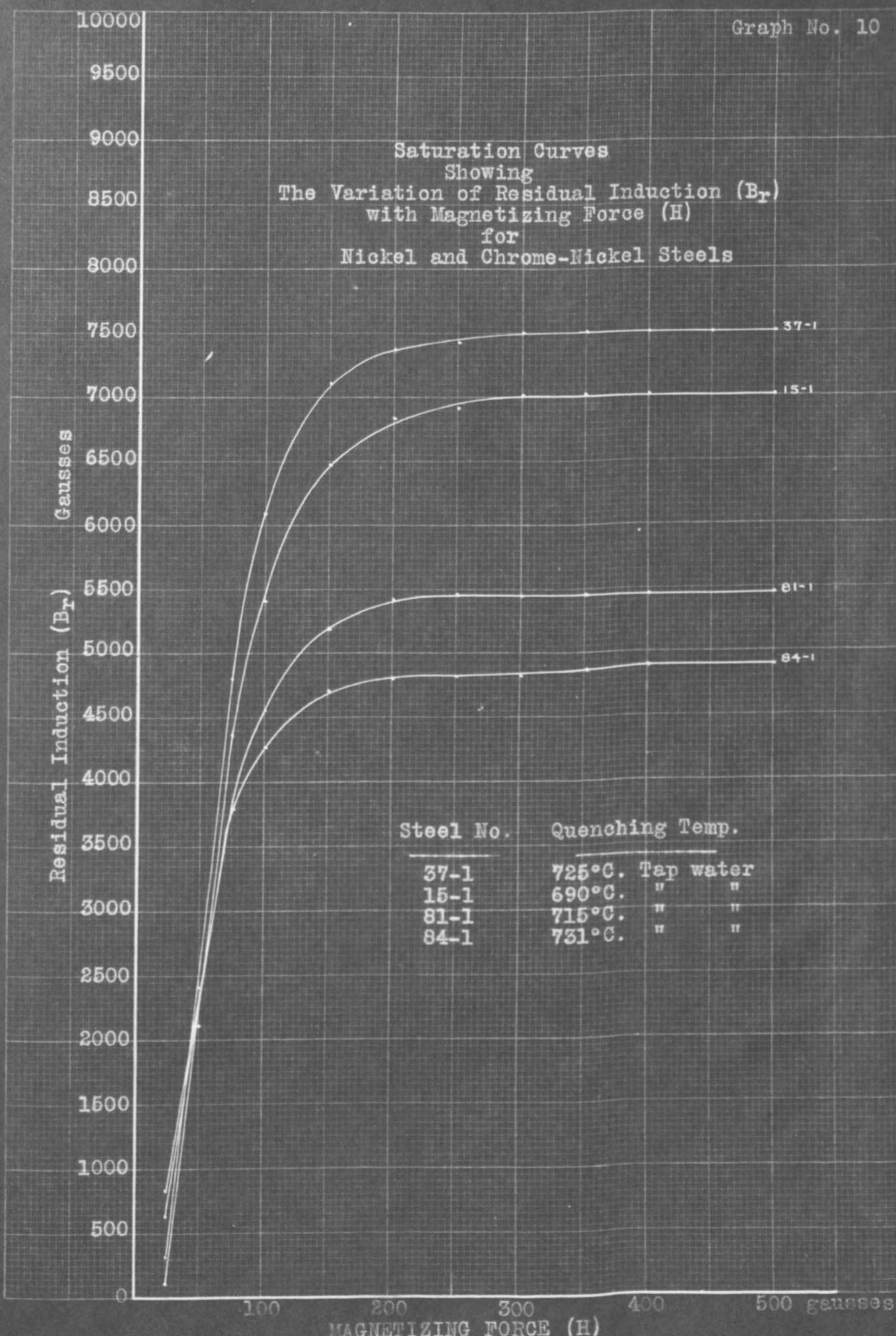
The curves show that each steel has practically reached its saturation at 350 gausses. It has been proven that the stronger the magnetizing force the greater the residual induction but above 350 gausses the percentage increase is very small.

The data showing the results of the variation of residual induction and coercive force with drawing temperature are given in Table 6. These data are shown graphically in graphs 13 and 14.

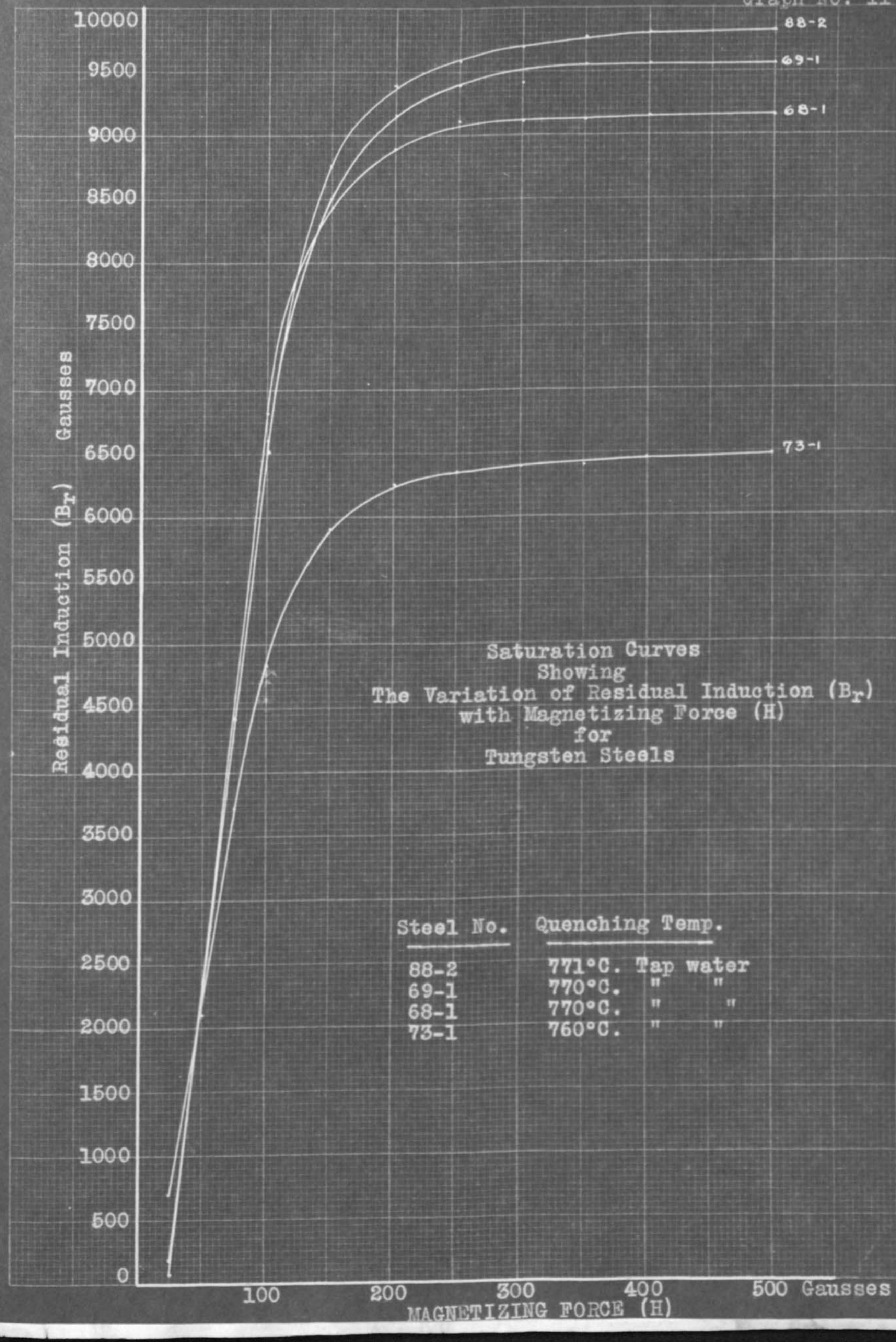

Graph No. 8
Saturation Curves
Showing
The Variation of Residual Induction (B_r)
with Magnetizing Force (H)
for
Carbon Steels
Residual Induction (B_r) Gausses
10000
9500
9000
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
100
200
300
400
500 Gausses
51-1
54-1
76-1
Steel No. Quenching Temp.
51-1 760°C. Tap water
54-1 745°C. " "
76-1 810°C. " "



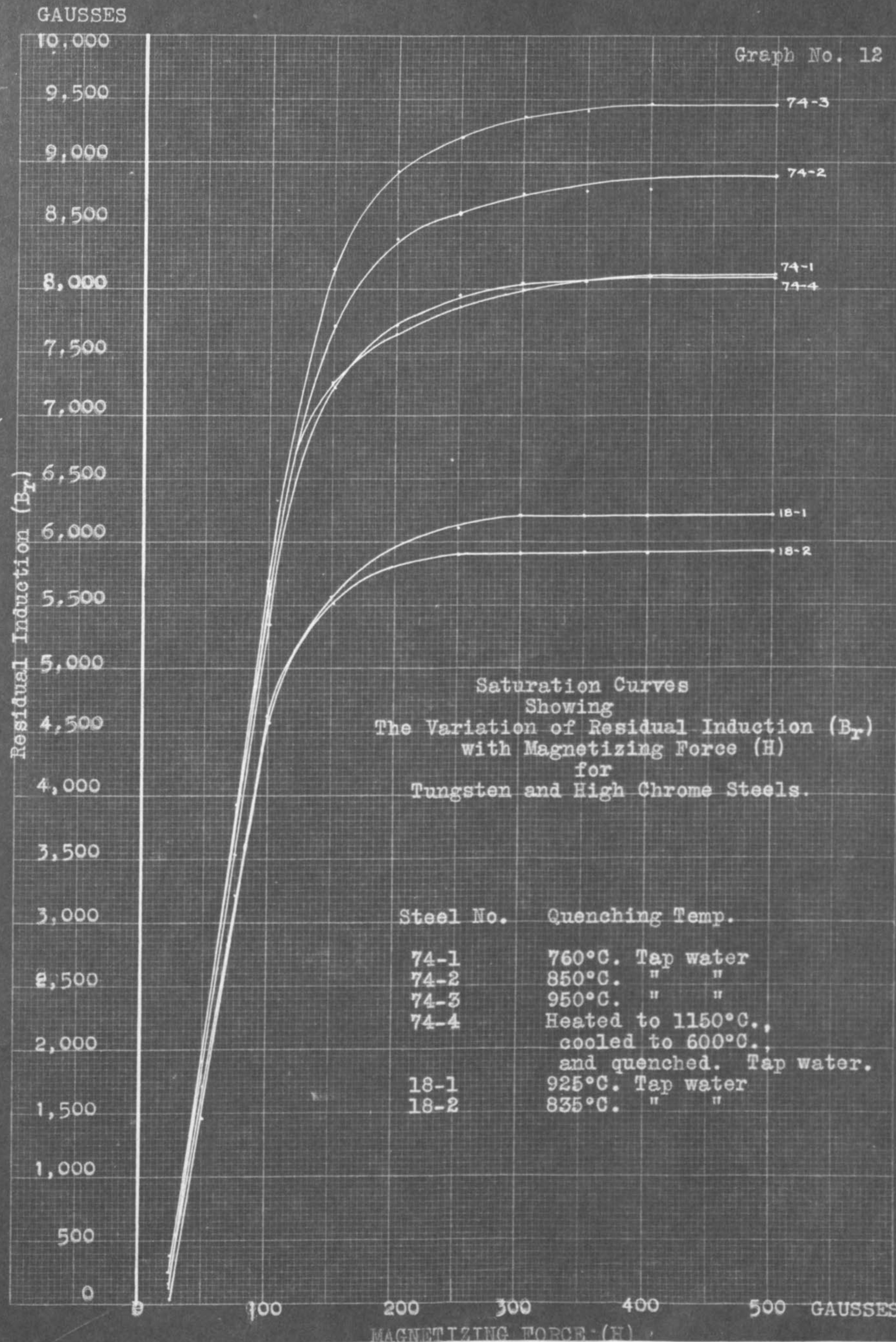
Graph No. 9
Saturation Curves
Showing
The Variation of Residual Induction (B_r)
with Magnetizing Force (H)
for
Chromium Steels
Steel No. | Quenching Temp.
70-1 | 865°C. Tap water
71-1 | 775°C. " "
67-1 | 775°C. " "
70-1 71-1
67-1
Residual Induction (B_r) Gausses
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
8000
8500
9000
9500
10000
100
200
300
400
500 Gausses
MAGNETIZING FORCE (H)

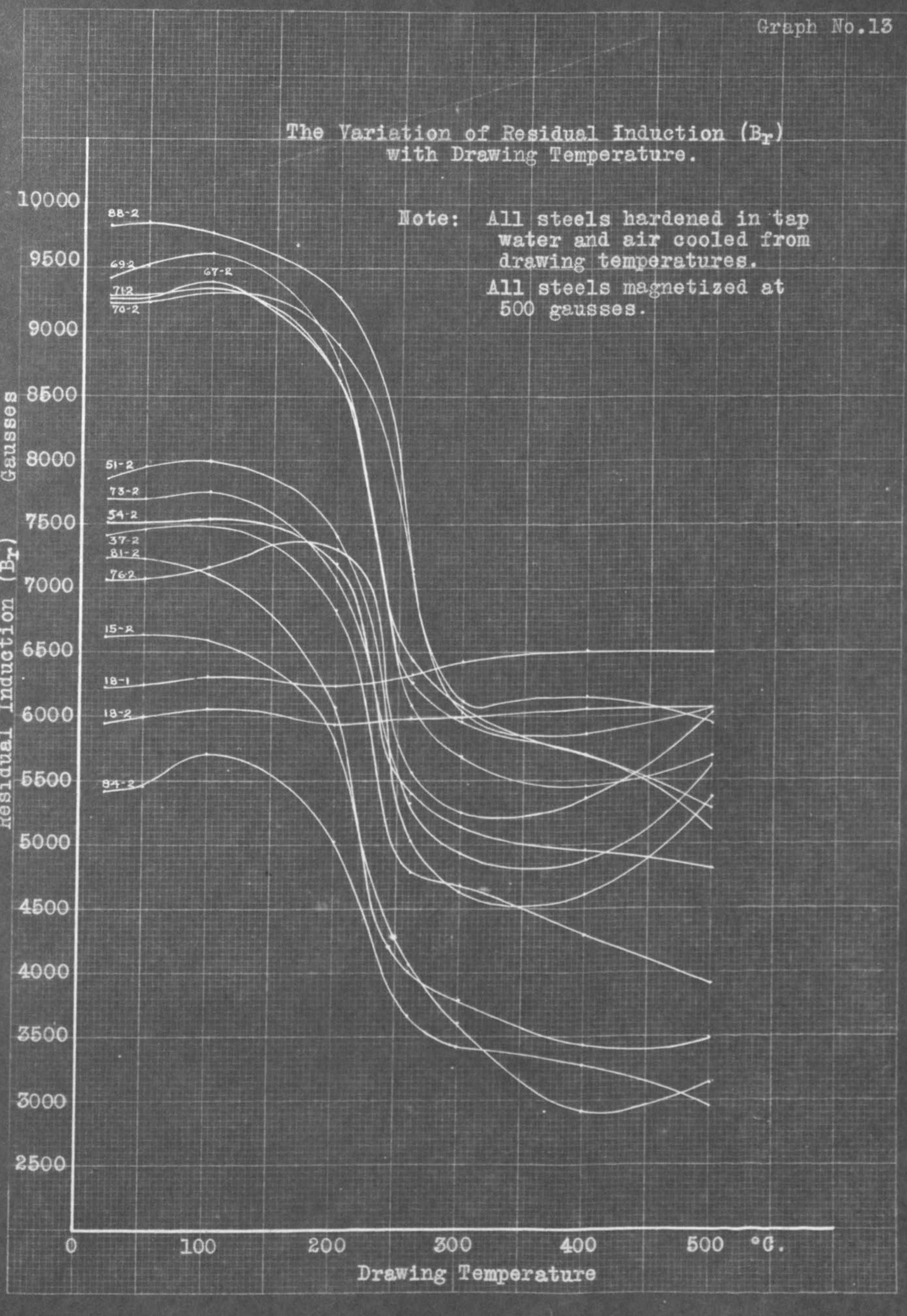


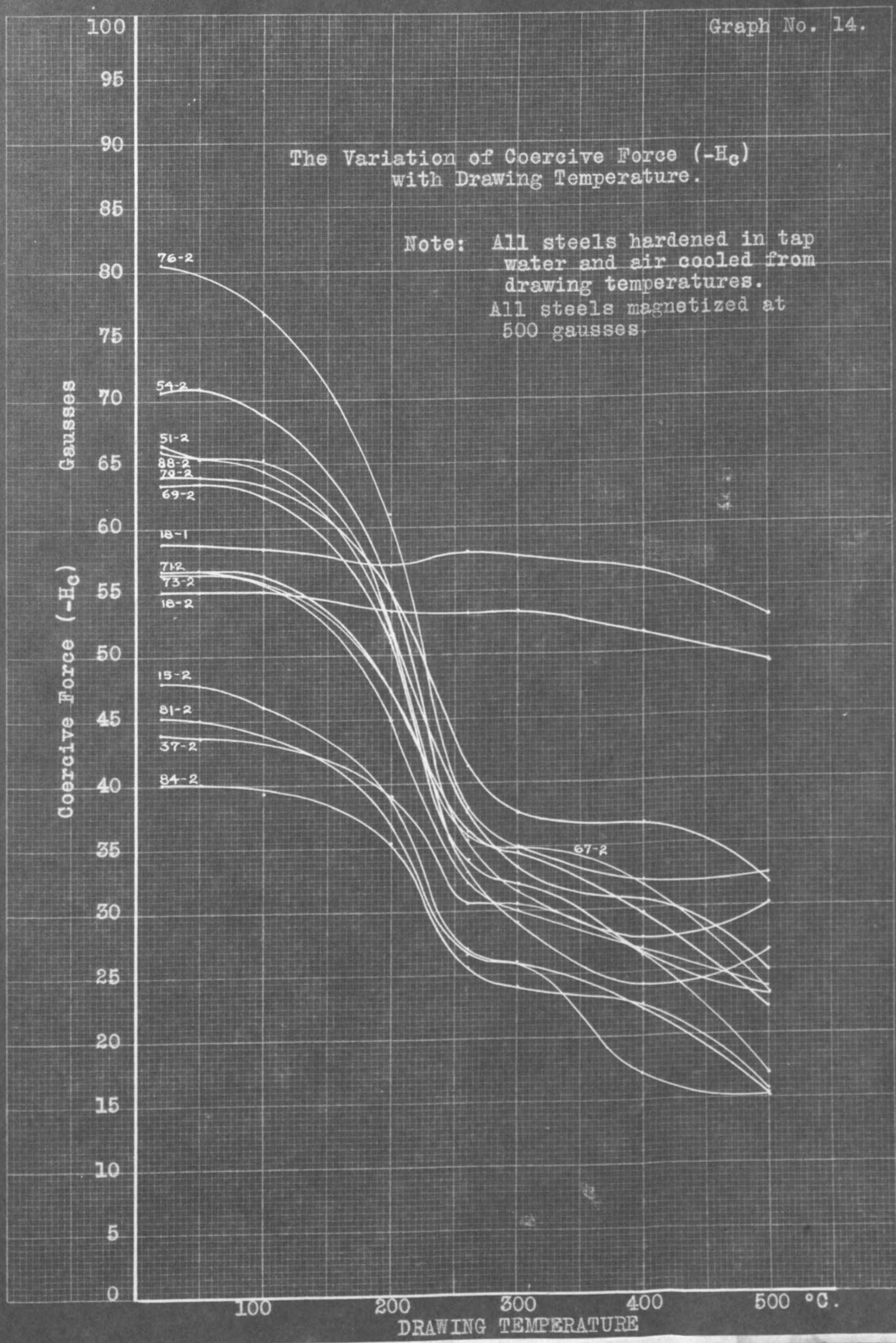
Graph No. 10
Saturation Curves
Showing
The Variation of Residual Induction (B_r)
with Magnetizing Force (H)
for
Nickel and Chrome-Nickel Steels
Residual Induction (B_r) Gausses
10000
9500
9000
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
100
200
300
400
500 gausses
MAGNETIZING FORCE (H)
37-1
15-1
81-1
84-1
Steel No.
Quenching Temp.
37-1
725°C. Tap water
15-1
690°C. " "
81-1
715°C. " "
84-1
731°C. " "



10000
9500
9000
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Residual Induction (B_r) Gausses
88-2
69-1
68-1
73-1
Saturation Curves
Showing
The Variation of Residual Induction (B_r)
with Magnetizing Force (H)
for
Tungsten Steels
Steel No. Quenching Temp.
88-2 771°C. Tap water
69-1 770°C. " "
68-1 770°C. " "
73-1 760°C. " "
100
200
300
400
500 Gausses
MAGNETIZING FORCE (H)


GAUSSES
Graph No. 12
10,000
9,500
9,000
8,500
8,000
7,500
7,000
6,500
6,000
5,500
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
Residual Induction (B_r)
74-3
74-2
74-1
74-4
18-1
18-2
Saturation Curves
Showing
The Variation of Residual Induction (B_r)
with Magnetizing Force (H)
for
Tungsten and High Chrome Steels.
Steel No. Quenching Temp.
74-1 760°C. Tap water
74-2 850°C. " "
74-3 950°C. " "
74-4 Heated to 1150°C., cooled to 600°C., and quenched. Tap water.
18-1 925°C. Tap water
18-2 835°C. " "
0
100
200
300
400
500 GAUSSES
MAGNETIZING FORCE (H)


Graph No.13
The Variation of Residual Induction (B_r) with Drawing Temperature.
Note: All steels hardened in tap water and air cooled from drawing temperatures.
All steels magnetized at 500 gausses.
Residual Induction (B_r) Gausses
10000
9500
9000
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
0
100
200
300
400
500 °C.
Drawing Temperature
88-2
69-2
67-2
71-2
70-2
51-2
73-2
54-2
37-2
81-2
76-2
15-2
18-1
18-2
84-2



Graph No. 14.
The Variation of Coercive Force (-Hc) with Drawing Temperature.
Note: All steels hardened in tap water and air cooled from drawing temperatures.
All steels magnetized at 500 gausses.
Coercive Force (-Hc) Gausses
DRAWING TEMPERATURE
100
200
300
400
500 °C.
76-2
54-2
51-2
88-2
79-2
69-2
18-1
71-2
73-2
18-2
15-2
81-2
37-2
84-2
67-2

Table No. 5

Effect of Intensity of Magnetizing Field on Residual Induction in Permanent Magnets.

Bar No.	Coercive Force	Residual Induction in Gausses (B_r) for H 25	H 50	H 75	H 100	H 150	H 200	H 250	H 300	H 350	H 400	H 500
74-1	57.3	384	2075	3935	5687	7265	7720	7850	8050	8050	8129	8129
74-2	65.0	269	1615	3510	5660	7730	8400	8580	8760	8760	8790	8805
74-3	72.2	131	657	2670	5560	8150	8940	9200	9370	9420	9459	9459
74-4	63.1	176	1230	3510	5355	7240	7720	7950	8000	8040	8082	8082
68-1	58.2	211	1370	....	6815	8448	8890	9117	9117	9117	9158	9158
70-1	65.0	153	919	3765	6130	8140	8750	9020	9120	9150	9192	9192
76-1	81.0	44	396	1580	3700	5767	6565	6872	7048	7135	7174	7174
54-1	69.3	131	962	2620	4680	6565	7088	7310	7480	7500	7529	7529
51-1	65.0	111	935	2980	5515	7170	7695	7880	8020	8056	8056	8056
81-1	43.5	625	2415	3800	4560	5185	5410	5455	5455	5455	5455	5455
73-1	54.0	715	2100	3620	4830	5900	6260	6348	6385	6385	6465	6481
67-1	56.1	112	1390	4570	6950	8560	9060	9100	9197	9197	9197	9197
84-1	36.0	808	2425	....	4267	4717	4807	4807	4807	4850	4898	4898
71-1	56.6	133	1370	4465	6920	8520	8970	9100	9150	9150	9195	9243
69-1	63.0	66	1020	3865	6660	8570	9150	9380	9420	9559	9559	9559
15-1	47.0	201	2100	4371	5412	6480	6843	6925	7018	7018	7018	7018
37-1	44.5	311	2400	4800	6091	7105	7375	7420	7511	7511	7511	7511
18-1	58.8	183	1147	3210	4540	5550	5970	6100	6200	6200	6219	6219
18-2	55.0	257	1450	3415	4625	5520	5805	5900	5900	5900	5925	5945
88-2	66.0	178	932	3555	6525	8750	9380	9580	9680	9772	9800	9822

Note: All of the steels, except the last three 18-1, 18-2, and 88-2 were remagnetized, after the coercive force determination, at 500 gausses and put in storage. They were suspended from strings in a vertical position.

Table No. 6

Effect of Drawing Temperature on Coercive Force and Residual Induction in Permanent Magnets.

Bar No.	Room Temp.		50°C.		100°C.		200°C.		260°C.		300°C.		400°C.		500°C.	
	$-H_c$	B_r	$-H_c$	B_r	$-H_c$	B_r	$-H_c$	B_r	$-H_c$	B_r	$-H_c$	B_r	$-H_c$	B_r	$-H_c$	B_r
18-1	58.8	6219	58.8	6242	58.3	6320	57.0	6242	58.2	6335	57.7	6420	56.7	6506	52.5	6490
18-2	55.0	5944	55.0	5992	55.0	6060	53.4	5944	53.2	5992	53.4	5992	51.5	6067	49.0	6060
88-2	66.0	9822	65.5	9867	65.5	9770	51.8	9280	37.8	7115	33.4	6040	30.7	5850	24.9	6060
70-2	64.0	9239	64.2	9239	63.4	9315	54.8	8920	41.4	7150	37.5	6140	36.7	6155	31.7	5940
69-2	63.4	9428	63.5	9517	62.5	9620	51.0	8750	34.0	6090	32.2	5685	26.4	5475	23.0	5690
71-2	56.7	9271	56.7	9271	56.4	9390	47.2	8650	36.1	6440	34.5	6080	29.5	5701	22.1	5285
73-2	56.5	7691	56.3	7691	55.7	7760	45.0	7065	32.1	5400	30.0	5105	26.9	4952	23.7	4815
67-2	56.7	9284	56.7	9284	55.6	9340	47.2	8630	35.8	6270	34.9	5965	31.8	5708	23.3	5110
54-2	70.6	7511	71.0	7511	68.9	7530	55.0	7200	35.5	5335	31.5	4935	27.7	4882	30.2	5620
15-2	47.9	6661	47.9	6639	46.0	6590	38.8	5820	27.0	4070	26.0	3610	17.0	2913	15.3	3140
84-2	40.1	5422	40.2	5467	39.2	5700	35.5	5020	25.5	3660	24.0	3420	22.5	3285	15.5	2960
51-2	66.7	7869	66.3	7958	64.6	7985	51.5	7400	33.0	5040	29.0	4637	24.0	4611	26.6	5360
76-2	80.5	7073	76.7	7073	76.7	7170	61.0	7310	37.7	5565	34.8	5255	32.0	5371	32.5	6025
81-2	45.2	7238	45.0	7238	43.0	7110	36.7	6075	26.6	4020	26.0	3790	22.0	3429	15.6	3495
37-2	44.0	7417	43.6	7462	....	....	39.0	6740	30.7	4780	30.7	4685	26.5	4208	17.0	3920

Drawing Temperatures (column groups above).

Note: Drawn at the above temperatures for one hour; air cooled.
Magnetizing force 500 gausses.

VII. SUMMARY OF RESULTS AND CONCLUSIONS.

A. Thermal Analysis.

1. Inverse-rate curves are given for practically all of the magnet steels which show the critical points.

2. The lowering temperature for a typical tungsten magnet steel of .60-.70% carbon and 5.00-5.50% tungsten has been found to be between 1100° and 1150°C. when slowly cooled.

3. The typical chrome magnet steels of 2.00-2.25% chromium and .85% carbon are not affected by the initial or maximum temperature. However, faster rates of cooling from any initial temperature will lower the critical points slightly.

B. Heat Treatment.

1. The bars were all annealed about 40°C. above their upper criticals for one hour. This operation softened the bars so that they could be readily machined to size.

2. Micrographs and the scleroscope hardness of the hardened magnets show that the magnets hardened 10° above the critical (Ac_3) are not quite as near a solid solution as those hardened 100°C. above the critical.

3. Heating tungsten steel magnets to the lowering temperature and air cooling to above the Ac_3 before quenching will make the magnet harder than any other treatment, but will generally crack it, without raising the induction.

4. Some of the bars were slightly warped in the center, probably due to the corrugated center of the holder cooling too fast and heating hot water around it. A remedy for this is suggested as follows: Grind off the threads and make the center rod of the holder smaller (See Fig. 3).

5. A temperature of only 10°C. above the upper critical will give an induction only 16% lower than the highest induction obtained on a typical 5% tungsten steel. This highest induction was obtained 200°C. above the critical. The coercive force, however, is 21% less at 10°C. above than at 200°C. above.

C. Magnetic Testing.

1. A method of open circuit testing has been worked out, the necessary apparatus has been constructed and described, where the usual apparatus in the laboratory could not be used, which makes it possible to measure with an accuracy of about 1% those properties which determine the value of a permanent magnet, i.e., residual induction, coercive force, and ageing. The expensive permeameter, therefore, becomes unnecessary.

2. All of the steels practically have been found to reach their saturation in a field of 350 gausses.

3. On the curves (residual induction vs. drawing temperature) it is shown that practically all of the steels reach their highest induction at a drawing temperature of 75° to 100°C., except a 14% chrome steel, 18-1 and 18-2, which have their highest value at 500 gausses.

These increases in induction are probably due to some austenite being retained on quenching, which on drawing changes to martensite, austenite being non-magnetic and martensite being strongly magnetic.

4. No theory is advanced for the rise in induction of some of the steels between drawing temperatures of 400° and 500°C.

5. Steel 88-2, a tungsten magneto steel, gives the highest induction and also the highest coercive force of any of the alloy steels tested.

6. The coercive forces of the carbon steels rise between a drawing temperature of 400° to 500°C.

7. In straight carbon steels, the higher the carbon content the greater the coercive force.

VIII. BIBLIOGRAPHY

Critical Points of Tungsten and Chrome Steels

1. 1892, Osmond. Reported in R.A.Hadfield's "Alloys of iron and tungsten."
J.Ir.St.Inst.1903,II,p.14.

2. 1904, Osmond. Contribution a la Theorie des aciers rapides."
Rev.de Met. 1904, p.348.

3. 1904, Böhler. Wolfram und Rapidstahl, Vienna 1904.

4. 1905, Carpenter. The types of structure and the critical ranges on heating and cooling of high speed steel under varying thermal treatment.
J.Ir.St.Inst.1905,I, p.433.

5. 1906, Guillet. Etude industrielle des Alliages metalliques, Paris 1906.

6. 1907, Swinden. Carbon-tungsten steels.
J.Ir.St.Inst.1907, I, p.291.

7. 1908, Edwards. Function of chromium and tungsten in high speed tool steel.
J.Ir.St.Inst.1908,II, p.104.

8. 1909, Swinden. The constitution of carbon-tungsten steels.
J.Ir.St.Inst.1909, II, p.223.

9. 1917, Dejean,P. Les points critiques de refroidissement des aciers auto-trempants et la formation de la troostite et la martensite.
Rev.de Met.1917, p.641.

10. 1919, Merica,P. Simplification of inverse rate method for thermal analysis.
Bull.A.I.M.E.#151,July 1919, p.1021

Bibliography (Continued)

Magnets and Magnetic Properties.

11. 1898, Mme.Curie. Magnetic properties of tempered steels.
Electricien 1898, 15, p.28
Bull.Soc.d'Enc.5, 3, p.58
Ecl.Electro. 16, p.151
Metallographist 1898, 1, 107; p.229
12. 1900, Osmond. Steel for magnets.
Metallographist 1900, 3, p.35
13. 1901, Klemencic. Testing magnet steel.
Ann.d.Phys.4,2,p.316
Akad.Wiss.Wien.Sitz.Ber.109,IIa,p.827.
14. 1902, Barrett, Brown and Hadfield.
Conducting and magnetic properties of iron alloys.
Inst.Elec.Eng.J. 31, p.674.
15. 1902, Abt. Residual magnetism in different steels.
Ann.d.Phys. 6, 4, p.774.
16, 1902, Ascoli. Stability of magnetism, temporary and permanent.
N.Cimento 1902, 3, p.5.
17. 1902, Trowbridge. Magnetisation at -185°C.
Phys.Rev.1902, 14, p.181.
18. 1907, Burrows. The best method of demagnetizing iron in magnetic testing.
Bur.Stand.Scient.Paper #78.
19. 1908, Gray and Ross. Magnetic sensitiveness produced by annealing.
Royal Soc.Edin.Proc.28, p.616.
" " " 1910,29, p.182.
20. 1909, Swinden. Magnetic properties of tungsten steels.
Inst.Elec.Eng.J. 1909, 42, p.641.
21. 1910, Burgess and Aston.
Some alloys for permanent magnets.
Met.Chem.Eng.1910,8,p.673.
Met.& Chem.Ind. 8, p.673.
22. 1910, Mars. Magnet steel and remanent magnetism.
Stahl u.Eisen 1909,29,p.1673;1769.
Electrical World 1910,55,p.163.
23. 1910, Anon. Permanent magnets and magnet steel.
Ir.Tr.Rev.1910,46,p.391.
24. 1910, Shuddemagen. Demagnetizing factors for iron rods.
Physics Rev.1910, 31, p.165.
25. 1910, Honda. The magnetization of certain alloys as a function of their composition and temperature.
Ann.des Phys. 1910, 32, p.1003.

Bibliography (Continued)

26. 1911, Gray and Ross.
Apparatus and methods for the accurate measurement of the properties of metals and alloys.
Ann.Physik. 33, 1913.
Chem.Abs.1911,5,p.1363.

27. 1911, Hadfield and Hopkinson.
Magnetic properties of iron alloys.
Inst.Elec.Eng.J. 46, p.235.

28. 1912, Peirce. The anomalous magnetization of iron and steel.
Proc.Am.Acad.47, p.633
Chem.Abs.1912,6,p.3224.

29. 1912, Jones and Waggoner.
Relation of tensile to magnetic properties of iron-carbon alloys.
J.Ir.St.Inst.1912, 86, p.596.

30. 1913, Thompson. Magnetic testing and permanent magnets.
J.Inst.Elec.Eng.London,50, Feb. 1913, p.80.

31. 1914, Moir. Permanent magnetism of certain chrome and tungsten steels.
Phil.Mag. 1914, 28, p.738.
J.Soc.Chem.Ind.33,p.1090.

32. 1914, Honda, Moir, Wilson, Williams.
Summary of magnetic and electric properties of steel and steel alloys.
J.Ir.St.Inst.1914,2,p.375.

33. 1915, Smith and Sherman.
Magnetic qualities of stressed iron and steel.
Phys.Rev.4,2,p.267.

34. 1915, Thompson; Henderson.
Steel for permanent magnets.
Iron & Coal Tr.Rev.1915,90,p.212
Electrician, 1915, 75,p.65.

35. 1916, Paige. How to select metals for magnets.
Elec.Rev.W.Elec.1916,69,p.368.
Chem.Abs.10,p.2572.

36. 1916, Burrows. Correlation of the magnetic and mechanical properties of steel.
Bur.Stand.Sci.Paper #272.
Iron Age 1916, 97, p.795.

37. 1916, Magnetic testing.
Bur.Stand.Circ. #17.

38. 1916, Dushman. Theories of magnetism.
Gen.Elec.Rev.Vol.19,No.5,8,9,10,12.

Bibliography (Continued)

39. 1917, Burrows. Some applications of magnetic analysis to the study of steel products.
Iron Age 1917,100,p.74
Ir.Tr.Rev.1917,61,p.26
Met.Chem.Eng.1917,17,p.130.
Proc.A.S.T.M.1917,17,II,p.87.

40. 1917, Mathews. A new permanent magnet steel containing chromium.
Iron Age 1917,100,p.197.

41. 1917, Gumlich. Preliminary report on chrome steel magnets.
Elektrotechn.Z.1916,37,p.592.
Chem.Abs.1917,11,p.2450.

42. 1917, Honda and Murakami.
Structure of magnet steel and its change with heat treatment.
Sci.Rep.Tohoku Imp.Univ.1917,6,p.53
Chem.Abs.1917,11,p.2766.

43. 1918, Prever and Prever.
Use of magnetic properties in inspecting iron and steel.
Ind.Chim.Min.Met.5,p.153.
Chem.Abs.1919,13,p.707.

44. 1918, Fahy. The magnetic permeability of steel.
Chem.Met.Eng.1918,19,p.247.

45. 1918, Honda. On magnetic analysis as a means of studying the structure of iron alloys.
J.Ir.St.Inst.1918,98,p.375.

46. 1918, Honda and Takagi.
K.S. Magnet steel. (p.349.
Proc.Tokyo Math.Phys.Soc.(2)9,1918,
Chem.Abs.1918,12,p.2527.

47. 1919, Anon. Magnetic and mechanical testing of iron.
Engineering 1919,108,p.708.

48. 1919, Gebert. Investigation of magnetic steel analysis
Iron Age 1919,104,p.509.

49. 1919, Sanford. Testing steel by magnetic analysis.
Ir.Tr.Rev.1919,65,p.1181.

50. 1919, Burrows and Fahy.
Application of magnetic analysis.
Ir.Tr.Rev.1919,64,p.1686.

51. 1919, Nusbaum. Notes on making standard magnetic measurements.
Proc.A.S.T.M. 1919, 19, p.5.

52. 1919, Burrows and Fahy.
Notes on standard magnetic measurements.
Proc.A.S.T.M. 1919, 19, p.100.

53. 1919, Anon. Magnetic iron alloys.
Stahl u. Eisen 1918, 38, p.1042.
J.Soc.Chem.Ind.38,p.17A.
Chem.Abs.1919,13,p.1068.

Bibliography (Continued).

54. 1920, Brown. On the decay of magnetism in bar magnets.
Sci.Proc.Royal Dublin Soc.1920,16,p.78.
Chem.Abs.1920,14,p.2611.

55. 1920, McLachlan. Notes on a method of testing bars of magnet steel.
Proc.Phys.Soc.London 32, p.154.

56. 1920, Sanford and Kouwenhoven.
Locating flaws in rifle barrel steel by magnetic analysis.
Bur.Stand.Scient.Paper #343.

57. 1920, Wooldridge. Annealing magnetic material.
U.S.Pat. 1,331,889.
Off.Gaz.1920,p.261.

58. 1920, Honda. Magnetic steel, patents.
Can. 197,566; 197,567; 197,568.
U.S. 1,338,132-3-4.

59. 1920, Ishiwara. The magnetic determination of the A_0, A_1, and A_3 points in steels containing carbon up to 4.8%.
Proc.Phys.Math.Soc.Japan (3)2,91(1920).
Chem.Abs.1920,14,p.2906.

60. 1920, Honda and Saito. K.S.Magnet steel.
Proc.Phys.Math.Soc.Japan (3)2,p.32.
Chem.Abs.1920,14,p.2906.

61. 1920, Cheney. Measurement of hysteresis values from high magnetizing forces.
Bur.Stand.Sci.Paper #383.

62. 1920, Sanford and Cheney.
The variation of residual induction and coercive force with magnetizing force.
Bur.Stand.Sci.Paper #384.

63. 1920, Cheney. Magnetic testing of straight rods in intense fields.
Bur.Stand.Sci.Paper #361.

64. 1920, Nusbaum, Cheney and Scott.
Magnetic reluctivity relationship as related to certain structures of a eutectoid steel.
Bur.Stand.Sci.Paper #404.

65. 1921, Nusbaum and Cheney.
Effect of the rate of cooling on the magnetic and other properties of an annealed eutectoid steel.
Bur.Stand.Sci.Paper #408.

66. 1909. The determination of the magnetic induction in straight bars.
Bur.Stand.Sci.Paper #117.

67. 1920, Zelney. Laboratory Manual of Physics. Text.

68. 1909, Smith. Theory and Practice of Electrical Measurements, Purdue University, Lafayette, Indiana.

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