THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

New York, March 24, 1897.

The 114th meeting of the INSTITUTE was held this date at 12 West 31st Street, and was called to order by President Duncan at 8.30 P. M.

PRESIDENT DUNCAN:—The Secretary will announce the ticket nominated by the Council at the meeting this afternoon.

THE SECRETARY:—From the nomination returns received from the membership, the Council has selected the following names which will be printed on the ballots for the guidance of members in their choice of candidates.

For President:

FRANCIS B. CROCKER, of New York City.

For Vice-Presidents:

A. E. KENNELLY, of Philadelphia, Pa.

CHAS. S. BRADLEY, of New York City.

DUGALD C. JACKSON, of Madison, Wis.

For Managers:

ALEXANDER MACFARLANE, of South Bethlehem, Pa.

GANO S. DUNN, of New York City.

W. F. C. HASSON, of San Francisco.

HERBERT LAWS WEBB, of New York City.

For Treasurer:

GEORGE A. HAMILTON, of New York City.

For Secretary:

RALPH W. POPE, of New York City.

The Council has decided to hold the General Meeting of the INSTITUTE at Greenacre-on-the-Piscataqua, Eliot, Maine, beginning on July 26th. This place was the residence of the late Moses G. Farmer, who was one of the charter members of the INSTITUTE and made an Honorary Member October 21st, 1890. He died at Chicago, May 25th, 1893, having been actively engaged in the preparation of his personal exhibit for the World's Fair. The date selected will be the 50th anniversary of Prof.

Farmer's relinquishment of teaching and the taking up of electrical work. Greenacre is beautifully situated on the east bank of the Piscataqua River, about ten miles beyond Portsmouth, N. H., and is reached in two hours from Boston.

The Annual Meeting for the election of officers, presentation of yearly reports, etc., will be held at 12 West 31st Street, as provided by the Constitution, on Tuesday, May 18th, which is the third Tuesday in the month.

The following Associate Members were elected at the meeting of the Executive Committee in the afternoon :

Name.	Address.	Endorsed by.
BECHTEL, ERNEST J.	Superintendent, Power Plant, Toledo Traction Co., Toledo, O.	E. S. Reid. W. E. Harrington. R. W. Pope.
FORD, ARTHUR HILLYER,	Fellow in Electrical Engineering, University of Wisconsin, Madison, Wis.	J. E. Davies, D. C. Jackson. S. B. Fortenbaugh.
HOLBROW, HERMAN L.	With New York Telephone Co., New York City, residence Rutherford, N. J.	S. B. Austin. H. F. Thurber. W. M. Petty.
KELLY, WILLIAM F.	Student in Expert Course, Fort Wayne Electric Corporation, Fort Wayne, Ind.	F. S. Hunting. E. A. Barnes. A. L. Hadley.

Total 4.

THE PRESIDENT:—The paper to be read this evening is on "The Influence of Heat Treatment Upon the Magnetic Properties of Steel and Iron," by Dr. K. E. Guthe. The paper will be presented by Professor Carhart, whom we all know.

Professor Carhart then read the following paper :

THE INFLUENCE OF HEAT TREATMENT UPON THE MAGNETIC PROPERTIES OF STEEL AND IRON.

BY DR. K. E. GUTHE.

Steel and iron, when heated to high temperatures, show a decided change in their magnetic properties. The earlier investigations¹ have shown, that in general the temporary induction in iron and steel rods increases with increase of temperature. G. Wiedemann² found that very hard steel rods show at 100° a larger temporary magnetic moment than at 0°, soft rods a larger magnetic moment at 0° than at 100° for the same magnetizing force, after they had been repeatedly heated and cooled. Rowland³ showed that a rise of temperature causes an increase of induction, if the magnetizing force is small, but a diminution of induction if the magnetizing force is large. The same was observed by J. Hopkinson,⁴ who undertook a great number of experiments in this line, especially in order to show the relation between the critical temperature, at which iron ceases to be magnetic, and the recalescence, first discovered by Barrett. According to the former, recalescence occurs at the critical temperature. Osmond, who distinguishes three points of recalescence for soft steel, places the critical temperature at the second point of recalescence. Tomlinson's⁵ and Kunz's⁶ experiments show also the change in magnetic properties due to a rise of temperature.

1. Wiedemann's "Electricität," 2d ed., III., p. 848-860.

2. G. Wiedemann. *Pogg. Ann.* 122, 346, 1864.

3. Rowland. *Phil. Mag.* (4), 48, 321, 1874.

4. Hopkinson, *Phil. Trans.*, 180 A, 442, 1889. *Proc. Roy. Soc.*, 48, 442, 1890.

5. Tomlinson. *Phil. Mag.* (5), 25, 372, 1888.

6. Program Gymnasium zu Darmstadt, 1893.

After steel has been heated beyond recalcence and is suddenly quenched in cold water, the mechanical hardening is accompanied by a corresponding magnetic hardening, *i. e.*, the permeability decreases and the hysteresis loss increases greatly. This influence of hardening is well known, and was first thoroughly investigated by Ewing.¹ Very little is known about the influence of heat treatment on such hardened steel. Barus and Strouhal,² in an exhaustive paper, show the influence of tempering on the retentivity of steel magnets, and are the originators of the well-known method of seasoning magnets by subjecting them for several hours to a temperature of 100° , which method has recently been used very successfully by B. O. Pierce. Their results, as far as they have a bearing on the present research, are, (1) that the magnetic moment of a hardened steel magnet is smaller after reheating to about 100° than it was before, and that on heating to still higher temperatures it increases again; (2) that the length of time during which the bars have been at the high temperature is of some influence, especially for the lower temperatures. The present work was undertaken with a view of following the annealing process step by step, and obtaining the relations between the magnetizing force, maximum induction, remanence and coercive force for each of these steps. The results are also interesting from a theoretical point of view, since they show a decided difference in the rate of change of the magnetic properties for the different temperatures.

Description of the Method.—The rings were all of the same form, *i. e.*, hoops with an average diameter of 12.6 cm. and a thickness of only 8 mm. The diameters were measured by vernier calipers and the cross-section was found by dividing the volume, which was determined by the loss of weight in water, by the average circumference. New measurements were taken every time after the rings had been subjected to a temperature higher than 600° . They were wound with bicycle tape, and on this the primary coil. Before each experiment the insulation was carefully tested. Rowland's ballistic method was employed. Instead of the usual way of finding the constant of the galvanometer by means of an earth-coil, I charged and discharged a standard condenser through the galvanometer (see Carhart and

1. Ewing. *Phil. Trans.*, 547, 1885, or Ewing, "Magnetic Induction," etc., p. 82.

2. "U. S. Geological Survey," No. 14, 1885.

Patterson's "Electrical Measurements"). The equations used will then be

$$\mathfrak{B} = \frac{d_2 C E r}{d_1 n_2} \frac{100}{A}$$

where

$\mathfrak{B}$ = the increase in induction,

d_2 = the deflection due to the change of the magnetic flux through one square centimetre of the ring,

C = the capacity of the standard condenser expressed in microfarads (= .2 microf.),

E = the *E. M. F.* of the Carhart-Clark cell in volts,

r = the total resistance of the secondary circuit,

d_1 = the deflection obtained by the discharge of the condenser,

n_2 = the number of secondary turns around the ring, which was equal to 30 in every case,

A = the cross-section of the ring,

and

$$\mathfrak{H} = \frac{4 \pi n_1}{10 L} I$$

where

$\mathfrak{H}$ = the magnetizing force,

n_1 = the number of primary turns on the ring,

I = the magnetizing current expressed in amperes,

L = the average circumference.

The deflection due to the discharge of the condenser was taken on open circuit. This produces an error in the constant. An independent experiment showed that the value obtained is 1.50 per cent. too large. In order to obtain the absolute values for $\mathfrak{B}$ in the following tables, the data should be multiplied by .985. In order to eliminate the error due to the creeping up of the induction, the steps taken were as nearly as possible the same for the same ring at different stages of the treatment. I believe the total errors of observation to lie within .5 per cent. The experiments at each step for each ring consisted in the determination of the hysteresis curves for a number (8-10) of different magnetizing forces, the largest in every case being between 60 and 65. In the final results I give the hysteresis curves for the largest values of $\mathfrak{H}$ only. The magnetizing curves were taken, but they are not given under the following results, since, as Hopkinson has shown, this curve for virgin steel differs appreciably from one taken with a ring previously magnetized. It was thought

to be of more importance to represent the curves for $\mathcal{B}_m$ and $\mathcal{B}_r$ as functions of the maximum magnetizing force. (See Fig. 4.). Moreover, it was possible to show the influence of the reheating upon Houston and Kennelly's law,¹ i. e., that for small magnetizing forces the remanence ($\mathcal{B}_r$) is a linear function of the maximum induction ($\mathcal{B}_m$). These two values, $\mathcal{B}_m$ and $\mathcal{B}_r$, are plotted on Fig. 5, and these curves are of great interest, showing the range through which this law holds good in the different stages of the heating process, and what variations in the constants are produced by the tempering.

Chemical Analysis.—the chemical analysis of the rings gave the following results:

	Ring I. Crescent Steel.	Ring II. Basic Steel.	Ring III. Very Soft Steel.	Ring IV. Swedish Iron.
Carbon	.868%	.309%	.0755%	.144%
Silicon	.234	.025	.0155	.0624
Sulphur	trace	.059	.0645	.015
Phosphorus	.0172	.146	.124	.018
Manganese	.27	.78	.36	trace

For the chemical analysis and the heat treatment of the rings, I am greatly indebted to Prof. E. D. Campbell, director of the metallurgical laboratory, and his assistant, Mr. A. R. Miller. I gladly express my deep obligations to them, especially to Professor Campbell, who devised and superintended every particular of the complete heat treatment.

The rings were first heated in the original state and then subjected to the heat treatment. The different steps taken are the following:

- A. Rings in the original state.
- B. Heated to about 670° and quenched.
- C. Heated to a little over 900° and quenched.

The hardened rings were then tempered by reheating to the temperatures indicated below, and then allowed to cool slowly. D, 100° for one hour; E and F, 100° for 24 hours; G, 200°; H, 300°; I, 450°; K, 800°; L (only for Rings II. and III.), about 950°.

RESULTS.

In the following tables n_1 designates the number of primary turns, c the deflection of the galvanometer, obtained by the discharge of a capacity equal to .2 microfarad charged by a Carhart-Clark standard cell, d the deflection of the galvanometer due to the change of the lines of magnetic force in the ring, $\mathcal{B}$ the calculated

1. *Electrical World*, 25, 631, 1895.

value of the induction, I the current in the primary measured in amperes, $\mathcal{H}$ the value of the magnetizing force.

It will be noticed that I give only the values of $\mathcal{B}$ and $\mathcal{H}$ for one side of the hysteresis curves. Since the same steps were taken on the ascending and descending branch of the loop, the values were generally identical, and are therefore not recorded in the following tables, though the whole cycle was taken in the actual experiments :

A. BEFORE HEATING.

TABLE I.

RING I: $n_1 = 298$; const. = 141.5; $\mathcal{B} = 18.7$ $\times d$; $\mathcal{H} = 9.45 I$.			
d	$\mathcal{B}$	I	$\mathcal{H}$
—	+7966	0	0
48	7096	.270	2.55
14	6807	.350	3.31
47	5928	.538	5.09
64	4731	.705	6.67
184	1290	.940	8.89
197	-2394	1.210	11.44
192	5984	1.7	16.07
88	7630	2.09	19.76
87	9257	2.66	25.15
107	11257	3.86	36.50
63	12436	4.9	46.33
75	13838	6.5	61.46
47	12959	4.1	38.76
69	11669	2.1	19.86
88	10023	.86	8.13
110	7966	0	0

TABLE II.

RING II: $n_1 = 292$; const. = 141.5; $\mathcal{B} = 22.2$ $\times d$; $\mathcal{H} = 9.39 I$.			
d	$\mathcal{B}$	I	$\mathcal{H}$
—	+8303	0	0
112	5816	.16	1.5
202	0	.285	2.7
137	-3041	.392	3.7
101	5284	.538	5.0
79	7037	.705	6.6
73	8658	.94	8.8
57	9923	1.21	11.3
66	11389	1.70	16.0
68	12898	2.70	25.2
41	13808	3.90	36.2
28	14430	4.90	45.9
29	15074	6.65	62.4
19	14652	4.80	45.0
45	13653	2.25	21.1
85	11766	.70	6.6
29	11122	.49	4.6
129	8258	0	0

TABLE III.

RING III: $n_1 = 304$; const. = 141.5; $\mathcal{B} = 16.3d$; $\mathcal{H} = 9.63 \times I$.			
d	$\mathcal{B}$	I	$\mathcal{H}$
—	+9568	0	0
93	8052	.16	1.54
154	5542	.285	2.74
288	848	.36	3.47
107	-880	.394	3.79
202	4173	.48	4.62
134	6357	.58	5.50
115	832	.713	6.87
105	9943	.93	8.96
75	11166	1.19	11.46
77	12421	1.6	15.41
74	13627	2.6	25.04
21	13969	3.2	30.82
49	14768	4.75	45.74
32	15289	6.7	64.52
40	14621	3.75	36.11
41	13953	2.00	19.26
49	13154	1.1	10.59
27	12714	.80	7.70
52	11866	.45	4.33
141	9568	0	0

TABLE IV.

RING IV: $n_1 = 291$; $c = 141.5$; $\mathcal{B} = 16.5 \times d$; $\mathcal{H} = 9.23 \times I$.			
d	$\mathcal{B}$	I	$\mathcal{H}$
—	+6600	0	0
155	4042	.08	.7
322	-1270	.165	1.5
225	4983	.298	2.75
185	8036	.410	3.8
55	8943	.558	5.2
54	9834	.731	6.75
49	10643	.973	8.98
35	11220	1.248	11.5
39	11864	1.78	16.4
40	12524	2.78	25.7
27	12969	3.98	36.7
44	13695	6.60	60.9
34	13134	4.0	36.9
38	12507	2.11	19.5
60	11517	.9	8.3
59	10544	.5	4.6
20	10214	.4	3.7
219	6600	0	0

B. HEATED TO 675° AND QUENCHED.

TABLE V.

RING I; $n_1 = 298$; $c = 135.5$; $\mathcal{B} = 19.5 \times d$; $\mathcal{H} = 9.46 \times I$.			
d	$\mathcal{B}$	I	$\mathcal{H}$
—	+7283	0	0
20.	6893	.3	2.84
9.	6718	.4	3.78
12.5	6474	.58	5.2
17.5	6133	.72	6.81
29	5507	1.00	9.5
105.5	3510	1.42	13.4
201.	— 410	2.15	20.3
128.	2886	2.72	25.7
206.	6903	4.0	37.8
125.	9341	5.10	48.2
116.	11603	7.10	67.2
51.	10608	4.15	39.3
58.	9477	2.18	20.6
39.	8717	1.21	11.4
36.5	8005	.58	5.49
37.	7283	0	0

TABLE VI.

RING II: $n_1 = 292$; $c = 135.5$; $\mathcal{B} = 23d$; $\mathcal{H} = 9.39 \times I$.			
d	$\mathcal{B}$	I	$\mathcal{H}$
—	+6925	0	0
46.5	5842	.13	1.2
164.	2021	.28	2.6
125.	— 892	.40	3.7
94.	3082	.55	5.2
79.	4923	.70	6.6
74.	6647	.95	8.9
94.	8837	1.42	13.3
78.	10654	2.10	19.7
45.5	11714	2.68	25.2
67.	13275	3.90	36.6
42.5	14265	5.00	47.0
48.	15383	7.08	66.5
52.	14171	4.10	38.5
77.	12377	2.15	20.2
93.	10210	.85	8.0
49.	9068	.45	4.2
54.	7810	.18	1.7
38.	6925	0	0

TABLE VII.

RING III $n_2 = 304$; $c = 135.5$; $\mathcal{B} = 17.0 \times d$; $\mathcal{H} = 9.58 \times I$.			
d	$\mathcal{B}$	I	$\mathcal{H}$
—	+6956	0	0
76	5660	.13	1.2
104	3887	.20	1.9
247	— 324	.28	2.7
155	2966	.40	3.8
127	5131	.52	5.0
95	6751	.70	6.7
80	8115	.95	9.1
97	9760	1.40	13.4
85	11218	2.05	19.6
53	12121	2.60	24.9
81	13502	3.75	35.4
50	14371	4.75	45.5
57	15343	6.50	62.3
65	14236	3.90	37.4
102	12497	2.08	19.9
128	10315	.85	8.14
67	9173	.45	4.3
40	8491	.30	2.9
33	7828	.18	1.7
57	6956	0	0

TABLE VIII.

RING IV; $n_1 = 291$; $c = 135.5$; $\mathcal{B} = 17.2 \times d$; $\mathcal{H} = 9.24 \times I$.			
d	$\mathcal{B}$	I	$\mathcal{H}$
—	+4610	0	0
108	2752	.07	.65
194	— 585	.15	1.30
134	2890	.20	1.85
90	4438	.30	2.77
79	5797	.40	3.70
68	6967	.55	5.08
57	7947	.72	6.65
57	8927	1.00	9.24
86	10406	1.45	13.4
83	11834	2.18	20.1
50	12694	2.75	25.4
65.5	13821	4.00	37.0
34	14406	5.10	47.1
37	15042	7.05	66.1
49	14198	4.2	38.8
97	12530	2.2	20.3
152	9916	.90	8.32
87.5	8411	.48	4.44
114	6450	.18	1.66
107	4610	0	0

TABLE IX.

RING I.			RING II.			RING III.			RING IV.		
β_m	β_r	$\mathcal{C}$	β_m	β_r	$\mathcal{C}$	β_m	β_r	$\mathcal{C}$	β_m	β_r	$\mathcal{C}$
11603	7283	67.2	15383	6925	66.5	15343	6956	62.3	15042	4610	66.1
8444	5343	35.2	13339	6839	36.6	13671	6913	35.5	14035	4816	35.1
6222	3136	24.1	10858	6454	19.5	11276	6683	19.6	10630	4747	13.7
3783	2165	19.0	9204	5951	13.3	8336	5813	9.1	9133	4592	9.24
1833	819	13.2	7386	5103	8.9	5950	4364	5.0	8273	4489	6.93
527	98	6.3	2318	1526	2.6	4705	3427	3.8	6347	4283	3.70
			594	221	1.7	3401	2412	2.7	3870	2563	1.85
			4928	3530	5.2	1884	1091	1.9	1514	310	.46
			3612	2540	3.7						

C. HEATED TO 900° AND QUENCHED.

TABLE X.

RING I; $n_1 = 305$; $c = 115$; $\beta = 22.9 \times d$;
 $\mathcal{C} = 9.68 \times I$.

d	β	I	$\mathcal{C}$
—	+3786	0	0
10.	3351	.66	6.39
6.5	3232	.87	8.42
14.5	2870	1.3	12.6
23.	2344	1.9	18.4
22.	1841	2.32	22.5
66.	331	3.30	31.9
93.	—1797	4.15	40.2
47.	2872	4.52	43.8
87.	4862	5.50	53.2
81.	6715	6.90	66.8
43.	5731	4.00	38.7
36.	4907	2.08	20.1
32.	4175	.55	6.29
17.	3786	0	0

TABLE XI.

RING II; $n_1 = 292$; $c = 116$; $\beta = 27.4 \times d$;
 $\mathcal{C} = 9.19 \times I$.

d	β	I	$\mathcal{C}$
—	+8876	0	0
27	8135	.38	3.49
13	7778	.50	4.59
20	7229	.65	5.97
44	6022	.90	8.27
171	1302	1.38	12.68
169	—3336	2.00	18.38
100	6080	2.55	23.43
143	10004	3.70	34.00
62	11705	4.75	43.65
57	13269	6.70	61.6
36	12281	3.90	35.8
54	10799	1.60	14.7
31	9948	.75	6.89
39	8878	0	0

TABLE XII.

RING III; $n_1 = 300$; $c = 115$; $\beta = 20.3 \times d$;
 $\mathcal{C} = 9.53 \times I$.

d	β	I	$\mathcal{C}$
—	+8993	0	0
23	8526	.12	1.14
39	7734	.25	2.32
43	6861	.38	3.62
122	4384	.50	4.76
210	121	.65	6.2
166	—3249	.90	8.58
192	7146	1.38	13.15
135	9886	2.00	19.06
69	11287	2.52	24.02
89	13093	3.60	34.59
54	14189	4.65	44.31
66	15529	6.40	61.00
58	14352	3.80	36.21
102	12281	1.60	15.25
66	10941	.75	7.15
34	10251	.40	3.81
62	8992	0	0

TABLE XIII.

RING IV; $n_1 = 275$; $c = 122$; $\beta = 19.3 \times d$;
 $\mathcal{C} = 8.73 \times I$.

d	β	I	$\mathcal{C}$
—	+4622	0	0
94	2808	.072	.63
162	—319	.125	1.00
122	2672	.195	1.70
83	4275	.268	2.34
71	5645	.368	3.21
59	6784	.495	4.32
51	7768	.660	5.76
52	8772	.865	7.55
75	10219	1.28	11.2
68	11531	1.82	15.9
39	12284	2.25	19.6
54	13326	3.60	31.4
32	13944	4.60	40.1
35	14619	6.30	55.0
44	13770	3.88	33.9
120	11454	1.58	13.8
104	9447	.75	6.55
66	8173	.42	3.67
105	6147	.122	1.07
79	4622	0	0

TABLE XIV.

RING I.			RING II.			RING III.			RING IV.		
$\mathcal{B}_m$	$\mathcal{B}_r$	$\mathcal{H}$	$\mathcal{B}_m$	$\mathcal{B}_r$	$\mathcal{H}$	$\mathcal{B}_m$	$\mathcal{B}_r$	$\mathcal{H}$	$\mathcal{B}_m$	$\mathcal{B}_r$	$\mathcal{H}$
6715	3786	66.8	13268	8875	61.6	15529	8993	61.0	14629	4632	55.0
5193	2700	53.2	11731	8219	43.7	14180	8821	44.3	13510	4825	32.0
3580	1453	44.3	10291	7300	33.8	13134	8648	34.6	11696	4786	17.5
1990	480	31.9	7684	5434	23.0	11784	8313	24.0	8850	4584	7.94
927	114	18.4	6216	4212	18.2	10343	7460	19.1	6929	4053	4.52
389	23	8.6	3818	2401	12.1	8292	6161	13.15	4883	3146	2.36
207	3	5.0	1825	919	8.09	6029	4486	8.58	2470	1602	1.07
			933	306	5.97	4273	2974	6.2	1038	546	.63
			370	69	3.49	2690	1695	4.76			
						1238	648	3.8			
						650	203	2.32			
						264	41	1.72			

D. TEMPERATURE FOR ONE HOUR AT 100°.

TABLE XV.

RING I; $n_1 = 305$; $c = 147$; $\mathcal{B} = 17.9 \times d$; $\mathcal{H} = 9.68 \times I$.			
d	$\mathcal{B}$	I	$\mathcal{H}$
—	+3714	0	0
42	2952	.985	9.53
27	2469	1.5	14.5
52	1538	2.3	22.3
65	374	3.06	29.6
86	-1165	3.70	35.8
141	3689	4.66	45.1
160	6543	6.5	62.9
14	6292	5.66	54.8
86	4753	1.9	18.4
25	4306	1.00	9.7
15	4037	.51	4.9
18	3715	0	0

TABLE XVI.

RING II; $n_1 = 292$; $c = 119$; $\mathcal{B} = 26.75 \times d$; $\mathcal{H} = 9.19 \times I$.			
d	$\mathcal{B}$	I	$\mathcal{H}$
—	+8719	0	0
45	7515	.531	4.88
23	6900	.703	6.46
52	5509	.938	8.62
180	694	1.414	13.00
171	-3880	2.09	19.20
99	6528	2.66	24.44
135	10139	3.93	36.12
58	11690	5.07	46.59
57	13215	7.2	66.17
38	12197	4.15	38.14
56	10699	1.65	15.16
26	10003	.832	7.65
20	9468	.488	4.48
28	8719	0	0

TABLE XVII.

RING III; $n_1 = 300$; $c = 119$; $\mathcal{B} = 19.6 \times d$; $\mathcal{H} = 9.53 \times I$.			
d	$\mathcal{B}$	I	$\mathcal{H}$
—	+8507	0	0
67	7174	.278	2.65
47	6253	.388	3.70
147	3372	.534	5.09
195	— 450	.707	6.74
155	3488	.940	8.96
183	7075	1.412	13.46
127	9564	2.08	19.82
65	10838	2.63	25.05
87	12543	3.83	36.51
52	13562	4.92	46.89
66	14856	6.9	65.75
59	13701	4.08	38.88
102	11702	1.66	15.50
51	10702	.935	8.92
43	9859	.492	4.69
69	8507	0	0

TABLE XVIII.

RING IV; $n_1 = 275$; $c = 136$; $\mathcal{B} = 17.3 \times d$; $\mathcal{H} = 8.73 \times I$.			
d	$\mathcal{B}$	I	$\mathcal{H}$
—	+4921	0	0
125.5	2750	.08	.70
152.	120	.129	1.13
144.	-2371	.200	1.75
97.	4049	.277	2.42
86.5	5545	.388	3.39
71.	6773	.532	4.64
60.	7811	.705	6.15
60.	8849	.938	8.19
87.	10354	1.410	12.31
80.	11738	2.10	18.33
46.	12534	2.65	23.13
63.	13624	3.88	33.87
34.	14212	5.00	34.65
38.	14869	7.01	61.20
48.	14038	4.11	35.9
129.	11806	1.67	14.6
148.	9246	.623	5.44
139.	6841	.174	1.52
111.	4921	0	0

TABLE XIX.

RING I.			RING II.			RING III.			RING IV.		
$\mathcal{B}_m$	$\mathcal{B}_r$	$\mathcal{J}\mathcal{C}$	$\mathcal{B}_m$	$\mathcal{B}_r$	$\mathcal{J}\mathcal{C}$	$\mathcal{B}_m$	$\mathcal{B}_r$	$\mathcal{J}\mathcal{C}$	$\mathcal{B}_m$	$\mathcal{B}_r$	$\mathcal{J}\mathcal{C}$
6543	3714	62.9	13215	8721	66.2	14857	8487	65.7	14868	4921	61.2
3813	1718	45.1	11690	8078	46.3	12573	8222	36.3	12568	4904	23.3
2542	788	35.9	10339	7303	35.8	9918	7174	19.8	10392	4794	12.35
1898	403	29.2	7944	5644	24.4	7987	5939	13.34	7923	4429	6.17
1235	179	22.3	6393	4440	19.2	5860	4371	8.92	5951	3702	3.40
734	72	14.7	4066	2675	12.96	4253	3077	7.00	3720	2457	1.75
292	14	6.56	1832	923	8.58	2675	1754	5.04	2405	1557	1.05
134	9	3.05	589	134	4.87	1215	568	3.65	1263	727	.72
			254	27	2.55	617	186	2.65			

G. TEMPERATURE AT 200°.

TABLE XX.

TABLE XXI.

RING I; $n_1 = 292$; $c = 114$; $\mathcal{B} = 23.1 \times d$; $\mathcal{J}\mathcal{C} = 9.27 \times I$.				RING I.		
d	$\mathcal{B}$	I	$\mathcal{J}\mathcal{C}$	$\mathcal{B}_m$	$\mathcal{B}_r$	$\mathcal{J}\mathcal{C}$
—	+4662	0	0	7834	4662	64.0
17.5	4258	.515	4.78	5215	2665	45.4
5	4143	.685	6.35	3211	1205	35.2
9	3935	.915	8.48	1655	339	24.0
20	3473	1.385	12.8	462	46	8.44
33	2711	2.05	19.	166	5	3.5
36	1880	2.60	24.1			
136	-1258	3.8	35.2			
146	4627	4.9	45.4			
139	7834	6.9	64.0			
44	6820	4.00	37.3			
49.5	5690	1.60	14.8			
26	5078	.612	5.67			
18	4663	0	0			

H. TEMPERED AT 300°.

TABLE XXII.

TABLE XXIII.

RING I; $n_1 = 300$; $c = 127$; $\mathcal{B} = 20.7 \times d$; $\mathcal{J}\mathcal{C} = 9.56 \times I$.				RING II; $n_1 = 300$; $c = 129$; $\mathcal{B} = 24.7 \times d$; $\mathcal{J}\mathcal{C} = 9.44 \times I$.			
d	$\mathcal{B}$	I	$\mathcal{J}\mathcal{C}$	d	$\mathcal{B}$	I	$\mathcal{J}\mathcal{C}$
—	+8931	0	0	—	+9399	0	0
63	7628	.922	8.81	60	7916	.506	4.78
43	6738	1.401	13.38	27	7249	.670	6.32
82	5041	2.09	19.98	74	5421	.890	8.40
127	2412	2.64	25.24	164	1370	1.155	11.13
275	-3481	3.14	30.02	242	-4507	1.60	15.10
250	8455	3.79	36.2	127	7744	1.99	18.79
134	11229	4.04	47.2	86	9868	2.49	23.5
97	13237	6.95	66.4	85	11968	3.60	34.0
38	12450	4.8	45.9	42	13005	4.62	43.6
88	10628	1.76	16.8	48	14190	6.42	60.6
82	8931	0	0	37	13276	3.8	35.9
				72	11498	1.338	12.65
				43	10436	.550	5.19
				42	9399	0	0

TABLE XXIV.

RING III; $n_1 = 295$; $c = 129$; $\mathcal{B} = 18.1 \times d$; $\mathcal{H} = 9.69 \times I$.			
d	$\mathcal{B}$	I	$\mathcal{H}$
—	+8905	0	0
58.	7855	.263	2.55
33.	7258	.370	3.58
66.	6063	.505	4.89
225.	1990	.670	6.49
226.	—2101	.890	8.62
255.	6717	1.352	13.08
161.	9631	2.00	19.4
73.	10952	2.55	24.7
93.	12635	3.72	36.0
56.5	13658	4.80	46.5
70.5	14934	6.78	65.7
59.	13866	3.92	38.0
125.	11603	1.34	13.0
72.	10300	.550	5.33
77.	8906	0	0

TABLE XXV.

RING IV; $n_1 = 300$; $c = 128$; $\mathcal{B} = 18.4 \times d$; $\mathcal{H} = 9.52 \times I$.			
d	$\mathcal{B}$	I	$\mathcal{H}$
—	+5640	0	0
127.	3303	.077	.73
150.	433	.120	1.14
153.	—2382	.192	1.83
101.	4240	.207	2.54
90.	5896	.375	3.57
70.	7184	.510	4.86
61.	8306	.674	6.42
62.	9447	.897	8.54
87.	11048	1.355	12.9
73.	12391	2.00	19.0
38.	13090	2.51	23.9
44.5	13909	3.6	34.3
23.	14332	4.6	43.8
27.	14829	6.3	60.
32.5	14232	3.82	36.4
57.	13184	2.02	19.2
96.	11477	1.02	9.71
99.	9595	.49	4.66
111.	7553	.154	1.47
105.	5621	0	0

TABLE XXVI.

RING I.			RING II.			RING III.			RING IV.		
$\mathcal{B}_m$	$\mathcal{B}_r$	$\mathcal{H}$	$\mathcal{B}_m$	$\mathcal{B}_r$	$\mathcal{H}$	$\mathcal{B}_m$	$\mathcal{B}_r$	$\mathcal{H}$	$\mathcal{B}_m$	$\mathcal{B}_r$	$\mathcal{H}$
13237	8932	66.4	14190	9399	60.6	14934	8905	65.7	14830	5640	60.0
11168	7628	46.5	12029	8793	34.0	12679	8624	36.2	12402	5612	19.0
9656	6552	35.6	8596	6595	18.9	9909	7475	19.4	8409	5031	6.4
7214	4398	29.25	6793	5064	15.1	7792	6036	13.1	5161	3542	2.5
3926	1610	24.85	3940	2680	11.13	5190	3969	8.65	2511	1739	1.13
			2186	1223	8.4	3310	2367	6.5			
						1548	869	4.9			

I. TEMPERED AT 450°.

TABLE XXVII.

RING I; $n_1 = 300$; $c = 127$; $\mathcal{B} = 20.7 \times d$; $\mathcal{H} = 9.56 \times I$.			
d	$\mathcal{B}$	I	$\mathcal{H}$
—	+12198	0	0
37	11431	.513	4.92
15	11121	.676	6.44
26	10583	.900	8.6
87	8782	1.368	13.1
85	7022	1.62	15.5
95	5056	1.80	17.2
98	3927	1.89	18.1
250	—2143	2.00	19.1
211	6516	2.17	20.7
123	9662	2.35	22.5
94	11008	2.68	25.6
65	12359	3.22	30.8
69	13782	4.48	42.8
62	15065	7.00	66.9
69	13637	2.00	19.1
25	13119	1.015	9.7
44.5	12198	0	0

TABLE XXVIII.

RING II; $n_1 = 300$; $c = 127$; $\mathcal{B} = 25.1 \times d$; $\mathcal{H} = 9.44 \times I$.			
d	$\mathcal{B}$	I	$\mathcal{H}$
—	+11207	0	0
88	8998	.51	4.81
54	7643	.673	6.35
103	3552	.895	8.45
130	—289	1.011	9.53
145	3351	1.157	10.9
133	6689	1.352	12.74
173	11031	2.00	18.88
57	12402	2.54	24.0
61	13993	3.65	34.46
31	14771	4.7	44.37
34	15024	6.49	61.3
28	14921	3.86	36.4
48	13716	1.6	15.1
36	12812	.754	7.12
64	11206	0	0

TABLE XXIX.

RING III; $n_1 = 300$; $c = 127$; $\beta = 18.4 \times d$; $\mathcal{H} = 9.53 \times I$.			
d	β	I	$\mathcal{H}$
—	+9890	0	0
36	9228	.136	1.3
112	7167	.373	3.55
220	3119	.51	4.86
200	— 561	.626	5.97
60	1065	.676	6.44
221	5731	.90	8.58
222	9816	1.368	13.1
123	12079	2.03	19.3
58	13146	2.6	24.8
75	14526	3.8	36.2
41	15280	4.88	46.5
42	16053	6.82	65.0
38	15354	4.02	38.3
93	13043	1.62	15.44
61	12521	.902	8.60
57	11472	.459	4.37
86	9890	0	0

TABLE XXX.

RING IV; $n_1 = 300$; $c = 126$; $\beta = 18.7 \times d$; $\mathcal{H} = 9.52 \times I$.			
d	β	I	$\mathcal{H}$
—	+6189	0	0
130	3590	.078	.74
175	318	.120	1.14
175	— 2954	.190	1.81
112	5049	.262	2.49
102	6956	.375	3.57
76	8377	.570	5.43
66	9611	.673	6.41
66	10845	.896	8.53
79	12322	1.35	12.85
46	13182	2.00	19.0
19	13537	2.54	24.2
25	14005	3.60	35.3
17	14323	4.60	43.8
23	14753	6.26	59.7
47	13874	2.60	24.8
46	13014	1.15	10.95
73	11649	.649	6.18
163	8601	.169	1.61
129	6189	0	0

TABLE XXXI.

RING I.			RING II.			RING III.			RING IV.		
β_m	β_r	$\mathcal{H}$	β_m	β_r	$\mathcal{H}$	β_m	β_r	$\mathcal{H}$	β_m	β_r	$\mathcal{H}$
15065	12198	66.9	15624	11207	61.3	16053	9890	65.0	14753	6189	59.7
12689	10536	31.0	13855	10617	34.4	14545	9743	36.2	10892	5975	8.49
10205	8197	22.2	11031	8923	18.9	10066	8446	15.6	7237	4825	3.54
6231	4347	18.35	7932	6350	12.74	9052	7231	11.25	2552	1748	1.14
3167	1615	15.5	4616	3388	9.5	6357	4996	7.8			
932	186	8.68	1852	1000	6.89	4811	3670	6.00			
			803	276	4.81	2668	1766	4.38			
						530	153	2.28			

K. ANNEALED.

TABLE XXXII.

RING I; $n_1 = 300$; $c = 127$; $\beta = 21.5 \times d$; $\mathcal{H} = 9.54 \times I$.			
d	β	I	$\mathcal{H}$
—	+6751	0	0
115	4278	.500	4.77
77	2623	.66	6.3
133	— 237	.88	8.4
181	4128	1.331	12.7
128	6880	2.00	19.1
67	8321	2.52	24.0
95	10363	3.62	34.5
60	11653	4.62	44.1
75	13266	6.42	61.2
45	12298	3.81	36.3
101	10127	1.57	15.0
52	9009	.89	8.5
45	8041	.45	4.29
60	6751	0	0

TABLE XXXIII.

RING II; $n_1 = 300$; $c = 127$; $\beta = 25.5 \times d$; $\mathcal{H} = 9.44 \times I$.			
d	β	I	$\mathcal{H}$
—	+10838	0	0
99	8313	.190	1.79
147	4565	.265	2.50
250	— 1810	.370	3.49
146	5533	.500	4.74
94	7930	.660	6.23
71.5	9753	.878	8.20
74	11040	1.328	12.55
50	12915	2.00	18.0
24	13527	2.50	23.6
33	14369	3.60	34.0
20	14879	4.60	43.4
25	15520	6.30	59.5
27	14841	3.78	35.7
42	13770	1.55	14.63
31	12980	.745	7.03
22	12419	.418	3.95
62	10838	0	0

TABLE XXXIV.

RING III; $n_1 = 300$; $c = 127$; $\mathcal{B} = 18.8 \times d$; $\mathcal{H} = 9.52 \times I$.			
d	$\mathcal{B}$	I	$\mathcal{H}$
—	+10105	0	0
85	8507	.110	1.05
84	6028	.170	1.62
212	2942	.230	2.19
142	272	.27	2.57
262	— 4635	.371	3.53
158	7605	.506	4.81
99	9469	.669	6.37
78	10932	.888	8.36
82	12474	1.349	12.84
56	13527	2.10	20.0
28	14053	2.59	24.6
38	14767	3.75	35.7
23	15199	4.84	46.0
31	15782	6.8	65.0
35	15124	3.99	38.0
53	14128	1.60	15.23
35	13470	.885	8.43
32	12868	.550	5.23
147	10104	0	0

TABLE XXXV.

RING IV; $n_1 = 300$; $c = 127$; $\mathcal{B} = 19.0 \times d$; $\mathcal{H} = 9.52 \times I$.			
d	$\mathcal{B}$	I	$\mathcal{H}$
—	+6764	0	0
143	4047	.055	.53
222	— 171	.085	.84
140	2831	.116	1.10
142	5529	.182	1.73
69	6840	.258	2.45
54.5	7876	.365	3.47
37.5	8588	.50	4.76
28.5	9130	.66	6.28
25	9605	.876	8.34
20.5	10165	1.322	12.68
22	10583	1.95	18.6
32	11191	3.55	33.8
33.5	11828	6.10	58.1
44	10992	2.54	24.2
27	10479	1.278	12.19
20.5	10089	.782	7.44
21	9690	.508	4.84
48	8770	.200	1.9
38	8056	.09	.86
68	6764	0	0

TABLE XXXVI.

RING I.			RING II.			RING III.			RING IV.		
$\mathcal{B}_m$	$\mathcal{B}_r$	$\mathcal{H}$	$\mathcal{B}_m$	$\mathcal{B}_r$	$\mathcal{H}$	$\mathcal{B}_m$	$\mathcal{B}_r$	$\mathcal{H}$	$\mathcal{B}_m$	$\mathcal{B}_r$	$\mathcal{H}$
13266	6751	61.2	15520	10838	59.5	15782	10105	65.0	11828	6764	58.1
10428	6343	36.3	13490	10277	23.6	14645	9920	35.8	10298	6802	12.45
8546	5686	24.0	10226	8237	8.30	12446	9475	12.8	8854	6403	4.75
5278	3795	12.8	7319	5840	4.72	9073	7830	6.28	6270	4931	1.74
3064	2118	8.48	4066	349	3.49	6514	5349	3.51	4636	3010	1.12
1866	1178	6.37	2754	1811	2.50	4033	3149	2.50	3268	2508	.82
537	193	3.53	1033	446	1.79	2613	1871	2.17	665	247	.52
						1156	686	1.61			

L. RE-ANNEALED.

TABLE XXXVII.

RING II.			RING III.		
$\mathcal{B}_m$	$\mathcal{B}_r$	$\mathcal{H}$	$\mathcal{B}_m$	$\mathcal{B}_r$	$\mathcal{H}$
14813	7717	61.0	15517	9507	59.0
13611	7691	35.9	13438	9299	18.2
10993	7274	16.25	10943	8259	8.08
8615	6085	8.69	8240	6615	4.59
7933	5161	6.14	6502	5207	3.36
3605	2543	3.21	3969	3005	2.59
936	405	1.89	2552	1843	2.0
			1087	633	1.48

TABLE 1A.

RING I.		
B_m	B_r	$\mathcal{H}$
13847	7966	61.5
13315	7960	48.7
12180	7956	37.8
10120	7104	26.3
7112	5293	16.2
3639	2481	10.2
1425	724	7.1

A. Rings in the original state.

The measurements of rings gave the following data :

	Ring I.	Ring II.	Ring III.	Ring IV.
Mean diameter.....	12.607 cm.	12.699 cm.	12.63 cm.	12.667 cm.
Volume	95.099 cm ³	80.637 cm ³	109.29 cm ³	107.99 cm ³
Cross-section.....	2.401 cm ²	2.021 cm ²	2.754 cm ²	2.727 cm ²

As I stated before, these measurements were repeated every time after the rings had been subjected to a high temperature, so after the following steps: B, C, K and L. Each time a small decrease of the cross-section was observed.

In the original state, the hysteresis curves for only one maximum magnetizing field ($\mathcal{H}$) of about 60 were determined, except for Ring I, for which the value of $\mathcal{H}$ was varied.

The hysteresis curves show strongly the influence of carbon, the area of the loops diminishing with the decreasing percentage of carbon. The mild steel shows, indeed, a curve very similar to that of wrought iron. The maximum induction, taking the rings in the order I, II, III, has the values: 13840, 15070, 15290 lines of magnetic force, while the magnetizing force was very nearly the same in all cases. The corresponding coercive forces are 8.6, 2.7 and 3.6.

B. *Rings heated to 675° and quenched.*—The rings were then introduced into furnaces, which were well heated beforehand. On the bottom of the muffles was put a sheet of asbestos and over this two strips of the same material, on which the ring was placed. In order to prevent oxidation as much as possible, charcoal was put in the opening of the muffle. The heating to a dull cherry-red took about eight minutes. Then the ring was withdrawn quickly and quenched in water at 5° C.

Ring I has become magnetically harder, *i. e.*, the maximum induction for the same magnetizing field has decreased, the permeability, especially for low fields, is smaller, and the coercive force increased to more than twice its original value.

The iron ring shows an increase in permeability, which may be explained by a previous mechanical hardening, when it was turned to its proper shape.

In rings II and III there is no sign of magnetic hardening, the principal influence of this treatment being the remarkable drop of the remanence, while the maximum induction remained almost unchanged. The permeability, on the other hand, decreased a little. This sudden and unexpected drop in retentivity will again be met later on and discussed there more fully.

It is apparent that we have not passed the temperature at which low carbon steel is hardened. It is well known that the second and third point of recalescence for low carbon steel lie at a higher temperature than the corresponding point in the high carbon steel, which apparently had already been passed in the case of the high carbon steel. It is, therefore, probable, though I do not consider this experiment as an absolute proof, that the magnetic hardening takes place when steel is quenched after it has been heated to the same temperature at which recalescence occurs, *i. e.*, the critical temperature, at which, according to Hopkinson and others, iron loses its magnetic properties.

c. Rings heated to a little above 900° and quenched in ice-water of 5°.—The heat treatment was the same as in B, but the temperature was raised beyond the third point of recalescence of the low carbon rings.

All the steel rings show the hardening effect, the same being the smaller the less carbon the steel contained.

The high carbon ring (I) shows a decided increase in the hysteresis loss, which is much greater than the increase due to the first heating. While the first time the temperature was raised only a little beyond the point of recalescence, it was this time at least 250° higher. *We draw therefrom the important conclusion that steel becomes magnetically the harder, the more the temperature is raised beyond the recalescent point.* The passing of this point by only a few degrees is not sufficient for the maximum effect.

The hysteresis curves for the steel rings are given on Figs. 1–3, the maximum induction ($\mathfrak{B}_m$) and remanence ($\mathfrak{B}_r$) as a function of the magnetizing force on Fig. 4, and $\mathfrak{B}_r$ as a function of $\mathfrak{B}_m$ on Fig. 5.

D. Rings reheated to 100° for one hour.—The corresponding curves are marked by crosses on the plates and are drawn only

for the low carbon rings, the change being very small for the high carbon steel. The influence of this step becomes more apparent the less carbon the steel contains, and *it consists in a lowering of $\mathcal{B}_m$ as well as $\mathcal{B}_r$ in Rings II. and III., and in a slight raising of the same quantities in Ring I.* The coercive force in III. has become slightly larger. *The low carbon steel becomes,*

FIG. 1.

therefore, magnetically harder when it is reheated to 100°. This result is consistent with the observations of Barus and others, mentioned above.

E. and F. Rings were heated to 100° for 24 hours.—The heat treatment was the same as in the preceding case, except that the time of the heating was increased. I do not give the results,

since no decided change takes place. The curves almost coincide with the preceding ones, though there is an unmistakable increase of permeability, especially for small magnetizing fields, this change being largest for the high carbon steel. We have, therefore, a more or less pronounced influence of the time during

FIG. 2.

which the rings were subjected to this temperature, consisting in a slight increase of permeability.

g. *Rings reheated to 200°.*—Apparatus for the heat treatment: On the top of the heating table were placed two strips of asbestos, on this a disk of the same material with a round hole in the middle, then a layer of iron turnings and on this the ring. The

whole was surrounded with an asbestos ring, which was filled with iron turnings, so that the ring was entirely imbedded in the same. The temperature was read by means of a thermometer, which was placed so as to touch the ring inside. By the arrangement described, uniform distribution of heat from the centre was

FIG. 3.

procured. As soon as the temperature rose to 200° the ring was withdrawn and allowed to cool in the air.

I give the results for Ring 1. only, the others showing a very small increase in magnetic induction.

We will see from the comparison with the data given later on

that the increase of induction is comparatively small in all rings.

H. *Rings reheated to 300°*.—The heat treatment was practically the same as in G.

All rings show a decided increase in permeability, the change

FIG. 4.

being the smaller the less carbon the steel contains. The curve for Ring m., indeed, coincides so nearly with that of the hardened ring that the points corresponding to this step could be indicated only by dots in the plates. The wrought iron ring, that so far showed no sign of a change, has a larger permeability for small

fields than it had before. By comparing the curves on Fig. 4, we see a decided tendency towards an increase of the remanence for any given value of maximum induction. This will become more and more decided as we increase the temperature to which the rings are reheated.

FIG. 5.

The most important and rather unexpected result of this step is the sudden very large increase in the maximum induction of Ring 1. The number of lines of magnetic force has almost reached the value the ring had before it was heated at all. Therefore, whatever change in the chemical or physical consti-

tution of the ring produces the change in the magnetic properties, it is largest for the high carbon ring between 200° and 300° , *i. e.*, at a temperature which corresponds to that of the blue temper of steel.

1. *Heated to 450° .*—Heat treatment was practically the same as in g.

We observe a further increase of permeability and induction for all rings. The change for Ring 1. is only about one-third of the one in the preceding case, while we have a comparatively large change for Rings II. and III., corresponding to the large difference in $\mathfrak{B}_m$ of Ring 1., observed before, and to be attributed to the same causes.

It is to be noticed that, though the magnetic flux has practically reached its maximum for the field strength used, the value of the coercive force is still quite large in comparison with the corresponding value for the rings in the original state. The remanence for Ring 1. is larger after this step than in any other. The substance is Crescent steel, *i. e.*, magnet steel. It is apparent that, *in order to make strong magnets, it will be advisable to reheat the quenched steel to about 450° .* The magnets could be made more than twice as strong as if simply the hardened steel is used. Though I worked with closed magnetic circuits, the influence of the ends of the magnets will be the same in the two cases. It is of importance that the coercive force did not decrease nearly as fast as the remanence increased. Another factor in the making of magnets is their permanency. I mentioned the usual method of making permanent magnets in the introduction, and think that a similar treatment, by extending the range of temperature to 450° , will ensure permanency and produce stronger magnets.

k. *Rings annealed.*—The rings were again placed in muffles and heated to a bright red heat, the arrangement being the same as in b and c. After the temperature of about 850° was reached, the fire was banked and the rings allowed to cool inside the muffles. Charcoal was put in the mouth of the muffles. This treatment took about 24 hours.

The rings have become magnetically soft. While in the Rings II. and III. the saturation point was practically the same as before, the coercive force decreased to its smallest value, this last step being the largest in the whole series for the coercive force.

In the high carbon steel and the wrought iron, we find a re-

markable decrease in $\mathfrak{B}_m$, accompanied in Ring I. by a still greater decrease of $\mathfrak{B}_r$, while in the iron $\mathfrak{B}_r$ increases with respect to $\mathfrak{B}_m$. These changes can very plainly be observed on Fig. 5, where $\mathfrak{B}_r$ is plotted as a function of $\mathfrak{B}_m$. The curve obtained for Ring I. differs entirely from any of the curves taken after the ring was hardened, but it shows a great similarity to curve A taken in the original state.

Hoping to obtain similar curves for the other two steel rings they were again annealed, the temperature this time being raised to nearly 1000° . Cooling took place in the same way as before.

L. *Reannealed.*

Both rings show the decided decrease of $\mathfrak{B}_r$ and the different character of the curve. The one for Ring III. is indicated by dots only, and coincides partly with curve I. In both cases there is a great similarity with the curves B, obtained by heating the originally annealed steel to a high temperature below the point of recalescence and suddenly quenching. It almost seems that the steel by this process has become a different substance. These curves show more the characteristics of the iron (see ring IV. on Fig. 5) than of steel. Houston and Kennelly's law does not hold for nearly as wide a range as before. I believe that the effect observed in the last step is not an immediate effect of annealing, but that it is the conditions under which cooling takes place, that influence largely the retentivity of steel.

Steel heated to a high temperature below the point of recalescence and suddenly quenched as in B, will very easily lose its magnetism. This seems to me of practical importance. The maximum induction being the same, and the remanence a great deal smaller than in the ordinary state, it is apparent that the hysteresis loss will be much smaller, and therefore very mild steel, as our Ring III., treated in the way indicated above, is preferable to the ordinary mild steel used in transformers or other instruments, in which cyclic processes take place, if the induction is carried to high values.

Since the hysteresis loss has been found to increase appreciably in transformers after they have been used for some time, it is of great importance to investigate whether a similar effect takes place in steel treated in the manner suggested. A series of such experiments would be very valuable from a practical point of view.

In 1890, Osmond (*Phil. Mag.* 29, 511, 1890) advanced a theory according to which a bar of steel consists of an intimate mixture of α iron (magnetic) and β iron (unmagnetic). He considers the β modification as forming in a steel a porous framework, the ratio

between the amount of α iron and β iron not changing under the influence of currents and of magnets. "In the presence of the rigid network of β iron the polarized α particles are conceived as catching in the pores of the β structure and immovable in this position, thus resulting in a permanent magnet." Moreover, he supposes the temporary induction and the remanence to be a function of the ratio $\frac{m}{n}$, where m is the percentage of α iron, and n the percentage of β iron in the steel. Let mp and np (Fig. 6) represent the corresponding values; then the maximum induction is proportional to mp , the residual to mr . Further suppose, that

FIG. 6.

the fraction of the maximum induction forming the remanence (r) is proportional to the amount of β iron (n); he then derives the formula

$$r = K \left(n - \frac{m^2}{100} \right) = K \left(x - \frac{x^2}{100} \right)$$

Consequently the remanence is represented by a parabola starting from O upward and meeting the X axis at a point corresponding to 100% α iron.

Suppose this theory to be correct, then by a change of β iron to α iron the difference between the maximum induction and the remanence increases. My experiments show that this does not take place by reheating the hardened steel. (Compare results represented on Figs. 4 and 5.) On the contrary, the difference becomes smaller. We cannot assume a transformation of α iron to β iron, since the permeability increases decidedly on reheating. On the other hand, the sudden drop of the remanence observed before the point of recalescence is reached, would correspond very well to Osmond's theory, if we suppose a transformation of β to α iron has taken place.

I believe that we have also to take the influence of the carbon compounds into account, which has not been done by Osmond. Let us assume that the reheating has such an influence on the iron in the iron ring and on the carbon compounds as to decrease the relative distance (Fig. 6) between the maximum induction and the remanence, and that the rate of this change decreases, the higher the temperature to which the rings are reheated. Probably

the process producing this change, whatever its cause may be, is completed at high temperatures. If besides this there is any other influence present producing a relative drop of the remanence as should be expected from Osmond's theory, when not α iron changes to α iron, this latter effect is masked at the beginning by the effect mentioned first, but it becomes more apparent the higher the temperature and the smaller the change connected with the relative increase of the remanence. Finally at still higher temperatures only the influence of the transformation of non-magnetic iron to magnetic iron remains, the other process being practically completed.

Figs. 4 and 5 show that, while in the iron ring in which there is no β iron, only the first influence can be observed, we have both effects in the steel rings; here the second influence does not appear, until we have almost reached the point of recalescence, and it is the more prominent, the harder the steel or (with Osmond) the more non-magnetic iron the steel contains.

The results of this research may be summarized as follows :

1. The point at which steel becomes magnetically hardened by quenching, lies at different temperatures, according to the amount of carbon contained. It is considerably lower in high carbon steel than in low carbon steel, and corresponds closely to the different temperatures at which recalescence occurs.

2. The higher above the point of recalescence steel is heated before being quenched, the harder it is magnetically.

3. The magnetic hardening produced by quenching is the larger, the higher the percentage of carbon.

4. Reheating has in general a softening effect upon the magnetic properties of hardened steel, *i. e.*, the permeability increases, and is accompanied by an increase of maximum induction and a decrease of the coercive force. But a hardening is noticeable in the low carbon steel after it has been reheated for a short time to 100° . The greatest change in the maximum induction takes place for high carbon steel between 200° and 300° , for low carbon steel between 300° and 450° , beyond which temperature there is hardly any change in the practical limit of saturation. All change taking place in reheating beyond 450° consists in an increase of permeability for small magnetizing forces, *i. e.*, a decrease in the coercive force or hysteresis loss.

5. To produce strong magnets, the hardened steel should first be reheated to 450° .

6. Heating to a high temperature below the point of recalcence and sudden quenching, produces a steel with a very weak retentivity if the value of the magnetizing force has been large; in consequence of which the hysteresis loss in a cycle is greatly decreased. This result may also be obtained, though in a lesser degree, by annealing at a very high temperature.

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Physical Laboratory of the University of Michigan.

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DISCUSSION.

PROF. HENRY S. CARHART:—*The Bearing of this Investigation on the Theory of the Constitution of Steel.* The chemical composition of the steel and iron, whose magnetic properties Dr. Guthe has investigated, has been carefully determined. This was done because one of the chief objects in view was the bearing of the magnetic properties of steel and iron on the theory of their composition. The theory of steel has been studied by means of chemical analysis, by its microstructure and by its mechanical and magnetic properties. Dr. Guthe's paper connects the first method and the last two.

The old carbon theory of the hardening properties of steel and its corresponding changes in magnetic properties, has been strongly opposed by the most recent allotropic theory, of which Osmond, of Paris, and Roberts-Austen, of London, are perhaps the most conspicuous supporters. This theory appears to be based on the known chemical and structural changes which the carbon undergoes when the metal is raised to high temperatures, and on the recalcence or retardation points of iron.

Osmond distinguishes three allotropic forms of iron, which he calls α iron, β iron, and γ iron respectively. For the present purpose we need to distinguish between the α and β forms only. The α iron is magnetic, the β form non-magnetic.

The first point of recalcence, or of the retardation which iron exhibits either in the process of heating or of cooling, is from 640° to 690° C. Below this temperature, annealed low carbon iron consists almost entirely of α iron. The point of retardation of the temperature on cooling is about 30° lower than on heating, or the iron exhibits another characteristic form of hysteresis. Iron containing more than about 0.5 per cent. of carbon has only this first point of retardation. It is denoted by A_1 .

The second retardation point in low carbon iron, called A_2 , occurs at temperatures between 700° and 750° C. Iron having less than 0.5 per cent. carbon and more than 0.25 per cent. exhibits this second point of retardation in addition to the first.