T H E S I S .

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A STUDY OF THE MAGNETIZATION OF SHEET IRON.

By

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For

The Degree

Of

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In

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(Under Dr. Chas A. Perkins).

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A Study of the Magnetization of Sheet Iron.

1. THE MAGNETIC BALANCE.- The Magnetic Balance is an instrument for measuring the number of lines of force induced in a magnetic material by means of weighing, when this material is in a known magnetic field. By this means hysteresis curves and the permeability may be obtained for any magnetic material and thus becomes of great importance in the calculation of transformer and armature cores, such as the losses due to hysteresis. The instrument is so adjusted as to give the correct number of induced lines of force for a test piece having a cross-section of .5 sq. cm. and a length of 25 cm. between the faces of the clamp-cheeks which hold the ends of the test piece. There are two kinds of clamp-cheeks: one to hold test pieces with circular cross-sections and one for rectangular cross-section. These clamp-cheeks are fastened in sockets in two pillars resting on the ground plate of the instrument. These pillars have each a horizontal polished surface. A yoke pivoted a little off center and resting upon a frame between the pillars has also two similar surfaces which almost touch those of the pillars but are prevented from doing so by means of stops on the yoke which strike against adjusting screws on the pillars. The test piece is surrounded by a coil of wire between the two pillars. This coil has a definite number of turns so that for any given current flowing the strength of the field set up is known. When a current flows in the coil, a magnetic current is set up through the test piece, across the air gaps and through the yoke. Since the yoke is pivotted off center, the two moments of the forces

between the faces of the pillars and yoke are unbalanced. By means of a weight sliding along a graduated scale, attached to the yoke, equilibrium can be established between the two moments. As the forces of attraction between the faces are proportional to the square of the number of lines of force set up the instrument can be so adjusted as to read the number of induced lines per .5 sq. cm. directly.

The vertical component of the earth's field has to be compensated by means of two small vertical magnets sliding in rear of the yoke. If it were not for these compensating magnets the readings taken when the current was flowing one way would be different from the reading taken for corresponding strengths of reversed current on account of an unsymmetrical field. The average of any two readings, one taken for a direct current and one for a corresponding strength of reversed current is the same, however, whether the compensating magnets are used or not or whether they are properly adjusted, but to save time they must, of course, be in adjustment. I found that these compensating magnets had to be adjusted slightly different for each kind of material tested owing probably to the magnetization in the two ends of the test piece being slightly different. Curve No. 14 shows the effect also of these magnets not being in adjustment. Among other points noted, it seemed to make very little difference in the readings for a small change in the pressure of the clamp-cheeks, therefore causing no trouble when you wished to take out the test piece and replace it. Also the same average curve was

obtained when the test pieces were taken out and turned around but the two corresponding readings showed a slight variation which is probably due to a little difference in the magnetization between the two ends of the test piece, which fact would then account for the different adjustments that the compensating magnets would have to have.

After any test piece had been highly magnetized it was not possible to get a curve with a low maximum value unless the test piece was first demagnetized as much as possible.

For the two samples of iron tested the curves of each for different maximum values crossed the x-axis at the same place but the sample of steel showed a variation for each maximum value.

There was another peculiarity noted. The yoke was taken off and perfectly balanced on glass surfaces by means of a pair of lock nuts sliding horizontally. When the yoke was replaced and readings taken, it was found that in approaching the zero reading the weight came to the zero before the magnetization became zero and for zero current the weight required to be carried beyond the zero of the scale. On plotting an effect as shown in curve No. (14) was produced. The horizontal lock nuts then had to be adjusted so that the zero readings could be obtained. It is not clear how any arrangement of the lines of force could produce such an effect. If in making the adjustment to give a direct reading scale, the left gap were made much larger than the right, it is possible that such a result would follow.

By means of the adjusting screws on the pillars the play

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of the yoke can be made very small and unless the play is small, the readings can not be taken with very great precision. By adjusting the screws so that the yoke has barely enough play to hear the stops hit on the adjusting screws, you can then read accurately to within fifty of the actual reading. However when you come to plot the curve it will be found that it is not necessary to read closer than to the nearest hundred.

It was found that for a small fluctuation of the current at a rather high point of magnetism, there was no loss of energy, see curve No. (9). The short curve a b shows that in allowing the current to stop and raising it $\frac{1}{4}\phi$ the magnetization fell and rose along the same line.

In piling the strips of sheet iron to make up the test pieces it was not possible to get an even number of strips to give the required cross-section therefore corrections had to be made accordingly in all the readings, so as to give the number of lines of force per $\wedge^{.5}$ sq. cm. Corrections are not made closer than to the nearest fifty.

In obtaining I got two values of B in each strength of current, one with direct current and other with reversed current. Owing, of course, to the magnetization in the iron not being symmetrical it is impossible to adjust the compensating magnets so as to make both readings the same. The variation, however, can be made small and the reverse reading enabling you to obtain an average reading.

2. CURVES FOR DIFFERENT MATERIALS.- The curves shown in black are for the ordinary B B sheet iron. This test piece had

a cross-section of .488 sq. cm. and it was found that each reading had to be corrected by adding 48 to every 1000 lines of force. Below is given the table for curve No. I.

Curve No. I.

	Direct Current		Reversed Current		Aver'g B corrected for incrs current	Aver'g B cor'cted for decr. current.
H	B	B	B	B		
0	5950	5950	----	5850	6200	----
.95	5450	----	5550	----	5750	----
2.2	4450	----	4650	----	4700	----
3.1	3250	6850	3450	6750	3500	7100
4.55						
7.35	4550	7300	4250	7250	4600	7600
9.95	6300	7450	6200	7450	6500	7800
1.33	7600	----	7600	----	7950	----

The curves shown in red are for a sample of American Charcoal iron. The area of cross-section of the test piece was .482 sq. cm. (15 strips) and therefore the readings taken had to be corrected by increasing them 72 for every 1000 lines. Below are given the tables for the different curves;

Curve No. 6.

	Direct Current		Reversed Current		Average B corrctd for increasing current...	Average B corrctd for decreasing current...
H	B Inc.Cur	B Dec.Cur	B Inc.Cur	B Dec.Cur		
0	5700	5700	----	5700	6100	----
.55	5200	6000	5200	6000	5550	6400
1.55	3900	6500	3900	6500	4200	6900
2.9	300	7000	300	7000	300	7000
3.3	0	----	0	----	0	----
4.2	3300	7300	3300	7300	3550	7800
6.4	6200	7450	6200	7450	6600	8000
8.15	7600	----	7600	----	8100	----

Curve No.7.

0	7200	7400	----	7200	7800	----
.55	6500	7700	6900	7400	7200	8000
1.55	4700	8300	5200	8000	5300	8750
2.5	2100	----	2500	----	2450	----
3.3	0	----	0	----	0	----
4.6	3550	9600	3050	9400	3500	10200
7.5	7400	10100	7000	9900	7700	10800
10.05	9100	10300	8800	10300	9600	11050
13.2	10500	-----	10500	-----	11250	-----

Curve No. 8.

0	7900	7900	----	7900	8450	----
1.5	5900	8900	5900	9000	6300	9600
2.15	3900	----	4100	----	4300	----
2.4	3000	----	3200	----	3300	----
3.	1100	9700	1300	9800	1300	10400
3.3	0	----	0	----	0	----
4.35	2400	10200	2300	10300	2500	11000
6.85	6500	11000	6400	11100	7000	11850
8.95	8400	11400	8400	11500	9000	12300
11.65	10000	11700	10000	11900	10700	12650
13.25	10700	11900	10800	12000	11450	12800
17.5	12200	-----	12300	-----	13000	-----

Curve No. 9.

0	8400	8300	----	8400	9000	----
1.55	6200	9400	6200	9500	6700	10200
3.15	800	10300	800	10400	850	-----
3.3	0	-----	0	-----	0	-----
4.6	2500	10900	2500	11100	2700	11850
7.45	6800	11900	6800	12100	7300	12900
10.0	8900	12500	9800	12800	9550	13550
13.45	10800	13100	11000	13400	11700	14200
15.5	11600	13400	11800	13800	12550	14650
23.0	13200	13900	13500	14200	14300	15000
27.5	14100	-----	14400	-----	15250	-----

The curves shown in orange ink are for a sample of sheet steel. The cross-section of this test piece was .497 sq. cm. (1.3 strips 1) and hence the readings had to be corrected by adding 12 to every 1000 lines of force. Below are given the tables for the different curves;

Curve No. 10

0	3200	2900	----	3200	3100	----
1.5	1600	3600	1400	3800	1550	3700
2.3	0	----	0	----	0	----
2.5	400	3800	600	4000	500	3900
3.2	1700	3900	1900	4100	1800	4000
4.05	3000	4000	3200	4200	3100	4100
4.55	3600	4000	3800	4200	3750	4100
5.0	4000	----	4200	----	4100	----

Curve No. 11.

0	6800	6800	----	6800	6850	----
1.75	4000	7900	4000	8000	4050	8000
2.45	2300	8300	2300	8400	2300	8450
3.3	0	8700	0	8700	0	8800
4.5	2500	9100	2500	9100	2500	9200
6.5	5800	9500	5800	9550	5850	9600
8.0	7300	9700	7300	9800	7400	9800
9.5	8400	9900	8400	10000	8500	10000
12.0	9700	10150	9800	10250	9800	10250
13.3	10200	----	10300	----	10300	----

Curve No. 12.

0	7600	7600	----	7600	7700	----
1.6	5200	8700	5200	8800	5250	8900
2.5	2900	----	2900	----	2900	----
3.1	1300	9500	1300	9500	1300	----
3.6	0	----	0	----	0	----
4.5	2100	10100	2000	10300	2100	10300
7.0	2100	10700	6200	10900	6300	10950
9.1	8100	11200	8300	11500	8300	11450
11.9	9700	11500	9900	11800	9950	11750
13.5	10500	11700	10700	11900	10750	11900
17.5	11900	-----	12100	------	12150	-----

Curve No. 13.

0	8100	8100	----	8100	8200	----
1.6	5500	9200	5600	9300	5600	9350
2.5	3100	----	3300	----	3200	----
3.25	1500	10200	1700	10200	1600	10300
4.0	0	-----	0	-----	0	-----
4.75	2100	10800	1900	10900	2000	10950
7.7	6500	11600	6400	11800	6600	11850
10.3	8700	12300	8700	12300	8800	12450
13.45	10500	12800	10500	13000	10650	13050
15.8	11500	13100	11500	13300	11600	13300
21.8	12900	13400	13000	13700	13100	13700
27.5	13600	-----	13800	-----	13850	-----

4.- BUTT JOINTS-EFFECT OF DIFFERENT NUMBER OF AIR GAPS.- The first test piece made out of the B B sheet iron was cut in two and the ends of the two pieces were then butted together and then tested. The curve No. (15) was derived. This curve shows very little variation from the curve obtained by using the same strength of magnetization current on the whole test piece. The high inductions show very little variation. Below is given the table for the above curve:

Curve No. 14.

0	5650	5750	----	5650	5950	----
.5	5300	6050	5400	5950	5600	6300
1.5	4550	6450	4650	6400	4700	6750
3.05	2550	6850	2650	6850	2750	
4.4	0	----	0	----	0	----
4.5	500	7150	600	7150	550	7500
7.35	4250	7500	4050	7450	4350	7750
9.9	6250	7650	6150	7560	6500	8000
13.35	7850	----	7850	----	8200	----

Curves Nos. 4 and 5 were taken from the same test piece having four butt joints. Below are given the tables:

Curve No. 4.

0	2600	2400	----	2600	2650	----
.5	2300	2650	2150	2800	2350	2850
1.5	1850	----	1700	----	1850	----
2.45	1350	3250	1200	3550	1300	3500
3.1	1050	3350	850	3550	1000	3600
4.4	0	----	0	----	0	----
4.55	650	375P	550	3950	600	4000
7.4	1950	4150	2100	4400	2100	4400
9.95	3250	4350	3450	4600	3500	4700
13.3	4650	----	4850	----	4950	----

Curve No 5.

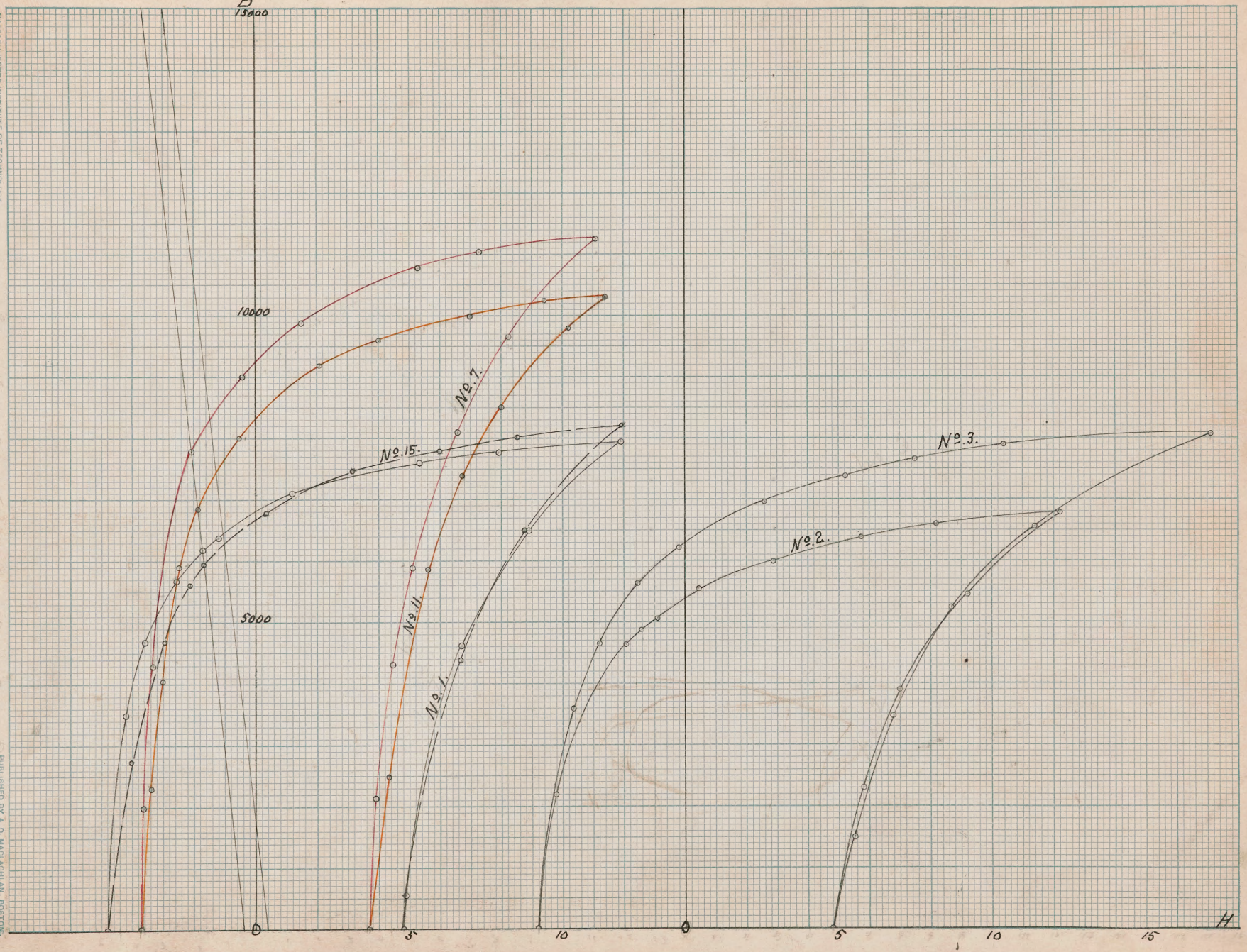
0	3450	3300	----	3400	3550	----
1.3	2700	3900	2500	4200	2650	4250
2.3	2100	4300	1900	4600	2100	2750
3.7	1200	4900	1100	5100	1200	5200
4.4	0	----	0	----	0	----
5.1	600	5300	800	5500	700	5550
6.9	1500	5900	1700	6100	1700	6300
9.6	2950	6500	3200	6700	3200	6900
14.4	5100	7100	5300	7300	5450	7550
18.4	6400	7400	6600	7600	6800	7850
23.5	7600	----	7800	----	8100	----

The effect of the air gaps in the test pieces with butt joints is that it requires a larger magnetixing current to bring it to the same point of induction than in the whole test piece. But it is seen that the loss of energy for the same point of induction is about the same. Integrating the areas of Nos. 1 and 5 which have approximately the same maximum induction, their areas in sq. ins. are respectively (9.43) and (10.03).

5.- LAP JOINTS.- This same test piece of B B sheet iron was also tested with four lap joints of.5 cm. Curves Nos. 2 and 3 show the results and below are given the tables;

Curve No. 2.

0	4700	4700	----	4700	4900	----
.55	4400	4850	4400	4850	4550	5050
1.6	3750	5150	3850	5200	3950	5450
2.55	2850	----	2950	----	3050	----
3.2	2050	5450	2150	5500	2200	5600
4.4	0	----	0	----	0	----
4.65	----	5700	----	5750	----	6000
7.45	3750	6000	3650	6050	----	6000
9.95	5250	6200	5200	6250	5450	6600
13.3	6400	----	6450	----	6800	----



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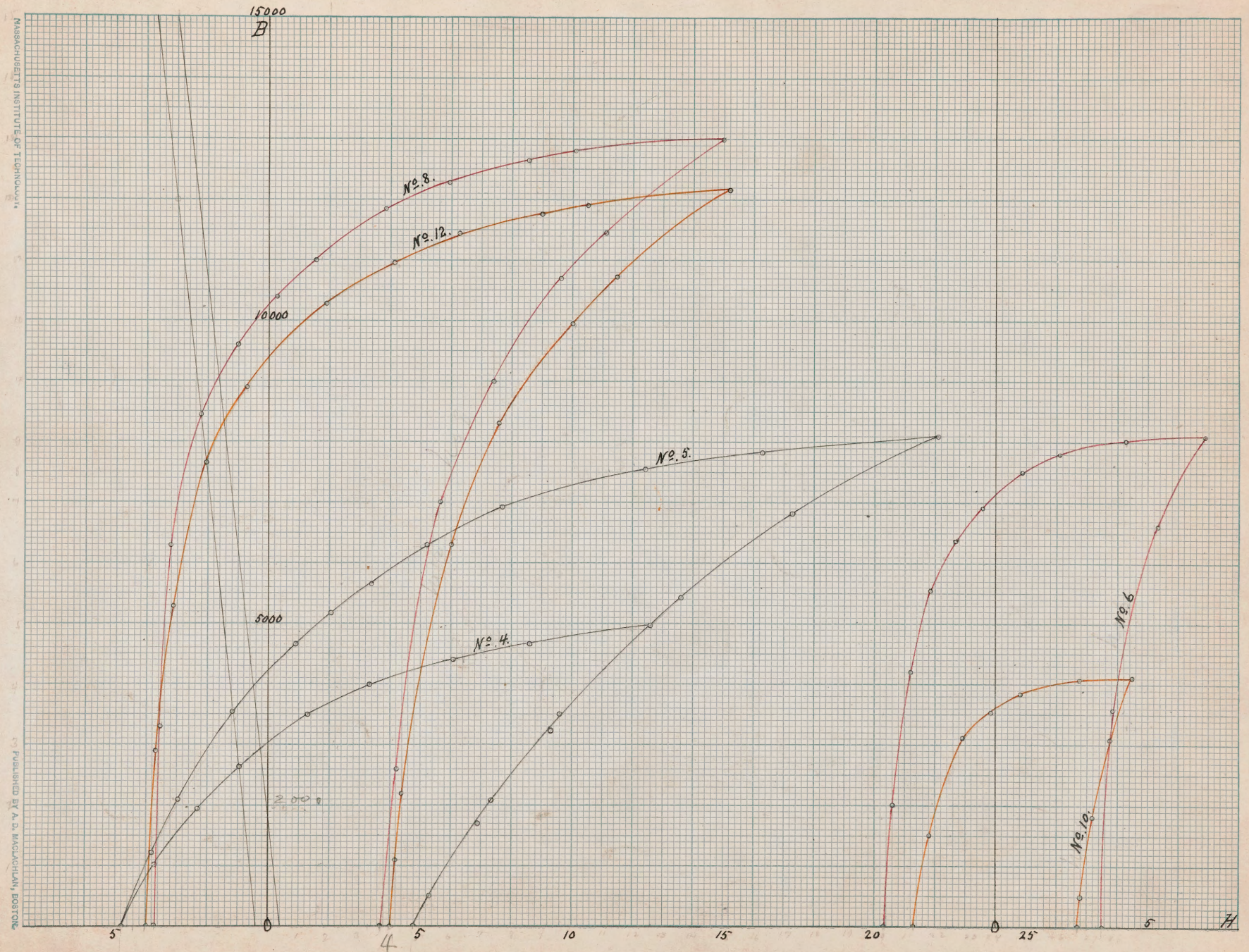

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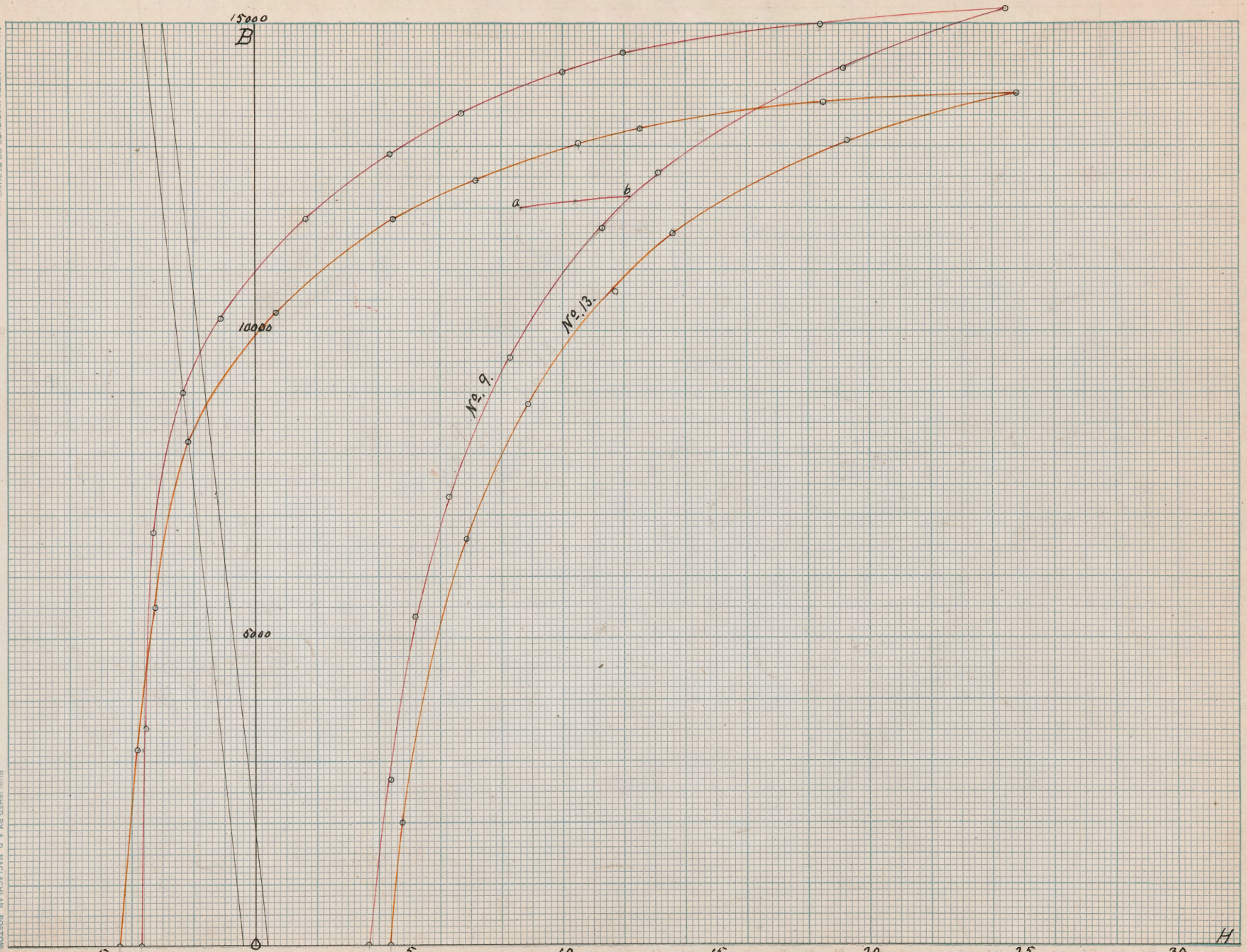

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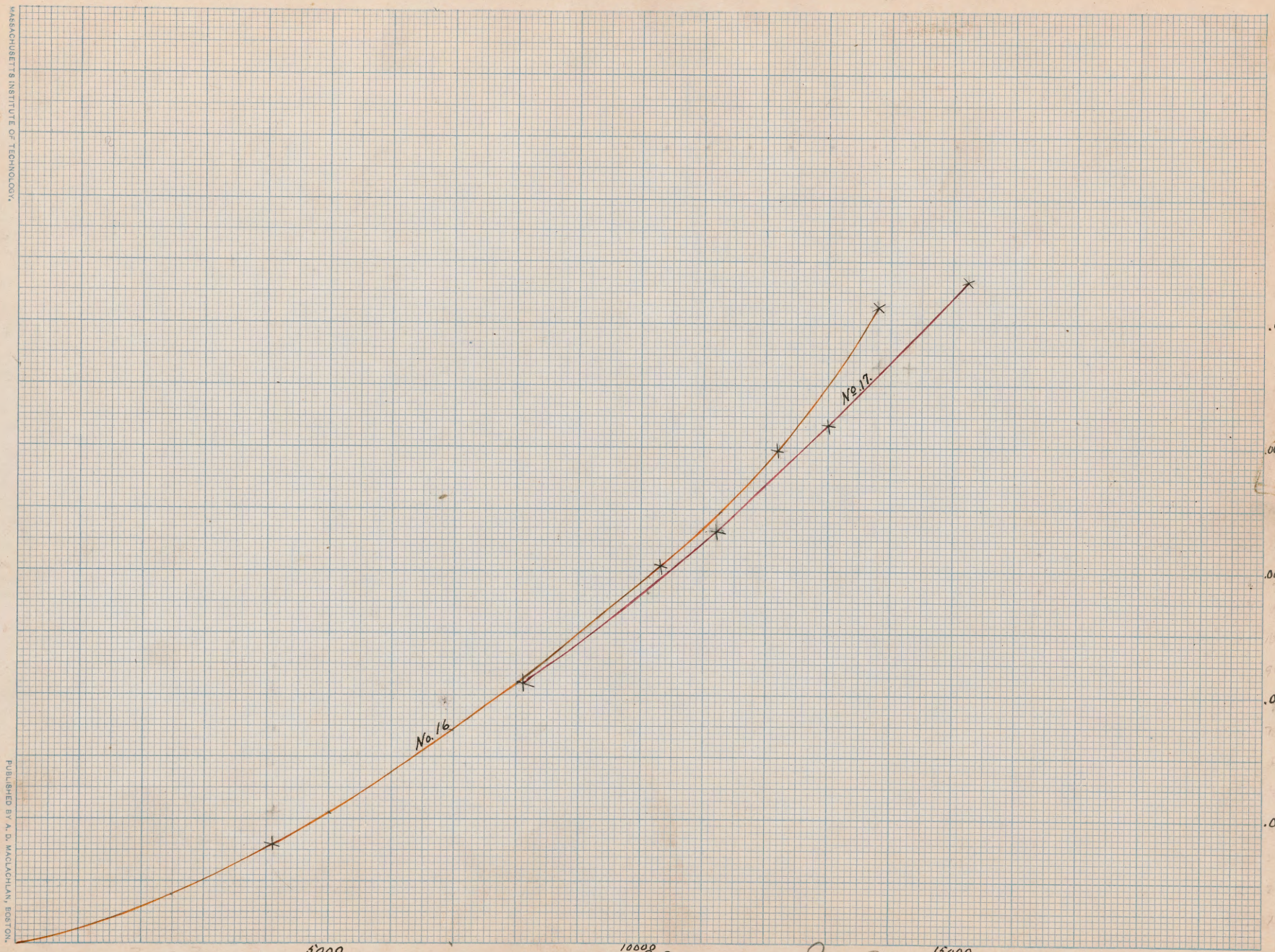
Curve No. 3.

0	5350	5300	----	5400	5650	----	
.55	5100	----	5000	----	5300	----	
1.55	4456	5800	5340	6000	4650	6200	
2.5	3500	----	3450	----	3600	----	
3.1	2650	6250	2650	7400	8800	6600	
4.4	0	6550	0	6700	0	6950	
7.2	3300	6900	3300	7100	3450	7400	
9.5	5000	7100	5000	7400	5250	7650	
12.5	6200	7400	6300	7600	6550	7900	
18.5	7600	----	7800	----	8050	----	

The effect of lap joints is about the same as that of butt joints only that it does not require so large a magnetizing current to bring the induction to the same point as in the case of butt joints.

6.- STEINMETZ LAW AS APPLIED TO THE MATERIAL TESTED.- Taking Steinmetz law, $\frac{1}{4\pi}\int_{-B_{max}}^{+B_{max}} H\,dB = \eta B^{1.6}$ it was found for the sample of charcoal iron that the exponent of B was found to be 1.5, 1.46, and 1.4 instead of 1.6, for the four curve obtained. The value for the coefficient N found using the average of the exponents found was: .012



? Examine that the ref = 12

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For the sample of sheet steel this exponent gave 1.47, 1.45 and 1.45 for the four curves obtained. The value of the coefficient N in this case was found to be .011 .

It is seen that there is an uniformity about the coefficient obtained for both samples. All of the curves obtained were for low maximum values of induction and it may be that Steinmetz used a much higher range of values in determining his law.

The curves between the joules per cu. cm. and maximum B are shown in curves Nos. 16 and 17.

7.- TRANSFORMER CALCULATION BASED ON HYSTERESIS LOSS IN CURVE NO.4.- From curve No. 4 the loss due to hysteresis may be obtained for a sample of BB sheet iron with four butt joints. It is intended to design a 5000 K.W. transformer having given the following data using the BB sheet iron for the core;

Ratio of transformation 20 to 1.

E ' = 2000, E '' = 100.

The size of core necessary was calculated by the following formula,

$$\mathcal{E}' = \frac{\sqrt{2}\,\pi\, n' N_m f}{10^8}$$

$$N_m = \frac{752{,}000{,}000}{2160} = 348{,}000 .$$

From a previous calculation it was found that 720 turns on the primary gave a core that was too large therefore three times this number of turns was taken which gave a core only one third as larhe.

$$\text{Cross-section of core} = \frac{N_m}{B_m} = \frac{348,000}{5000} = 69.6 \text{ sq. cm.}$$

In above calculation it was found best to make N' =2160 and therefore N" = 108. To calculate for size of wire for primary and secondary we refer to tables for this purpose. Allowing 1500 to 1200 circular mills per ampere, for secondary with C" = ~~2 1/2~~ 50 we find that about 65,000 circular mills is necessary. From the table four No, 8 wires will give this. Taking the core to be 25 cm. long and 8.4 cm. square we find that about six layers of this number of 8 wire is necessayr of about 4320 cm. long per each wire in parallel. Four lengths of the above wire in parallel has a resistance of .0227 ohms and the C^2" R loss = 56.7 watts or 1.1 per cent of whole output.

For primary it was necessary to use a density of about 3275 circular mills and the table gives No. 15 wire corresponding to this. About 16 layers of No. 15 wire of 119232 cm.length was found to be necessary for primary. The wire in the primary had a resistance of 12.63 ohms and the C^2' R loss was 78.9 watts or 1.5 % of whole output.

For the hysteresis loss the area of curve No. 4 was integrated and doubled to give the loss due to one cycle. From the scales used in plotting it was found that 1 sq. in. of area was equivalent to 8000 (HXB). The following formula was used in calculating this loss.

$$\text{Loss in watts} = \frac{.796}{10^8} f \text{ volume} \int_{B_{-max}}^{B_{+max.}} 1\!\!+ dB.$$

$$= \frac{.796}{10^8} \times 60 \times 660.24 \text{ cu. cm.} \times 8000 \times 10.2$$

$$= 25.8$$ which is .5 % of whole output.

The cubical contents of the core can be calculated from figures from figures shown on last page.

The Foucault current loss was calculated from a formula ~~from a formula~~ of Steinmetz,

$$U = M (d f B_m)^2 10^{-16}$$

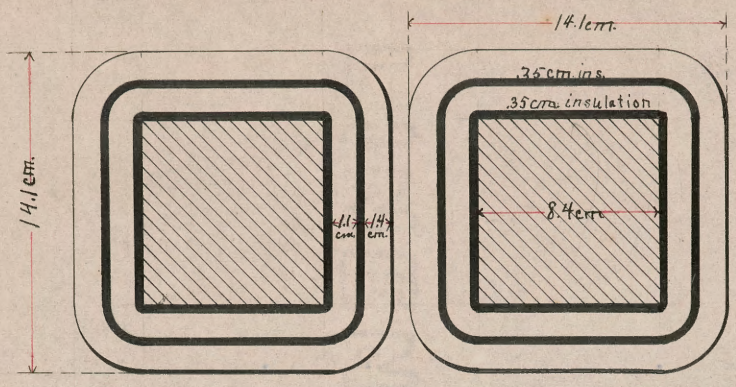
where d is the thickness of a sheet in mills.

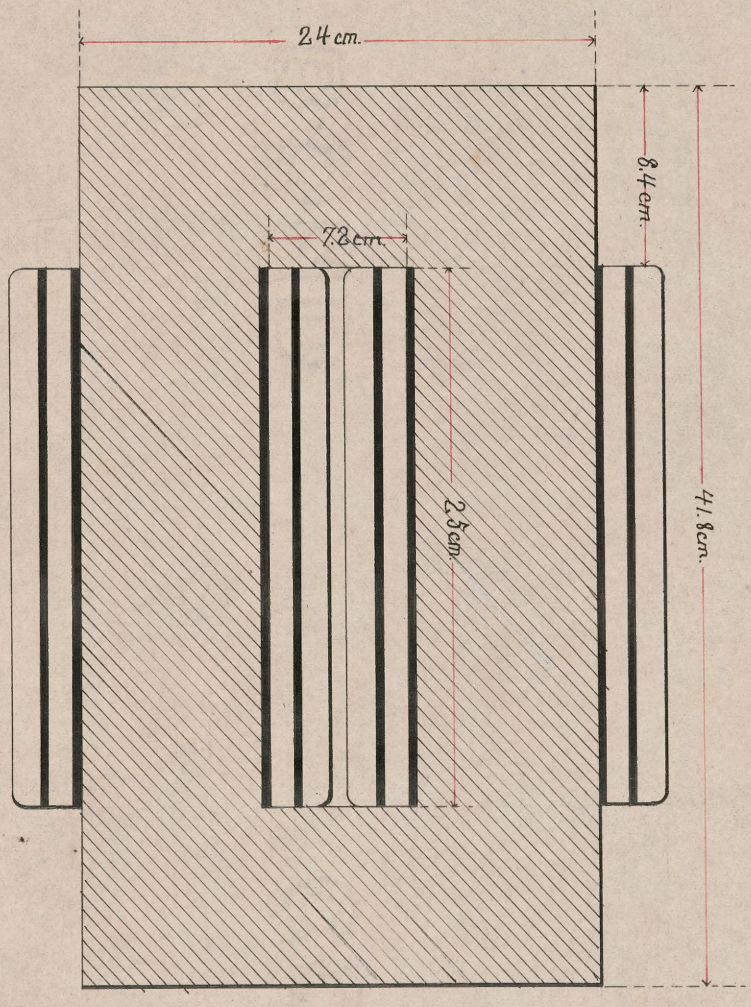
Watts = U = $660.24(19.4 \times 60 \times 5000)^2 \times 10^{-16}$

= 2.2 watts or, .04 % of whole output.

All the losses in this transformer amounts to 163.6 watts or 3.3 % of whole output.

On the last page are shown two sectional drawings of this transformer giving all dimensions.


14.1cm.
.35cm. ins.
.35cm. insulation
14.1 cm.
4.1 cm.
4.4 cm.
8.4cm.


24 cm.
8.4cm.
7.8cm.
23.5cm.
41.8cm.

Scale 1/8" = 1cm.