Thesis

The Design of a High Tension Testing Transformer

by

Albert W. Wells

Class of Nineteen Hundred and Fourteen

Department of Electrical Engineering

Throop College of Technology

Pasadena, Cal

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The Design of a 250,000 Volt Testing Transformer.

The transformer, the design of which is given in this thesis, is a transformer for experimental work and high voltage testing such as would naturally come under the work and direction of the Electrical Engineering Laboratories of a College of Technology. The design calls for a transformer of one hundred kilowatts capacity and a maximum potential of two hundred fifty thousand volts with one end of the high voltage winding grounded. Two such transformers, operated in series by connecting their grounded sides together would give a maximum potential of half a million volts between their ungrounded terminals, with only 250,000 volt potential strains to ground or neutral.

Voltage control will be obtained by varying the low tension voltage, except for the lower voltages around one-half and one-fourth of the normal. These reduced voltages will be obtained by changing the connections of the low tension winding, which will be in four parts, from multiple, to series-multiple, and series.

Following the general tendencies of design in transformers of this character, it is of the core type, with half of the windings on each leg of the core, and the condenser principle is utilized in all the high tension insulation. The design given was taken from three comparative designs which were started to determine the ratio of voltage to turns of wire which would give a transformer of lowest first cost for materials. Using .090 by .110 inch rectangular copper wire for the low tension winding, No. 26 B and S gage for the high tension winding, and high grade transformer steel for the core, the most economical design called for about six volts per turn of wire. Six and one-quarter was chosen as this allows the use of simple constants in changing the readings of commercial meters to the actual values of voltage and kilowatts developed by the transformer, the meters being connected to special terminals which will be brought out for that purpose. These terminals are such that the maximum voltage on the meters and to ground will be limited to two hundred, thus allowing for the protection of the instruments, and the operator from the high voltages when measurements are being taken.

The Core

The volts per turn having been determined, and the maximum flux density limited arbitrarily to 70,000 lines per square inch, which is known to be a safe value, the cross section of iron required was calculated, using the formula $e = \frac{4.44 \phi f}{10^8}$ in which e is the volts per turn, ϕ the total flux, and f the frequency in cycles per second.

Transposing $\phi = \frac{e \times 10^8}{4.44 f} = \frac{625 \times 10^8}{4.44 \times 50} = 2,820,000$ lines. Dividing 2,820,000 by 70,000 gives the necessary cross section of iron to be 40 square inches. This is the net area. Allowing a space factor for stacking of the laminations of 0.9, the gross area required is 44.5 sq. in. Making the core square, with each side measuring 6.75 inches, the cross section becomes 45.56 sq. in., which is on the safe side as it allows a slight reduction in the flux density. The window opening of the core will have a vertical height of 3 ft. 8.75 in. and a horizontal width of 3 ft. 1.75 inches. Expressed in inches these dimensions are respectively 44.75 and 37.75 inches. The mean length of magnetic circuit will, therefore, be 187.2 inches, or 475 cm. With the joints in the core arranged as shown in drawing No.3, the lengths of the individual punchings will be 4 ft. 3.5 in. and 3 ft. 8.5 inches. The sum of these two lengths is 8 ft. which is the length of stock sheets of this steel. The standard widths of the stock are 24 and 30 in. and unless special widths may be obtained at a reasonable price at the time when this transformer is built, the more economical method would be to use the 30 in. material and cut 4 short and 4 long punchings from each sheet, wasting only the three inch strip.

Basing calculations on data furnished by The American Sheet and Tin Place Company for their Apollo Special Electrical Steel, the weight of the laminated core will be

1725 lbs., and with a flux density of 70,000 lines per sq. in. the core loss will be 0.9 watts per pound or a total of 1550 watts. Counting all four sides of the core as being radiating surfaces, the radiation of heat from core to oil will be about 0.31 watts per sq. in. of surface. No. 29 gage or 14 mil iron will be used.

The core will be rigidly clamped together by means of bolts and clamps. Three-quarter inch bolts will be used for this, and they will be spaced as shown on drawings No. 2 and 3. All bolts on the core structure are to be insulated from the core by horn fibre tubes. The bolts which pass thru the legs of the core will have plates made of 4 in. lengths of $\frac{1}{4}$in. by 2 in. strap iron under their heads and nuts. These plates will be insulated from the core by means of horn fibre. The yokes will be held between 6 in. channels, with insulated bolts passing through the channels and yokes. The lower yoke clamp will also serve as a footing for the entire internal structure, as support for the external barrier, and as guides when the transformer is placed in, or removed from, its tank. The upper yoke clamp will carry the upper barrier braces, the coil steadying clamps, and the lifting eyes. The details of the footing are shown in drawing No. 3, as are also the lifting eyes. The coil clamps are shown in detail in drawing No. 4.

Low Tension Winding

The low tension or 2300 volt windings will be wound directly on the legs of the core. The winding is to be in four separate sections or coils, two wound on each leg, and all eight leads will be brought out so that the four coils may be operated in multiple, series-multiple, or series. The normal full voltage condition is to operate the four coils in multiple on 2300 volt mains. The other connections, with the same low tension voltage, give high tension voltages of 125,000 and 62,500 respectively.

Altho the core on which the low tension coils are wound is rectangular, the coils themselves are to be cylindrical in form, with an internal diameter one-half inch greater than the diagonal of the core. This internal diameter will be ten inches. Wooden strips spaced around the core, with oil ducts between them will form an approximately cylindrical surface on which to form the low tension coils. Each of the four coils will consist of 368 turns of 0.95 by .110 in. rectangular double cotton covered wire wound on edge, and should occupy not more than 41 inches of the available window opening of 44.75 inches. Beginning at the wooden forming strips which form a cylindrical surface ten inches in diameter, the low tension winding will be built up of the following materials in the order mentioned:

2 layers of 1/16 inch pressboard, 2 layers of 10 mil

varnished cambric, the first low tension coil, 1 layer of cambric, 2 layers of 1/16 inch pressboard, 1 layer of cambric, the second low tension coil, 1 layer of cambric, and finished with 2 layers of 1/2 lap cotton tape. The entire low tension windings and its insulation should not exceed 0.7 in. in thickness, and the insulation cylinders as wound in place will be 43 inches long.

With this construction the mean length of turn of the inner coils will be 29.87 in. and of the outer coils 31.57 inches. The average of these is 30.72 in. which gives a total length of wire in the 4 x 368 turns of 45,220 inches or 3770 feet. At 40.3 lb. per 1000 feet the copper will weigh 136 lb. The resistance, at 0.7964 ohms per 1000 ft. will be 3.002 ohms with the coils connected in series. The effective resistance for the series-multiple connection will be 0.75 ohms, and for the multiple connection 0.19 ohms. With a low tension current of 50 amperes, which is about normal full load current, the current in each of the four coils will be 12.5 amperes. The R I drop per coil will be 0.75 x 12.5 = 9.38 volts, which is 0.408% of 2300, and the R I^2 loss will be 0.75 x 12.5^2 = 117.5 watts per coil, and for the four coils 470 watts. For the radiation of this loss there will be available 5780 sq. in. of surface. This gives the low value of 0.0815 watts per square inch of radiating surface.

High Tension Winding

The high tension winding will be much more complex in its winding and insulation than the low tension coils. The entire winding will be of No. 26 B and S gage double cotton covered wire. 40,000 turns of wire will be required. The winding will be subdivided into 56 separate, flat, form-wound coils, which will be wound separately and assembled later. There will be three classes of coils, all the coils of each class being similar as regards insulation, number of turns per layer, and number of layers of wire, but will have different diameters. This variance of diameter is to save material in those coils which are around the smaller parts of the insulation between the high and low tension windings. Drawing No. 1 shows the different diameters of the coils and their relative positions, also their sequence of connection. Drawing No. 6 shows by means of a table the different dimensions of the individual coils.

The first class of coils will be four in number and will be the first four of the entire series, beginning at the high tension terminal. Altho these coils will be 7.15% of the number of coils, they will contain but 1.3% of the total turns, because they will have to stand the highest potential strains and the surges. The next twelve coils in the series will be second class coils and will contain 8.7% of the turns, and the remaining 40 coils will be third class coils and contain 90% of the turns. The foundation of each coil will be a ring of pressboard one-quarter of an inch thick and of a width equal to the width of the coils before taping. See table on Drawing 6. The internal diameter of this ring is the internal diameter of the coils. The insulation between layers will in all cases be one thickness of 15 and one of 10 mil paper, with whatever else is called for, depending on the class of coil. This 10 mil paper is to be cut three-quarters of an inch wider than required and the edges folded over as shown in drawing No. 6. The edges will thus be 40 mils thick and form between them a channel 30 mils deep in which to lay the wire. The 15 mil paper will not be folded.

The first class of coils will be very heavily insulated. They will have two turns of wire per layer and only 65 layers. The total turns will thus be 130, which at 6.25 volts per turn gives 812.5 volts per coil. The wire will be reemforced on both sides with 2 strands of four cord machine thread, which, as shown in the Westinghouse catalogue, section 804, has a diameter nearly equal to that of the double cotton covered wire used. Varnished cambric will be placed around the turns of the layers as shown on drawing No. 6.

The second class coils will not be as heavily insulated as the first class. Altho the voltage per coil is more the strain to ground and the surges will be less. These coils will have four turns of wire per layer, and 73 layers, which gives a total voltage per coil of 1825. Each turn of wire is reenforced with one strand of the same kind of thread used in the first class coils. Varnished cambric is placed over and under adjacent turns of wire and thread, as shown in drawing No. 6.

The third class coils will be wound entirely without cambric or thread. There will be ten turns of wire per layer and ninety layers, thus giving 900 turns per coil. The voltage per coil will be 5625. Aside from the stepped diameters the entire 40 of these coils will be similar, except the last one, No. 56. This is the coil, one terminal of which is grounded, and it differs from the others in that all the taps for the measuring instruments will be brought out from it. At a point 8 turns from the terminal lead the winding will be stopped, and tap No. 1 brought out. The winding will commence again at this same point, starting from tap No. 2, and be continued for 8 more turns where tap No. 3 will be brought out without interrupting the continuity of the wire. At a point 16 turns from tap No. 3, the fourth and last tap will be brought out. The scheme of these taps, and their location relative to the ground terminal is shown on drawing No. 5. Taps 1 and 2 make a break in the winding in which to insert an ammeter or the current coils of a wattmeter. The potential coils of a wattmeter would be connected from ground (the tank of the transformer) to taps 1 and 2, 3 or 4. With full voltage on the high tension winding, the voltage from ground, to taps 1 and 2, will be 50; to tap 3, 100; and to tap 4, 200. After the coils are wound they will be taped with one layer of cotton tape, with a minimum lap of one half, and thoroughly varnished. When the coils are stacked on the core during the assembling process they are to be separated, each by twelve wooden strips one inch wide, and of such thickness as to make the distance between centers of adjacent coils 1.5 inches. The bottom coil will be supported on blocks which will raise it 2 inches from the bottom yoke, and level it as well. Blocks will also be placed on top of each stack of coils and the coils held in place by the screws which pass thru the brackets on the upper yoke clamp and bear against these blocks. These supporting brackets are shown in detail in drawing No. 4.

The amount of wire required for the high tension windings will be about 334,000 feet. As this weighs 0.77 lbs. per 1000 ft, the total weight will be 257 lbs. The resistance at 40.84 ohms per 1000 feet would be 13,640 ohms. Basing all calculations at 0.5 ampere, which is 25% overload, the R I drop will be 6820 volts, which is 2.73% of 250,000. The $R I^2$ loss will be 3410 watts. With a total radiating surface on the 56 coils of 57,800 sq. in., the radiation per square inch will be, on an average, 0.059 watts.

But as 90% of the total loss is in 40 of the coils, the radiation on these coils will be 0.074, which is very low for a transformer for such intermittent use as one of this character has. At normal load the radiation would be only 0.0475 watts per sq. in. at a maximum. About 43,000 feet of the ten and fifteen mil folded strip will be required to build up the high voltage coils.

Insulation between high and low tension windings.

The high and low tension windings will be separated by two built up bushings, one surrounding each leg of the transformer. These bushings will consist of a series of concentric cylinders, separated by oil spaces. The cylinders will be held in place by spacing strips placed in the oil ducts. Shellac will be the material used to bind the bushings into one solid mass. The first or inner cylinder will be of solid bakelite micarta construction, with an internal diameter of twelve inches, a length of 3 ft. 6 in. and a thickness of 0.75 inches. The remaining cylinders will be of three thicknesses of .056 inch fullerboard, securely held together with shellac, and having the joints broken so as to avoid weak spots. On the outside of each cylinder, except the outside one, will be placedtwelve spacing strips one inch wide, with a length equal to the next cylinder to be wound, each composed of one thickness of .125 inch and two of .030 inch fullerboard. Successive rows of these strips will not be staggered, but will extend radially like the spokes of a wheel, so as to form an inflexible bushing support. The arrangement of these strips is shown in drawing No. 9. This construction will give each cylinder a thickness of 0.168 inch, and each oil duct a radial dimension of 0.185 inch.

The bushings will be stepped as shown in drawing No. 8. Each step will have a radial dimension of 0.706 in., this being the thickness of two fullerboard cylinders and two oil ducts. The other dimension will be equal to the distance between centers of the high tension coils, i.e., one and one-half inches, thus making any pair of cylinders three inches shorter than the next inner pair. At each step will be a band of tin foil one inch wide, extending around the cylinder and placed so as to leave 1.5 inches between the edge of the foil and the end of the cylinder. This will bring the two bands on any cylinder immediately under the edges of the next cylinder. The pair of bands on each cylinder will be connected electrically with a half-inch strip of ten mil copper. Each band will be connected to the inner terminal of high tension coil in whose plane it lies. The bands will thus serve to distribute the potential strains over the surface of the bushing, and, with their connecting wires, to connect the high tension coils in their proper sequence.

Each bushing will be supported on a wooden ring formed of one inch material. The internal and external diameter will be respectively 12 and 16 inches. These rings will be supported on blocks which will rest on the yoke and its clamps. Similar rings at the top, with blocking between them and barrier braces, will steady the bushings and keep them in place. To wind up the bushings about 75 sheets of fuller board, measuring 40 x 42 inches will be required. As these weigh 3.6 lbs. per sheet, the total weight will be 270 lbs. Including the spacing strips and micarta foundation, each bushing will weigh about 150 lbs. and cost for material at 17 cents per pound, about twenty-five dollars, exclusive of the inner micarta cylinder.

The External Barrier.

Surrounding the high tension coils and between them and the tank will be the external barrier. This will consist of layers of press-board separated by oil spaces. The structure will be carried on a wooden framework or support which will be secured to the core footing at the bottom and braced to the upper core clamps at the top. The details of this supporting frame are shown in drawing No. 10. The barrier will be stepped similar to the bushings, each step measuring one-half by one and one-half inches. Each layer of press-board will be composed of two thicknesses of one-eighth inch press-board, and the layers will be separated by one-fourth inch oil spaces, wooden strips placed about

12 inches apart, 1 x $\frac{1}{4}$ inches, being used as spacers. The narrowest layer will be twelve inches wide, and each following one three inches wider. There will be twelve layers of press-board in the barrier, thus giving three inches of solid material between the windings and tank. To this will be added seven inches of oil, one inch of which will be outside the barrier, two and three-quarters inches between the press-board layers, and the rest inside the barrier. As shown on the drawings the barrier will be 3 ft. 9 inches high. To construct this barrier about 160 sq. yds of one-eighth inch press-board will be required. The weight of this will be about 1200 lbs. and at 16 cents a pound will cost, for the material alone, about 190 dollars.

The Terminal Bushing.

As the transformer is to operate with one side grounded, only one high tension lead will be required. This will be of the condenser type. It will be built up solid of bakelite micarta with the layers of tin foil to distribute the potential strains worked in according to modern practice. The center of the bushing will be a 3/8 inch brass tube through which the terminal lead will pass, the connection being at the top, so as to avoid making it inaccessible underneath the oil. Potential strains and corona will be relieved at the ends of the bushing by means of a three inch diameter brass ball at the lower end and a big disk of tin foil covering a light wooden framework at the top. This disk will be four feet in diameter and six inches thick. The total length of the terminal will be nine feet. A cast iron ring around the largest diameter section will support it in the transformer cover. Drawing No. 12 is an outline drawing of the bushing. The Electric Journal for August, 1913, contains a full description of condenser terminals, and the methods used in their construction. The dimensions are given on drawing No. 12, and the building instructions will be taken from the Electric Journal mentioned.

The Tank and Cover.

The tank which is shown in outline in drawing No. 13 will be built of 3/8 inch boiler plate, sides and bottom. The inside dimensions of the tank will be:

Length -	9 ft.	1 in.
Width -	5 "	3 "
Height -	6 "	0 "

A thermometer will be fitted, also an oil gage, and a 3 in. globe valve for the removal of the oil. As this tank is to be purchased in the open market the details of construction and reenforcement will be left to the manufacturers. An angle iron around the top will be desired to carry the cover.

The cover of the tank will be of boiler plate the same as the tank, reenforced on the under side to prevent sagging. Lifting eyes will be inserted for convenience in handling.

Openings will be cut in the cover as follows: a hand hole for reaching the low tension terminal board, an opening for the terminal block for the low tension leads, an opening for the high tension bushing, and a small opening for a terminal block for the meter connection to the high tension winding. All these openings are to be closed tight to keep out dust and moisture. Drawing No. 14 shows the cover in outline.

The Terminal Blocks.

Terminal blocks of fibre will fill those openings in the cover through which the leads are brought. For the low tension leads No. 6 stranded, cambric covered cable will be used, and for the high tension meter connections, braided wire, such as is used for pigtails on brushes will be used. This same kind of braided wire will be used to connect the high tension coils together and to the ground connection on the core, also, to connect the ground terminal of the core to the tank cover. These will be run in cotton sleeving. Binding posts, numbered from 1 to 4 and connected to the taps of the same numbers in the high tension coil will be mounted on the little high tension block. Under posts 1 and 2 will be flat springs which will press against each other. These springs, at their point of contact, will be separated by a piece of paper which will puncture at 500 volts or less. The purpose of this is to automatically ground the end of the winding if for any reason the meter circuit should become opened.

A cylinder or drum switch, the plan of which is shown in drawing No. 5, will serve to change the connections of the low tension coils.

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The principal technical articles read and used in the preparation of this thesis are:

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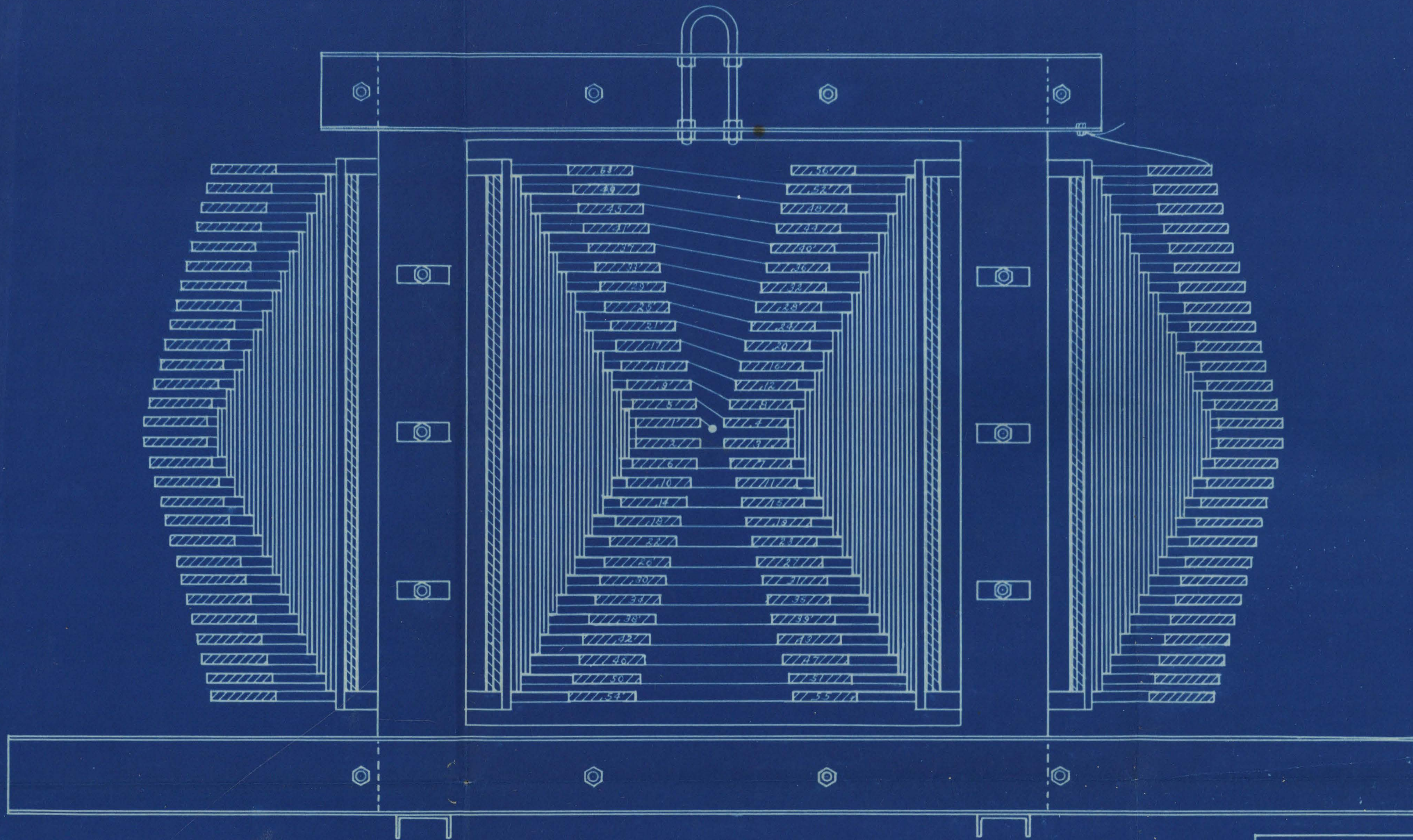
The Condenser Type of Outlet Terminal, Theory of Design, by C. Fortescue.

Construction and Application, by J. E. Mateer, in the Electric Journal for August, 1913.

TRANSFORMER CALCULATIONS.

CORE.			LOSSES.	
Net Weight and Quality of Iron.	1725 lb.	.014" Special	I^2R H.T.	3410
Size of Leg and Winding Space.	$6\frac{3}{4}$" x $6\frac{3}{4}$"	$37\frac{3}{4}$" x $44\frac{3}{4}$"	I^2R L.T.	470
Sq. In. Net C.S. and Total Flux Mgl.	40 Sq. In	2.82	Core Loss.	1550
Density and Loss per Lb.	70,000	0.9	Total Loss.	5430
WINDINGS.			**RADIATION CONSTANTS.**	
	Low tension.	High tension.		
Volts	2300	250,000	Sq. In. H.T. Coils	57800
Amperes	45	0.4	Sq. In. L.T. Coils	5780
Total turns.	1472	40,000,	Sq. In. Core	4800
No. of Coils	4	56	Sq. In Tank	17160
Turns per Coil.	368	130 - 292 - 900	Watts/Sq. In HT	0.059
Taps	——	See Spec.	Watts/Sq In LT	0.0815
Conductor	.090 x .110	No. 26, B&S.	Watts/Sq. In Core	0.31
Sq. In. C.S.	0.0099	0.0002	Watts/Sq. In. Tank	0.317
Amps per Sq. In.	1240	2000		
Lb. Cond.	150	260		
Length of turn.	2.56	8.75		
Total Length	3770	350,000	**COSTS.**	
Resistance.	3.0-0.75-0.19	13,600	Lb. Copper	410
RI drop, Volts	9.38	5,540	Lb. Iron	1725
RI drop, %	0.408	2.18	Cost Copper 0.22	90.20
Volts per turn	6.25	6.25	Cost Iron 0.07	120.75
Volts between layers	1150	12.5-25-62.5	Total Cost.	210.95
Volts between coils	——	22,500.		

A.W. WELLS.



TESTING TRANSFORMER

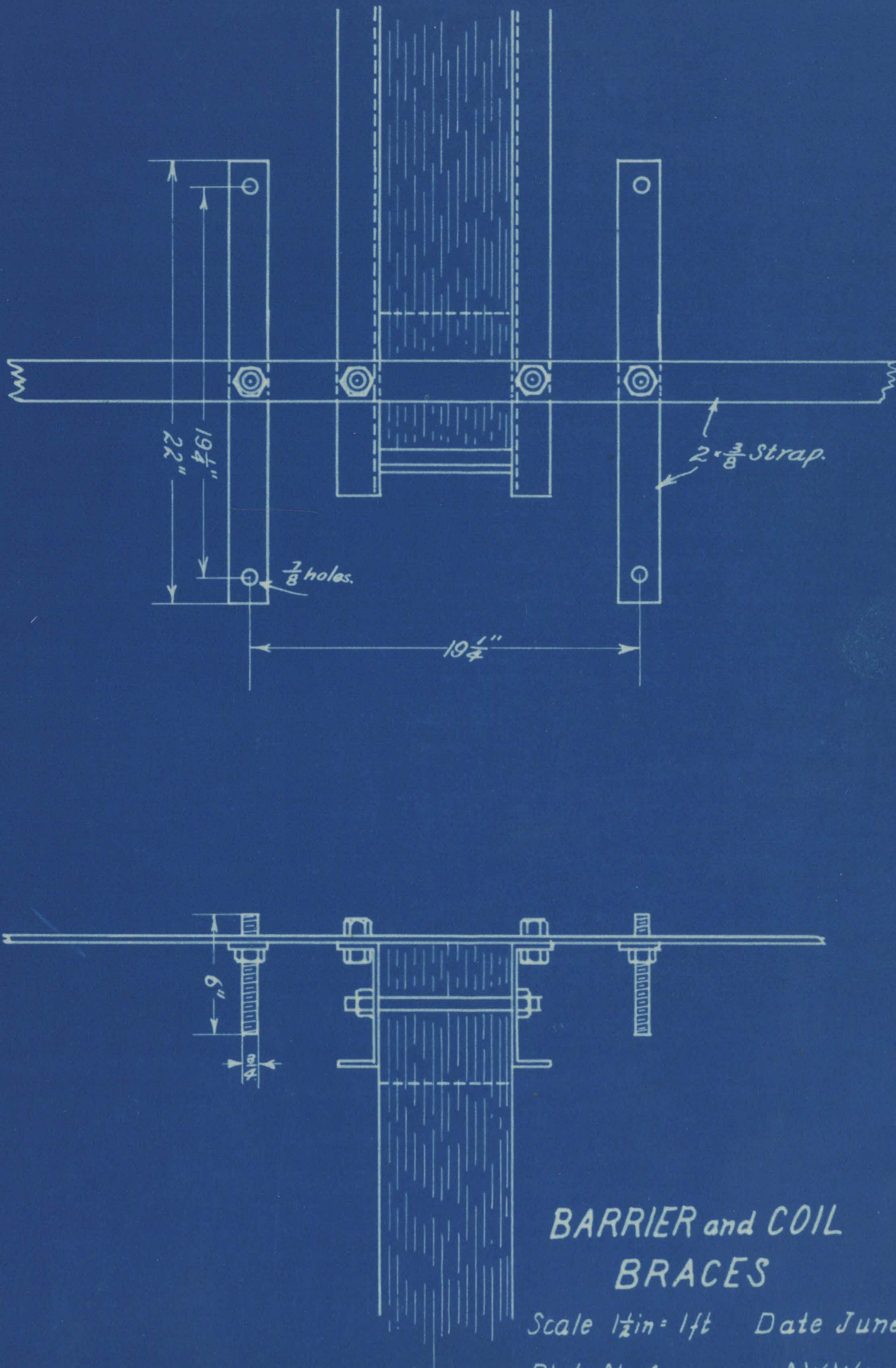
ASSEMBLY

THROOP COLLEGE of TECHNOLOGY

Pasadena California.

Scale 1½ in. = 1 ft   Date June 1914

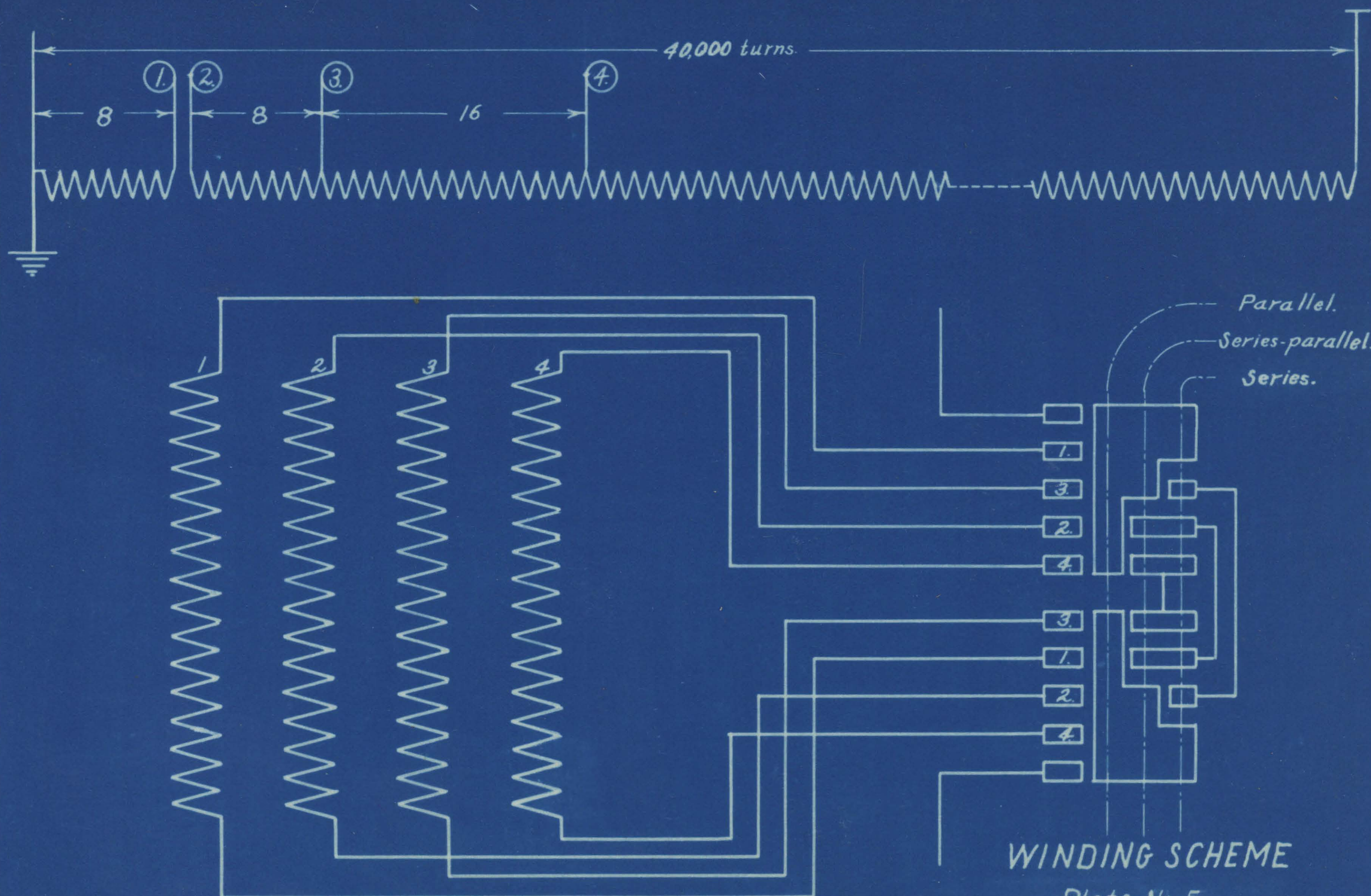
Plate No. 1   Drawn by A.W. WELLS.



BARRIER and COIL BRACES

Scale 1½ in = 1 ft Date June 1914

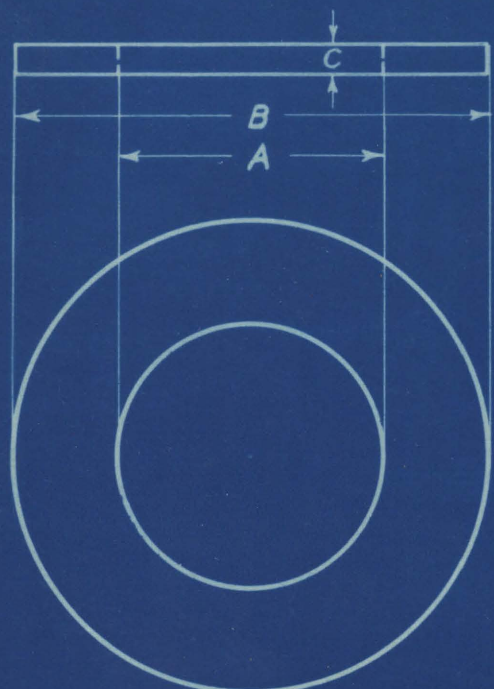
Plate No. 4. A.W. Wells.



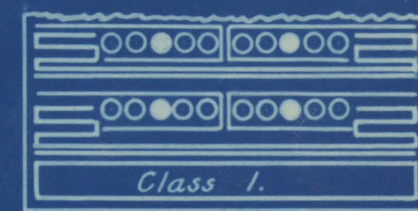
WINDING SCHEME

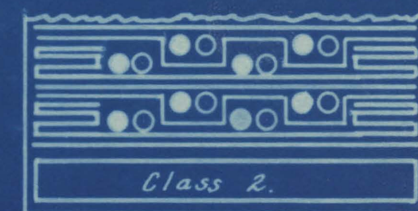
Plate No. 5.

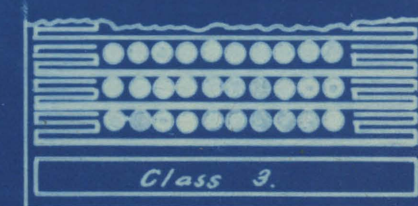
June 1914. A. W. WELLS.



Coil Dimensions.			
Coils.	A	B	C
1 to 4	33.0	43.0	0.72
5 " 8	32.2	42.2	"
9 " 12	31.5	41.5	"
13 " 16	30.7	40.7	"
17 " 20	29.9	39.9	"
21 " 24	29.2	39.2	"
25 " 28	28.4	38.4	"
29 " 32	27.6	37.6	"
33 " 36	26.8	36.8	"
37 " 40	26.1	36.1	"
41 " 44	25.3	35.3	"
45 " 48	24.5	34.5	"
49 " 52	23.8	33.8	"
53 " 56.	23.0	33.0	"



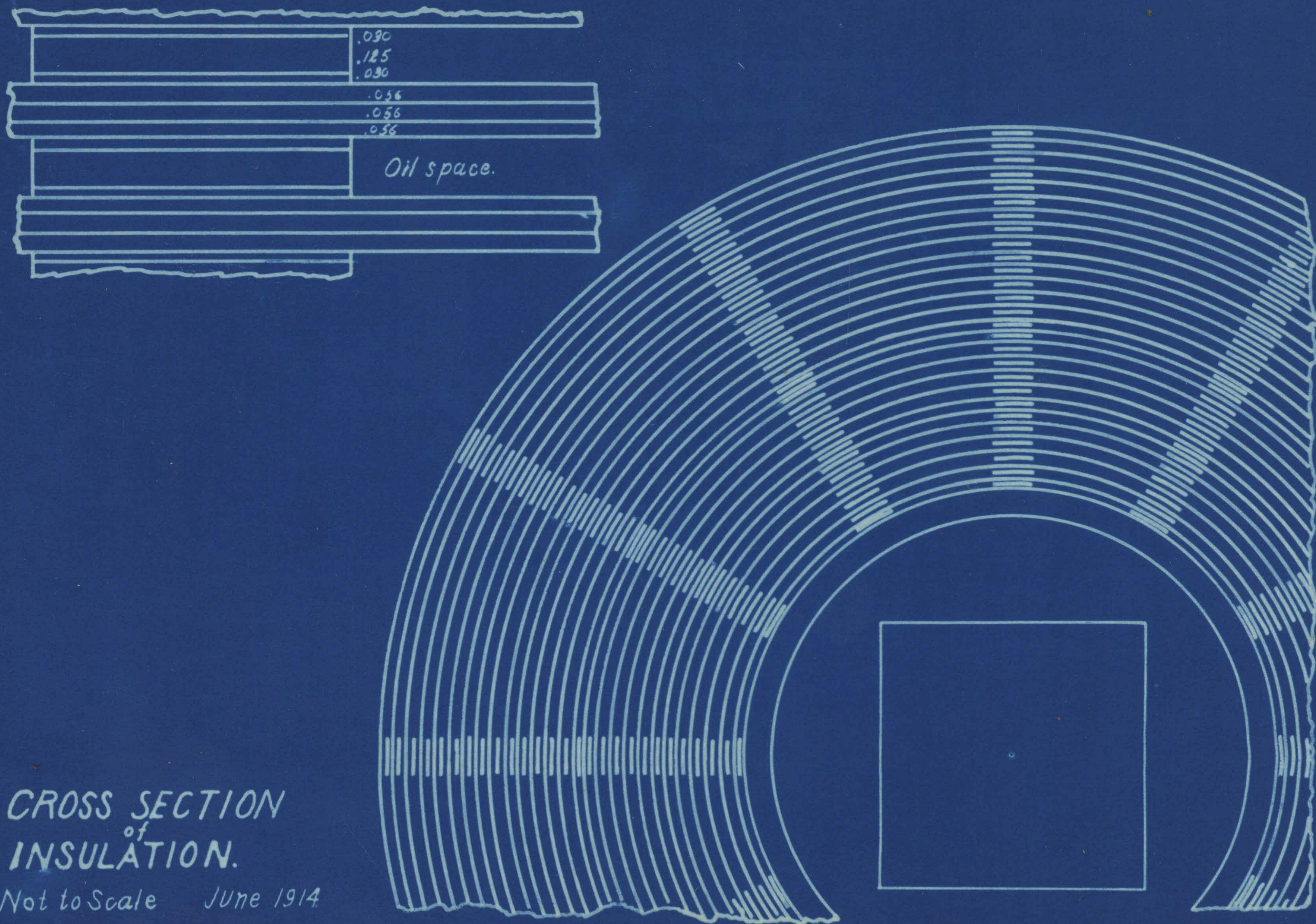




COIL BUILD

Not to Scale. Date June 1914

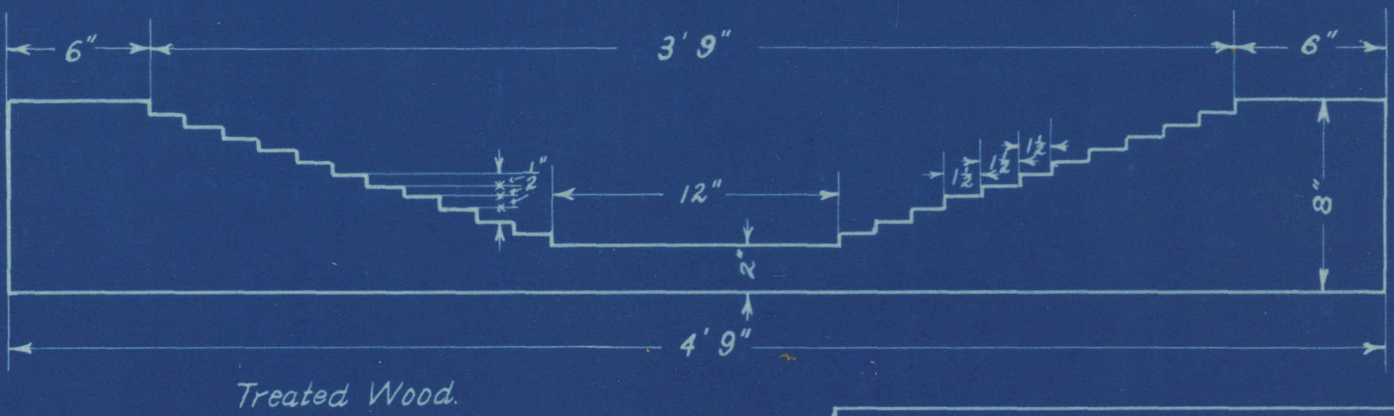
Plate No. 6 Drawn by A.W. WELLS.



CROSS SECTION of INSULATION.

Not to Scale June 1914.

Plate No. 9. A.W. WELLS.

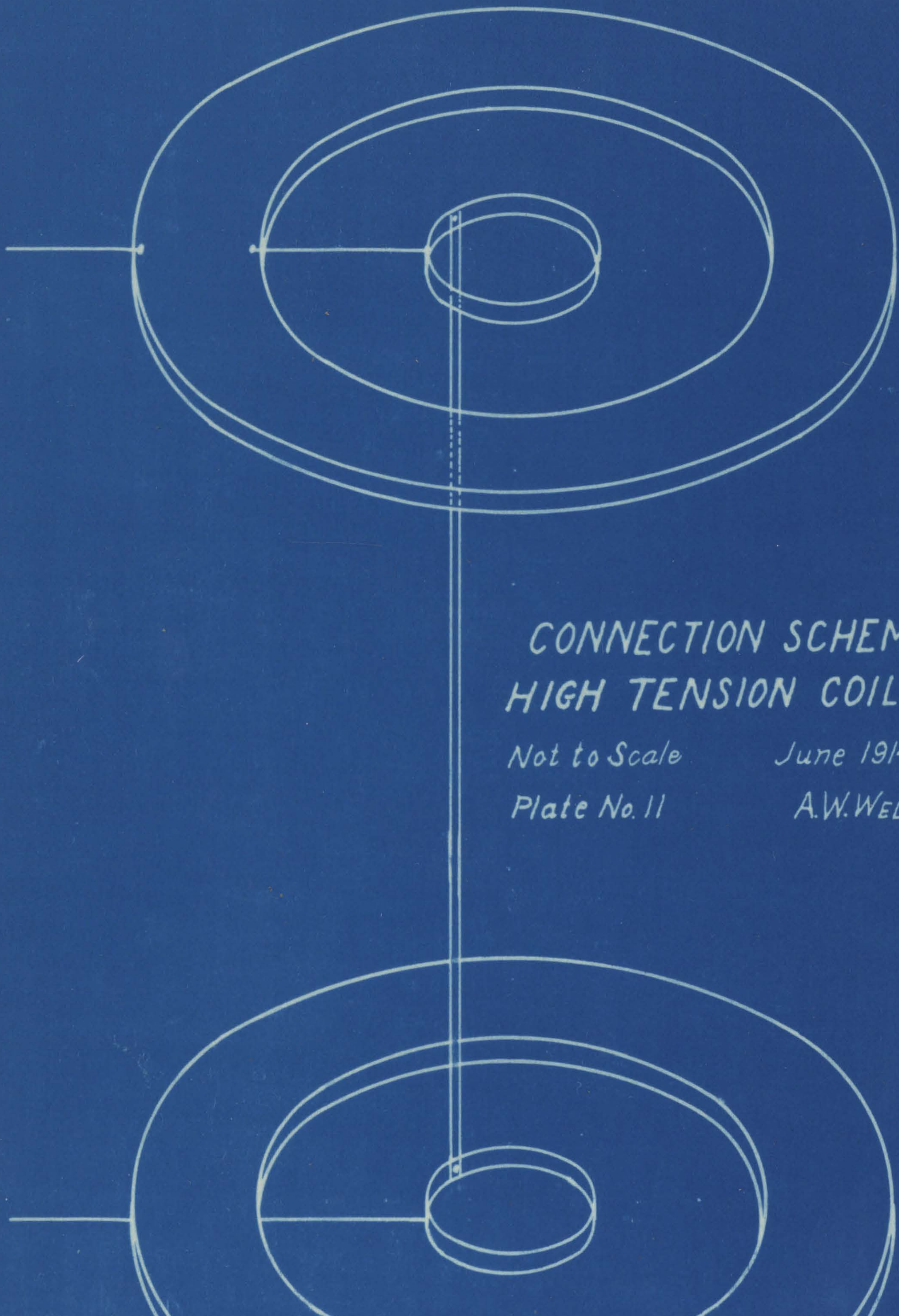


TESTING TRANSFORMER
BARRIER SUPPORT
THROOP COLLEGE of TECHNOLOGY

Pasadena California

Scale 1½ in = 1 ft Date June 1914

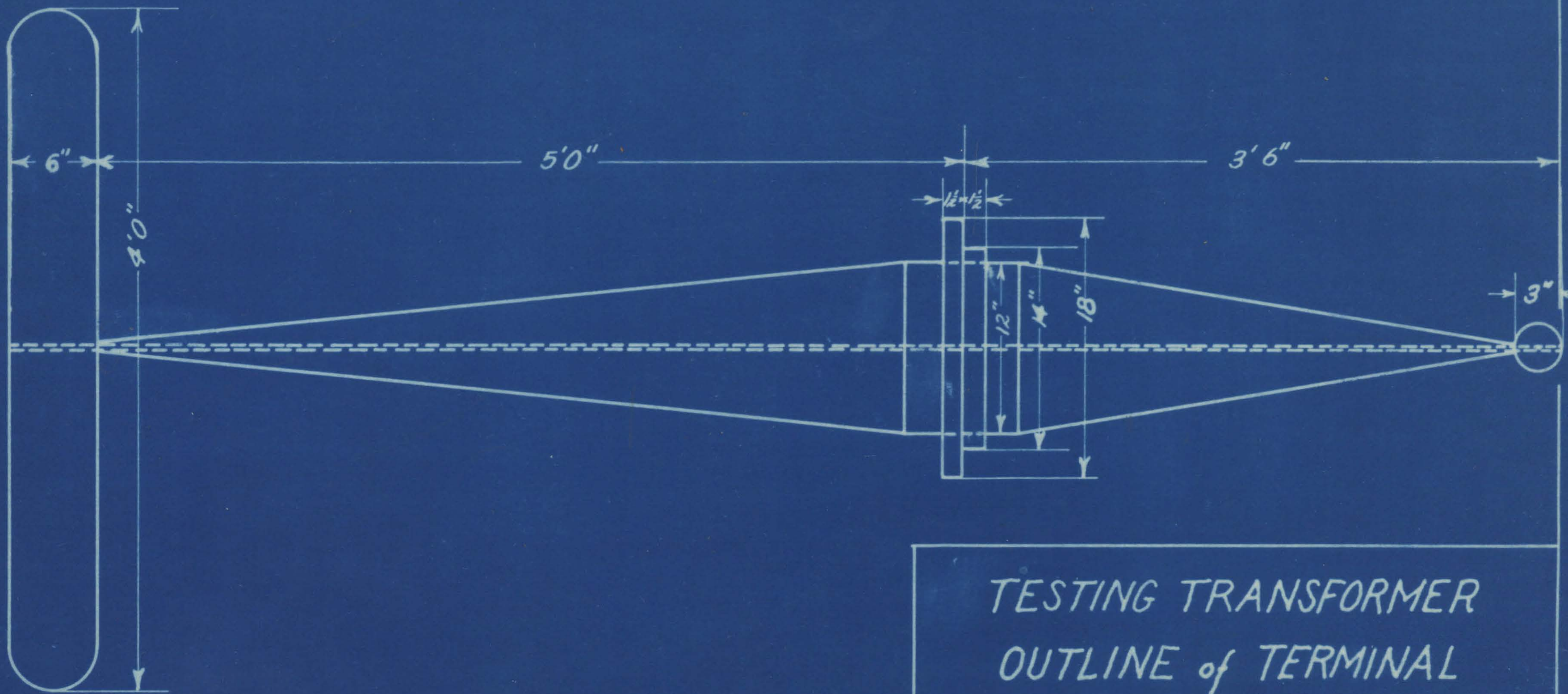
Plate No. 10 Drawn by A. W. WELLS.



CONNECTION SCHEME.
HIGH TENSION COILS.

Not to Scale June 1914

Plate No. 11 A.W. WELLS.

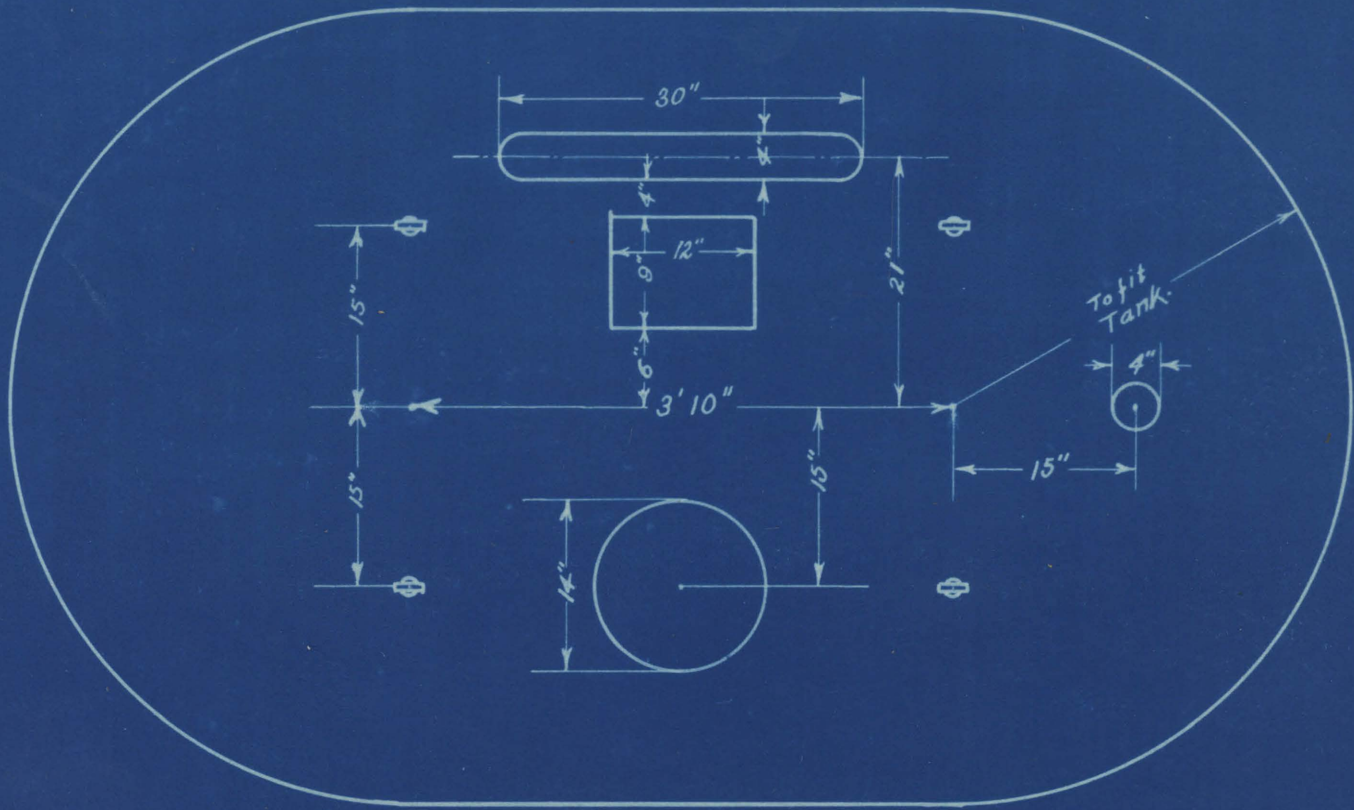


TESTING TRANSFORMER
OUTLINE of TERMINAL
THROOP COLLEGE of TECHNOLOGY

Pasadena California.

Scale 1in = 1ft   Date, June 1914.

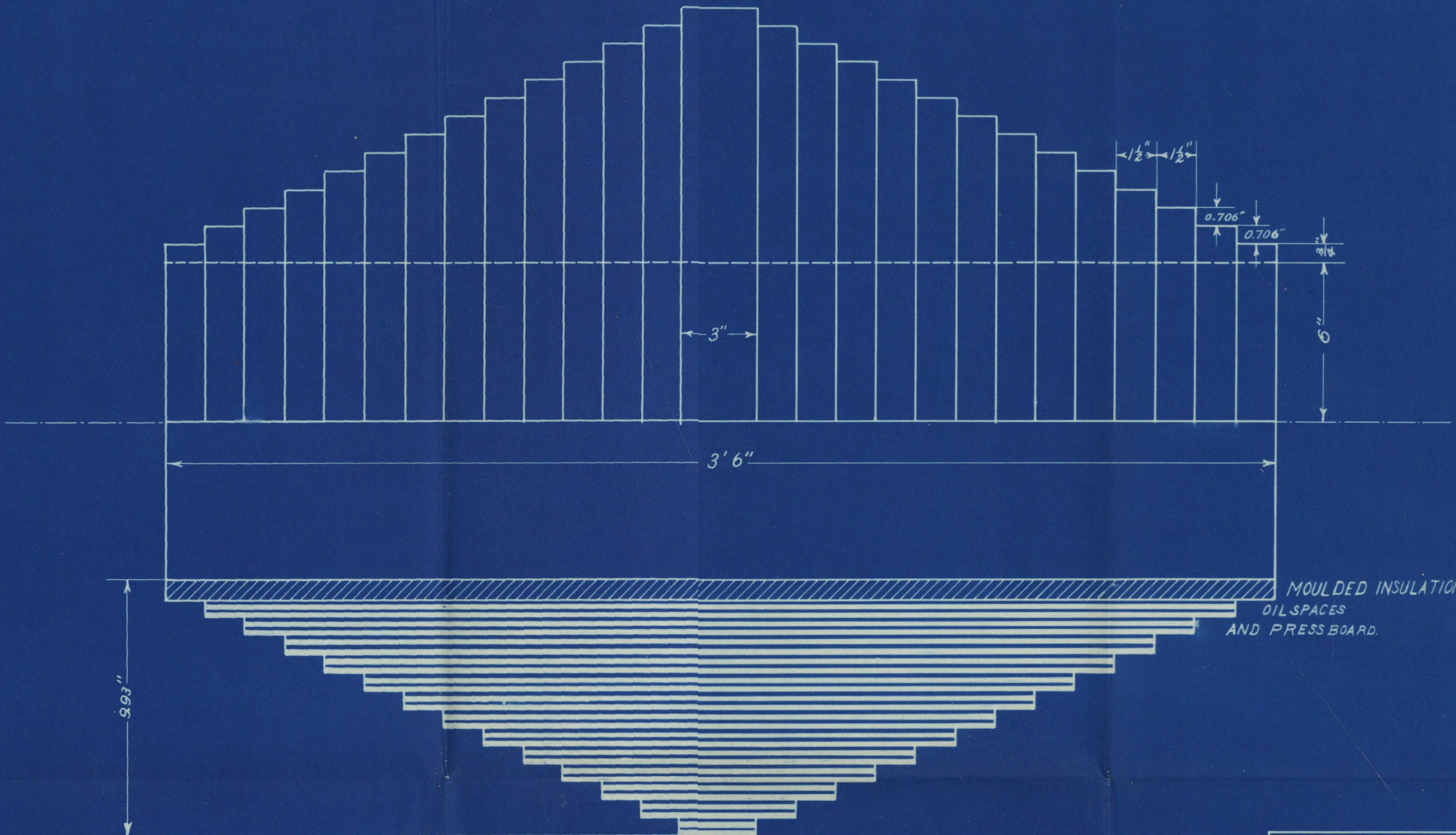
Plate No. 12   Drawn by A. W. WELLS.



OUTLINE of COVER

Scale $\frac{3}{4}$ in = 1 ft   Date June 1914.

Plate No. 14.   Drawn by A. W. WELLS.



TESTING TRANSFORMER

INSULATION BETWEEN WINDINGS

THROOP COLLEGE of TECHNOLOGY

Pasadena California

Scale 3 in. = 1 ft. Date June 1914.

Plate No. 8. Drawn by A. W. WELLS.