

DESIGN AND CONSTRUCTION OF A 10 K.W. (110/100000 volt)
TRANSFORMER.

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BY

W. C. Burnley and A. C. Weigel.

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Dr. Chas A. Perkins.

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TRANSFORMER.

The transformer whose design and construction is the subject of this thesis is intended for insulating testing and therefore little account is taken of efficiency, the main object being to secure a high voltage, with a reasonable cost of construction.

I. Design.

Conditions:

Primary E.M.F. 110 volts

Secondary E.M.F. 100000 volts

Frequency 60 cycles per sec.

Capacity 10 K.W.

The iron used in this transformer had an average thickness of .022 inches when will packed together. Tests were made by Mr. Hopkins on this iron. He took 13 strips of such width as to give 0.5 sq.Cm. cross-section and tested them on the Siemen's Halske Magnetic balance. To keep the number of turns as small as practicable, the induction must be high. For our purposes it seems that $B = 7000$ will not be too high. Results of tests as made by Mr. Hopkins for hysteresis loss may be found in Table & Curve No.I.

Wire to be used.

10 K.W. at 110 volts neassitates 91 amperes.

Allowing for losses and using 800 Cir. mills per ampere, an equivalent of No.I wire B.&S. gage was required, but as No.I

was too stiff to handle, 4 No.7 B.& S. gage, in parallel, was selected. In selecting the wire for the secondary, No.36 was found to be large enough to carry the current, but because of its greater cost and difficulty in handling, No.30 adapted itself better to our use. Insulation of this wire to be double cotton Covered.

CALCULATIONS.

As area of core and number of turns were unknown, it was necessary to assume one to find the other. In this case different sizes of core were assumed and a curve was made between the diameter of core and cost of material which is tabulated in Table and Curve No.2.

$$E' = 110 \text{ volts}$$

$$E_{\max} = E' \sqrt{2} = 156 \text{ volts}$$

$$B_{\max} = 7000$$

$$f = \text{frequency} = 60 \text{ cycles}$$

$$n' = \text{number turns in primary}$$

$$A = \text{area core in sq. c.m.}$$

$$\phi_{\max} = \frac{E_{\max} \times 10^8}{2 \pi n' f}$$

$$\phi_{\max} = B_{\max} A$$

$$B_{\max} \times A = \frac{EM \times 10^8}{2 \pi n' f}$$

Assuming diameter of 7 inches. A circle is drawn, and by inscribing a series of rectangles (cut No.1) it is found graphically that 83% of the area may be filled with iron if three widths of strips are used. Assuming .9 of the core to be actually occupied by iron, the iron will have an area of about 75% of that of the circle.

Substituting in formula,

$$7000 \times 186 = \frac{156 \times 10^8}{120 \pi n}$$

$$n' = 32 \text{ turns}$$

$$n'' = \left(\frac{100000}{110} \right) n'$$

$$n'' = 29000 \text{ turns}$$

Amount of wire in primary:

$$\frac{32 \times 4 \times \pi \times 7}{12} = 234.7 \text{ ft.}$$

No. 7 B. & S. wire, (15.6 ft. = 1 pound)

16 pounds No. 7 wire

Cost at 24¢ (D.C.C.) ----- \$3.84

Amount of wire in secondary .

Because the spark gap of 100000 volts in oil is about .66 inches the inner edge of the secondary should not be closer than 1 inch to outer edge of the primary, thus necessitating an inside diameter of secondary of 9 1/2 inches. In designing the secondary it was found that if only two coils were used, the difference in potential between the successive layers was too great to be practically insulated against, and as 1500 volts was as large as could be safely insulated in one coil, it was decided to use 70 coils.

Using 70 coils:

$$\frac{n'' \times \text{diam. of wire}}{70 \times \text{no. wires to layer}} + 9 \frac{1}{2} = \text{mean diam.}$$

Mean diameter = 10.6 inches.

$$\frac{10.6 \times \pi \times 29000}{12} = 80480 \text{ ft.}$$

4.

1 lb. No. 30 B. & S. = 2530 ft.

80480 ft. = 32 pounds

32 lbs. at .79¢ ----- \$25.28

Size of Core.

Allowing space for proper insulation, the length of yoke = 21 inches and length of core = 16 inches.

$$2(16 \times 21) \times \frac{\pi (7)^2 \times .75}{4} = 2188.8 \text{ cu.in.}$$

2188.8 cu.in. = 1.28 cu. ft.

1.28 cu.ft. = 604 pounds.

Cost of sheet iron at 4cts per pound ----- \$24.16

Total cost raw material (7" core)

Iron ----- \$24.16

Primary wire ----- 3.85

Secondary wire ----- 25.28

Total ----- \$53.29

Likewise the costs of the material for cores of 4 1/2, 5 and 6 inches in diameter were figured, the results of which are shown in Table No.2.

It is seen, from this curve, that a 7-inch core cost slightly more than a 6-inch core, but taking into consideration the difference in the number of turns, since the work of winding the coils is a large factor, the 7-inch core is plainly the best adapted for this transformer. Taking the largest cross-section that could be obtained in a 7-inch circle, and yokes of the same cross-sectional area, see Cut No. 1, the bill of material was determined and is given in Table No.2.

DESIGN.

The greatest difficulty in design was the insulation, because the spark gap of 100000 volts in air is about $9 \frac{3}{4}$ inches and in the best insulating oil, about .66 inch. varying from $1\frac{1}{2}$ " to $3\frac{1}{4}$ " according to the temperature. Therefore the transformer was submerged in oil.

The type of core best adapted to our conditions was a core type of transformer. The four primary coils were wound in parallel, two on each core, and was insulated from the core by heavy duck cloth, well saturated with shellac. The 70 coils used for the secondary would require ⁷⁰415 turns per coil and if placed 6 turns to a layer would make a coil 1.1 inches deep and .125 inch thick. Since the greatest difference of potential between the core and either side of the secondary is 50000 volts, the inside diameter of the secondary was taken 2.25 inches greater than the outside diameter of the primary. To insure insulation and proper circulation between the coils an oil space of $1\frac{1}{8}$ inch was left between them. To support the coils 2 sheets of $1\frac{1}{16}$

inch veneering glued together cross-grained was used under each coil thus making the total space for one coil .375 inches, and the total height of the secondary 13.125 inches. Allowing for wooden supports at top and bottom, 16 inches was taken as length of core between the yokes.

Each terminal for the secondary was carried through three 15 inch porcelain tubes placed one in the inside of the other, leaving as the inside diameter of the tubes as .25 inches, and as the outside diameter, 2 inches.

The can or case to hold this transformer is to be made of sheet iron, 30 inches long, 15 inches wide with circular ends, which will hold the transformer and 32.25 gallons of oil. See Cut No. 1 and 2.

II. CONSTRUCTION.

Core:

The core was built up with rectangular strips of sheet iron of which five such strips formed each layer; each layer overlapping the other thus tying the joints. One half inch bolts, well insulated, fastened the corners together. The laminated iron was also painted to prevent eddy current losses.

Primary:

After placing the core together, strips of heavy duck cloth were used to bind the core and also to prevent cutting of the insulation of the primary windings. This duck was given a heavy coat of shellac thus forming a good body. The wire of the primary was then wound, as heretofore stated, and at the completion the winding of the primary,

the core and windings were given a heavy coat of P. and B. Compound. Finally the wire was securely tied so that it might remain securely held if the shellac and compound should be dissolved out by the oil.

Secondary:

To wind these coils cast iron plates were turned to make a form. These plates are shown by Cut No. 3. The plates were mounted on a motor driven lathe, to the headstock of which a speed indicator was attached to register the number of turns. A spring fastened rigidly to the lathe-bed pressed in the groove and pressed the wires into their positions as they came upon the coil. To hold the windings in place, until put on the wooden supports, the wire was passed through a bath of hot paraffine. After the paraffine congealed, the plates were then taken apart and the coil removed. The coils were then tested for open circuits. After testing the coils were laid upon their wooden supports, and secured in this position by heavy thread wrapped about the coil and wooden ring. See Cut No. 1.

The coils were then connected in series, the middle point of the secondary being grounded upon the core. To place the secondary coils on the core, the top yoke was removed and replaced when the secondary was put in position.

Calculation of Losses.

Hysteresis Loss.

$$W_h = aVfB^{1.6}$$

$$a \text{ as found by Mr. Hopkins} = .0118$$

$$V = \text{volume of iron in Cu.Cm.} = 37036$$

$$f = \text{frequency} = 60$$

$$B = \text{Magnetic intensity} = 7000$$

$$\text{Then for these values } W = 989 \text{ watts}$$

Eddy current loss.

$$W_e = b V f^2 L^2 B^2$$

$$b = \text{constant given by Franklin and Esty} = \frac{1.6}{(10)^2}$$

$$V = \text{volume of iron in Cu. Cm.} = 37036$$

$$f = \text{frequency} = 60$$

$$B = \text{Magnetic intensity} = 7000$$

$$L = \text{thickness of lamination} = .022$$

$$W_e = \text{Eddy current loss} = 43.7 \text{ watts}$$

Copper Loss

$$W_c = R(I')^2 + R''(I'')^2$$

Let (') and (") represent primary and secondary resp't/

Length of wire in secondary is 80490 ft.

Resistance of 1000 ft. of No.30 wire is 73 ohms.

$$\text{Hence } R'' = 5875.77 \text{ ohms}$$

$$I'' = .1 \text{ amp.}$$

$$R''(I'')^2 = 58.75 \text{ watts.}$$

Length of wire in primary is 60 ft.

Resistance of 1000 ft. of No.1 wire is .116 ohms.

$$R' = .00696 \text{ Res. of primary from tables.}$$

$$I' = 100 \text{ amperes}$$

$$\text{for full load } R'(I')^2 = 69.6 \text{ watts.}$$

$$W_c = 128.35 \text{ watts}$$

Total Loss.

$$W = W_h + W_e + W_c$$

$$W_h = 989.$$

$$W_e = 43.7$$

$$W_c = 128.3$$

$$\text{Total loss} = 1161. \text{ watts.}$$

TESTS.

After the primary was wound a test for core loss was made. The current electromotive force and watts were taken.

$$\text{E.M.F.} = 110$$

$$I = 13.85$$

$$\text{Watts} = 898$$

Magnetizing Current 5.04 amperes.

After the transformer was put together tests were made on primary and secondary for their resistances.

$$\text{Primary Res.} = .00696 \text{ ohms}$$

$$\text{Secondary Res.} = 8280 \text{ ohms}$$

The results of these tests were used in calculating the regulation instead of the previously calculated values.

Regulation.

Drop in E.M.F. due to primary resistances is

$$(R' I') \frac{N''}{N'}$$

$$= 683.7 \text{ volts.}$$

Drop in E.M.F. due to secondary resistance is

$$R'' I''$$

$$= 587.6 \text{ volts}$$

Total drop in E.M.F. due to Res. of Copper = 1220.3

Loss in voltage due to leakage reactance.

P = inductance in henry's

n = number of turns

K = mean circumference of coils

l = length of coils

x = thickness of primary windings.

y = " " Secondary " .

10.

g = air-gap between primary and secondary

All linear dimensions in Cm.

$$P = \frac{\pi n^2 K}{1 \times 10^9} \left(\frac{x}{3} + \frac{y}{3} + g \right)$$

Leakage due to primary:

$$n' = 32 \text{ turns}$$

$$K = 24 \text{ cm.}$$

$$l = 17$$

$$x = .82$$

$$y = 4.1$$

$$g = 3.4$$

$$P = .0002228 \text{ henrys}$$

$$wPI = 7.52 \text{ volts drop in primary}$$

$$7.52 \times \frac{n''}{n'} = 6835.7 \text{ volts drop in secondary.}$$

Leakage around secondary;

$$P = \frac{\pi n^2 K}{1 \times 10^9} \left(\frac{x}{3} + \frac{y}{3} + g \right)$$

$$n = 29000$$

other values the same as above.

$$P = 18.77 \text{ henrys}$$

$$wPI = 705.75 \text{ volts drop due to leakage around secondary.}$$

Total drop due to leakage inductance:

$$6835.7 + 705.7 = 7601.4 \text{ volts.}$$

$$\text{External E.M.F. of secondary } E_T^2 = (E_X \cos \theta + RI)^2 + (E_X \sin \theta + wPI)^2$$

$$\cos \theta = 1$$

$$E_T = 100000$$

$$E_X = 98591 \text{ volts}$$

555
2
1110

11007

II.

TABLE NO. I.

Magnetic properties of Iron

H	B
6.82	7000
5.98	7000
4.92	7000
3.80	6800
2.81	6400
1.50	5700
0.00	4300
1.5	2000
2.81	0000
3.81	2900
4.88	4700
5.95	6100
6.82	6900
5.95	6900
5.86	6900
3.82	6400
2.81	6200
1.50	5300
0.	4300
1.5	1500
2.82	1900
3.81	4000
4.88	5500
5.91	6600
6.80	7000

TABLE NO.2.

<i>Diam Core</i>	<i>Cost Primary Wire</i>	<i>Cost Secondary Wire</i>	<i>Cost Iron</i>	<i>Total Cost</i>
4 1/2	11.50	64.75	9.00	85.25
5	5.52	51.35	13.00	69.87
6	4.56	31.97	16.20	52.73
7	3.85	25.28	24.20	53.33

See pages 3-4

#7 D.C.C. wire is assumed to cost 24 cts per lb.

#30 D.C.C. wire is assumed to cost 79 cts. per lb.

Sheet steel of this quality is assumed to cost
4¢ per lb.

TABLE NO. 3.

We for I' Amperes in Primary						
Formula We $R(I')^2 + R''[(I' - 13.75)\frac{N'}{N}]^2$						
Core loss			13.75 Amperes			
%load	$R(I')^2$	$R(I'')^2$	W_c	I'	I''	Total Loss in Watts
0	0	0	0	0	0	895
4.8	2.78	.19	2.97	20	.0048	895.97
24.8	11.14	5.05	16.19	40	.0148	901.19
94.8	25.06	16.61	41.67	60	.0448	936.67
64.8	44.54	34.77	79.31	80	.0648	974.31
84.8	69.6	59.62	129.22	100	.0848	1024.22
104.8	100.22	91.08	191.30	120	.1048	1086.3
124.8	136.41	129.17	265.58	140	.1248	1160.58
144.8	178.17	173.88	342.00	160	.1448	1237.00

TABLE NO.4.

Transformer Regulation:

Total drop in secondary E.M.F. due to resistance of

$$\text{wire} = (RI') \frac{n''}{n'} + R''I''$$

Total drop in secondary E.M.F. due to leakage induct-

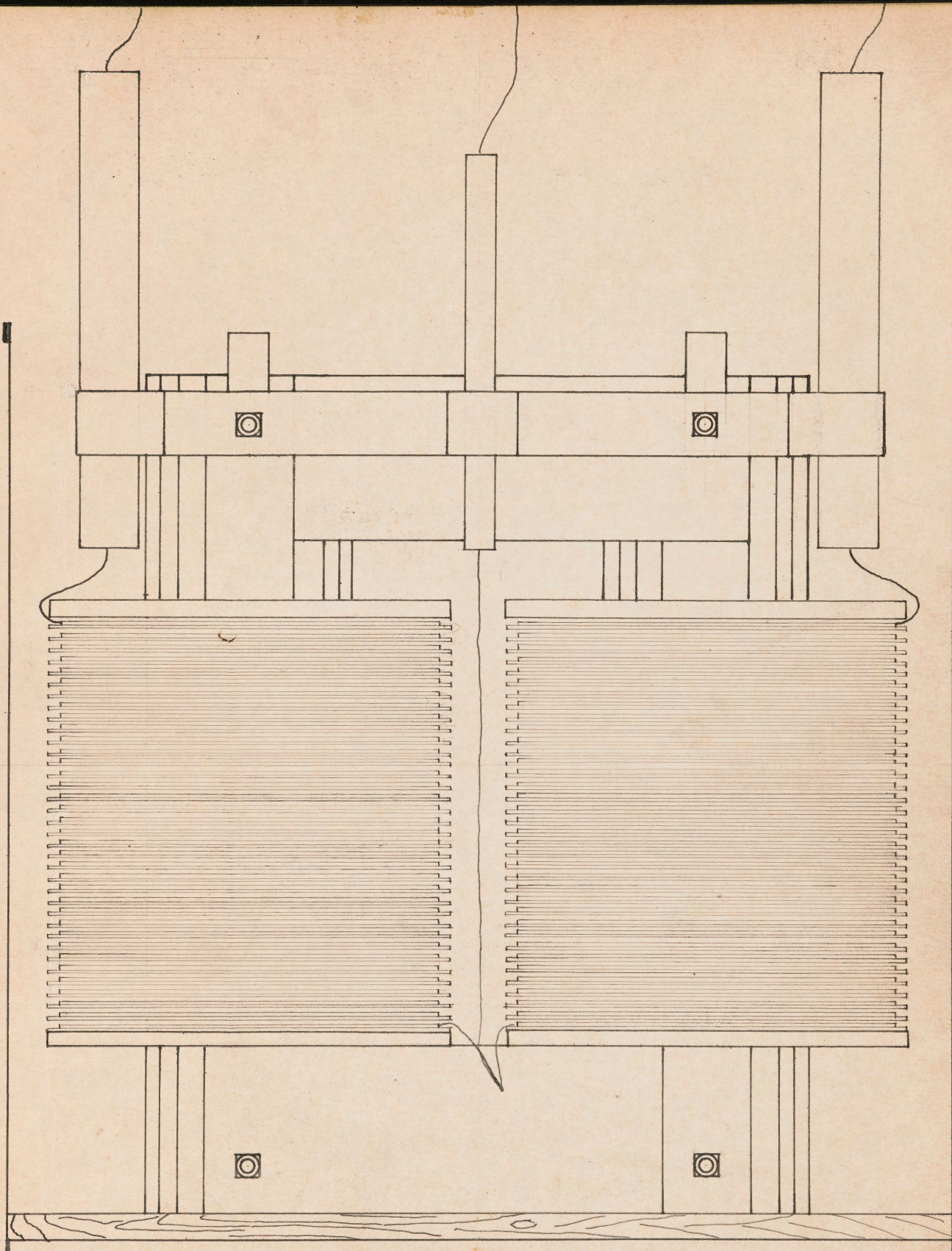
$$\text{ance} = (WPI') \frac{n''}{n'} + WPI'$$

$$E_{\text{Total}} = (E_{\text{ex}} \cos \theta + RI')^2 + (E_{\text{ex}} \sin \theta + XI')^2$$

$$E_{\text{total}} - E_{\text{ex}} = E_{\text{drop}}$$

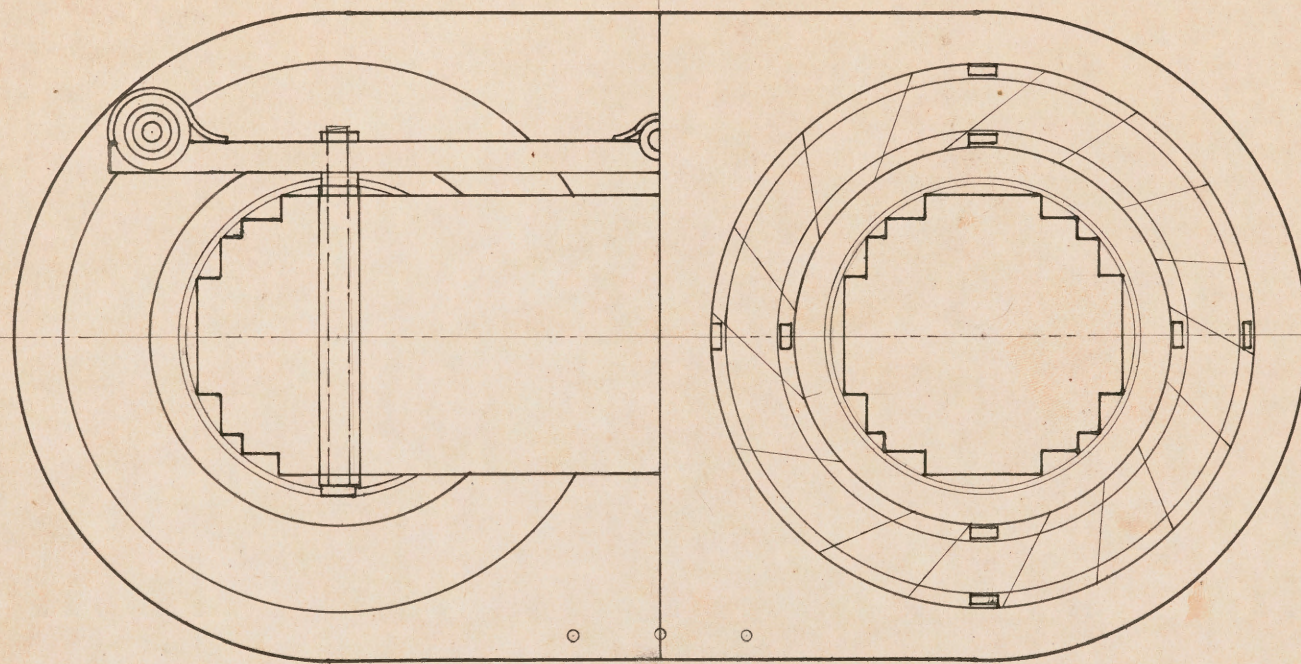
$$\text{Regulation} = \frac{E_{\text{drop}}}{E_{\text{ex}}}$$

<i>% Load</i>	<i>RI in</i>	<i>WPI</i>	<i>E_x</i>	<i>E_{drop}</i>	<i>% Regulation</i>
<i>Secondary Terms</i>					
0	0	0	100000	0	0
4.8	169	1400	99824	176	.18
24.8	359	2902	99630	370	.37
44.8	696	4407	99207	793	.80
64.8	963	5911	98837	1163	1.18
84.8	1231	6416	98564	1436	1.46
104.8	1498	8920	98102	1898	2.03
124.8	1866	10525	97577	2423	2.48
144.8	2034	11930	97366	2634	2.70



1/4 Scale

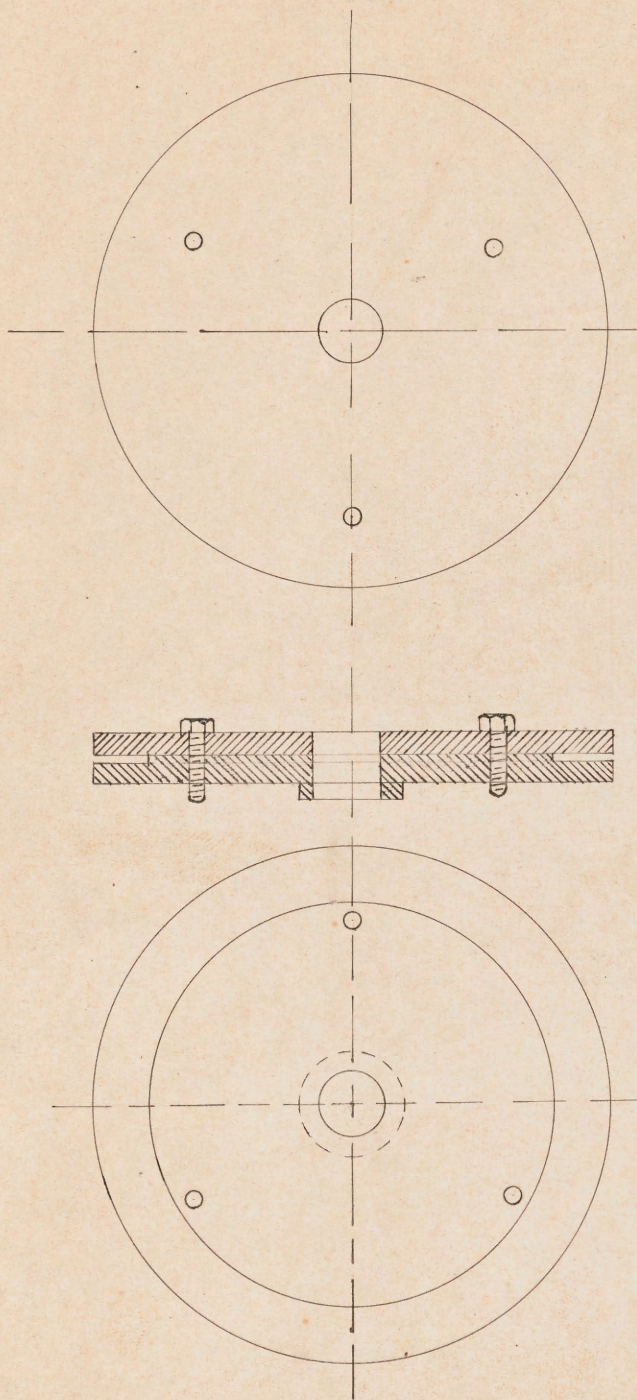
Cut No 2.



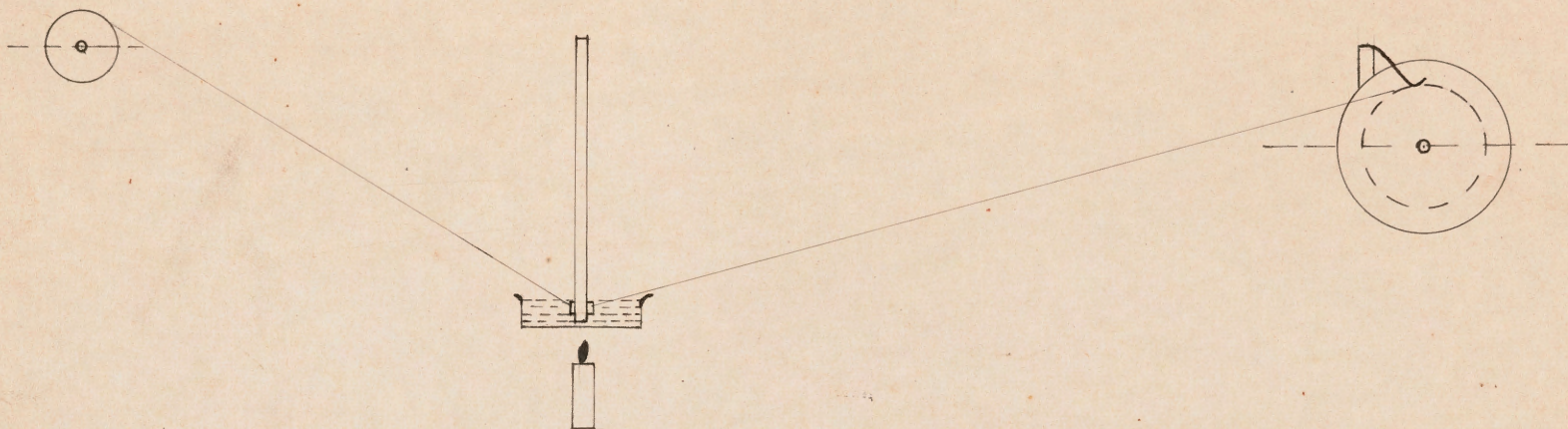
1/4 Scale

Cut No 1

Cut No 3



Winding Plates.
 $\frac{1}{4}$ Scale

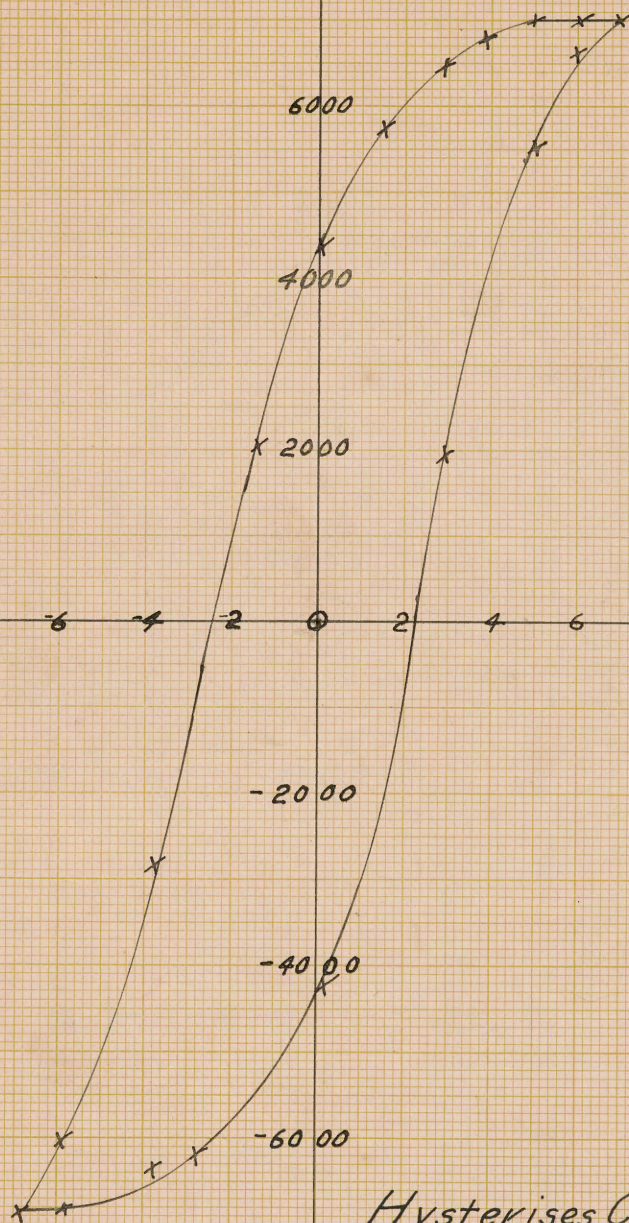


Cut No 4.

Winding Device.

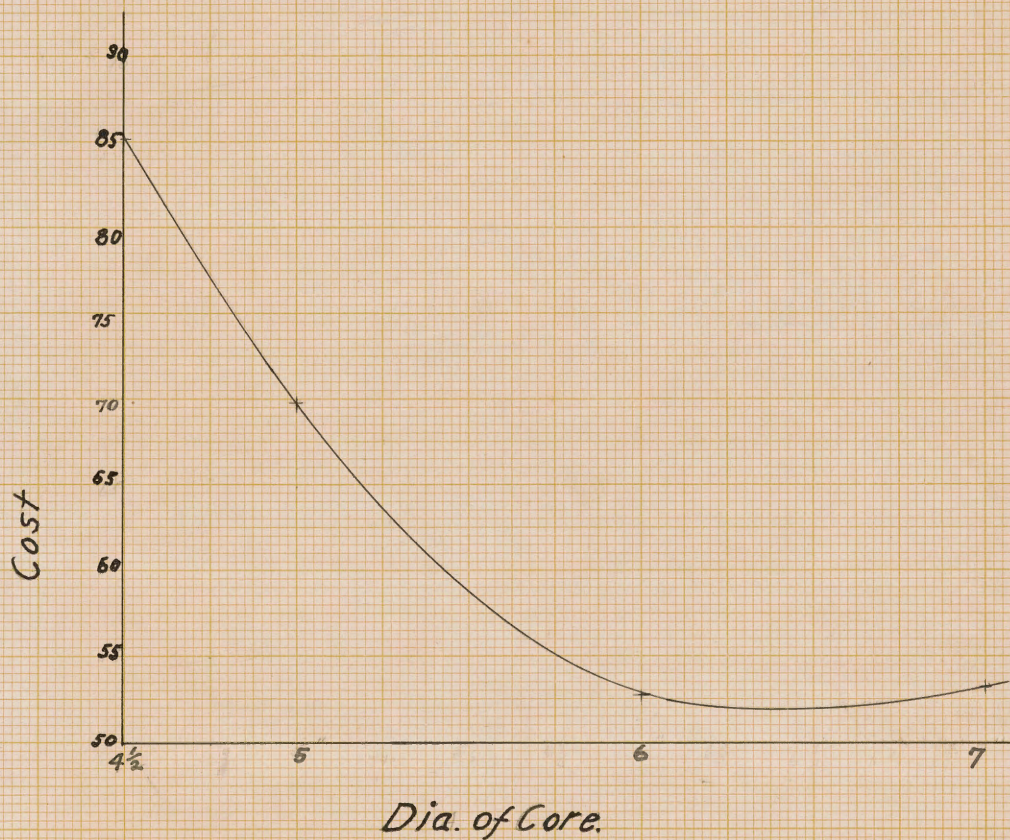
No 1

B



Hysteresis Curve
of Core Iron

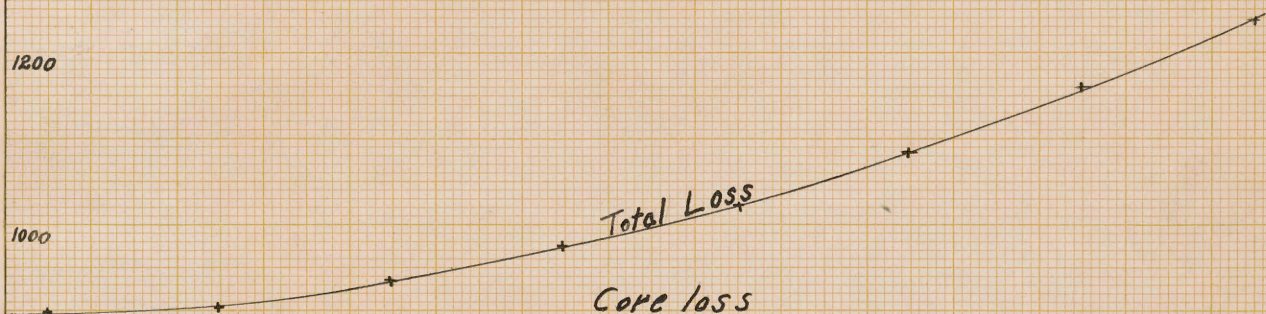
No 2



Cost of a 10 K.W.

110/100000 Volt Transformer.

No 3



Losses of a 10 K.W

110/100000 Volt Transformer.

