THE DESIGN OF
AN ELECTRIC RESISTANCE FURNACE
AND SUPPLY TRANSFORMER

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INTRODUCTION

The following work is the design of an electric resistance furnace for operation at high temperatures and pressures.

The design was undertaken for Dr. R. M. Boarts, Chemical Engineering Division, Tennessee Valley Authority.

It is unusual in many respects; differing from the accepted commercial furnace mainly in the method of heating.

The author wishes to acknowledge his indebtedness to Professor M. G. Northrop, University of Tennessee for assistance and suggestions in the electrical design; Professor E. S. Fabian, University of Tennessee, and Dr. R. M. Boarts, Tennessee Valley Authority, for valuable help in the mechanical design; Mr. E. H. Honeycutt and Mr. B. B. Simcox, Chemical Engineering Division, Tennessee Valley Authority, for helpful suggestions and assistance in the construction. The Tennessee Public Service Company, Knoxville, Tennessee, was kind enough to give the transformer core for the transformer.

PURPOSE

The purpose of this design is to furnish the Chemical Engineering Laboratory, Tennessee Valley Authority, with a furnace which will operate at variable temperatures from 100°C to 1000°C, be resistant to corrosion, and allow the use of as high pressures as can be reasonably expected over the range of temperature used.

MECHANICAL DESIGN

As originally intended, this furnace was to be used for the melting of sodium chloride at 850°C, without any means of temperature variation. After some discussion, it was decided to design and build a general purpose furnace, variable temperature, for operation at fairly high pressures.

A length of stainless steel tubing 3 inches outside diameter, 11/64 of an inch wall thickness, about 9-1/2 inches long was available from a previous construction and it was decided to use this length in the design. Electrically, it would have been desirable to have a cylinder of thinner walls so as to increase the resistance per unit length of the tubing.

The tubing, as mentioned, is of stainless steel, highly resistant to corrosion, Allegheny Metal, Grade A, of

the following composition:

Carbon	Maximum	0.08%
Manganese	"	0.50%
Phosphorous	"	0.025%
Sulphur	"	0.025%
Silicon	"	0.50%
Chromium		16.00 - 20.00%
Nickel		7.00 - 10.00%
Iron		Remainder

Other pertinent data are given:

O.D. ---------- 3.00"

I.D. ---------- 2.66"

Modulus of elasticity (hot worked) --- 28,600,000

" " shear ---------- 11,900,000

Mean coefficient of linear expansion - 2.02×10^{-5}/°C

Thermal conductivity ----- 0.069 calories/cm/sec/°C

Melting point ---------- 1430-1470°C

Specific heat ---------- 0.118

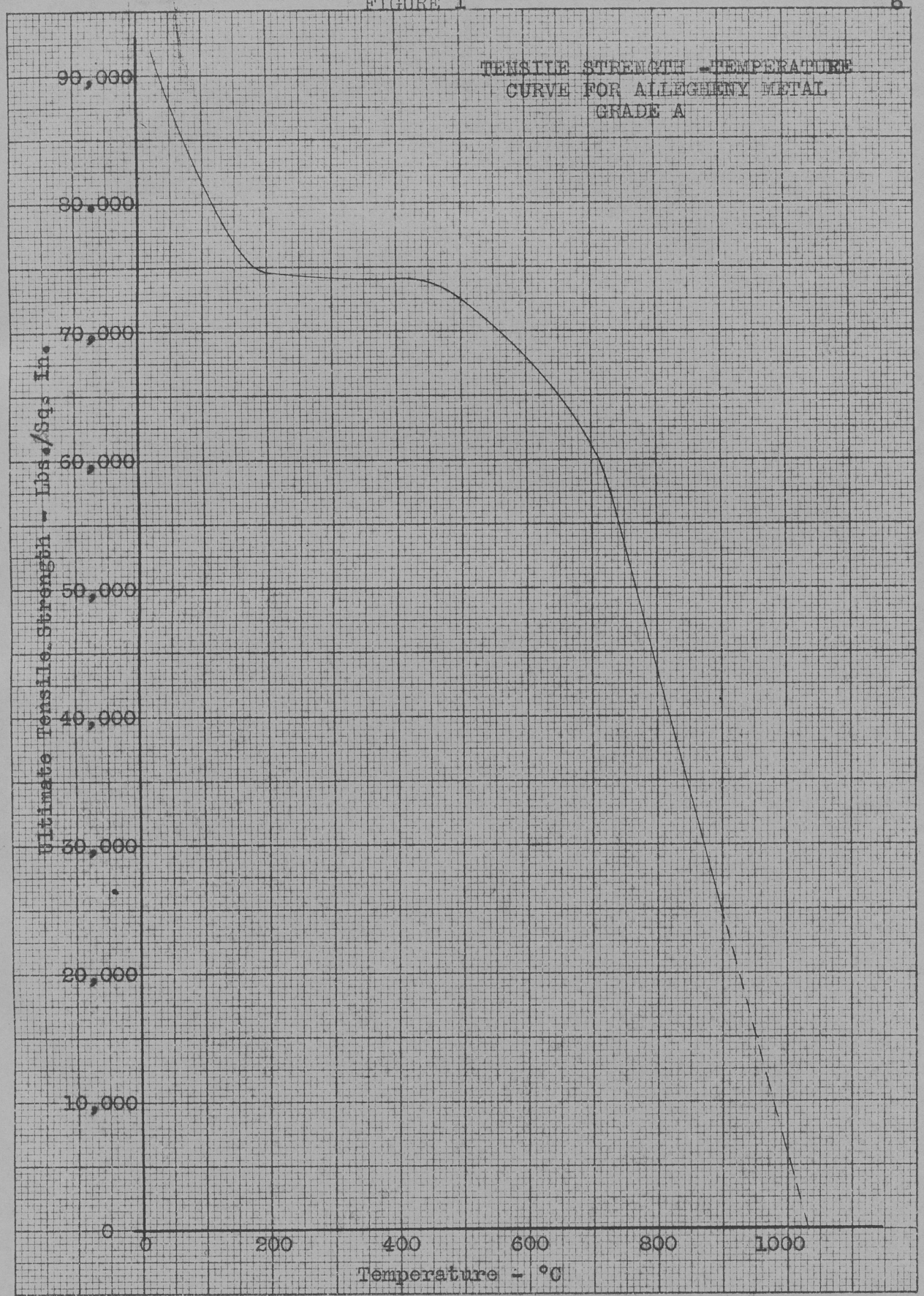
Specific gravity ---------- 0.285#/cu.in.

Ultimate tensile strength at elevated temperatures is given in Fig. I.

At the outset, it was decided to neglect creep and endurance limit because high pressure operation would not be over an extended period of time, and the cylinder would not be subjected to repeated pressure runs to warrant consideration of endurance limit.

The type of furnace being designed is one in which the cylinder is placed in the secondary circuit of a trans-

FIGURE 1


TENSILE STRENGTH -TEMPERATURE CURVE FOR ALLEGHENY METAL GRADE A
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
Ultimate Tensile Strength - Lbs./Sq. In.
0
200
400
600
800
1000
Temperature - °C

former, heating being due to the I^2R power loss in the cylinder. For this reason a cylinder as long as possible would be desirable from the electrical considerations, but reasonably short when the ease of cleaning is considered. Giving due consideration to both factors, a cylinder 7-1/4 inches long was decided upon.

All calculations for strength were based upon the maximum strength of the cylinder. Lamé's equation was used for calculation of allowable pressures in the cylinder, based upon ultimate tensile strength, using a factor of safety of 5. As noted in Fig. 1, it was necessary to extropolate the temperature-tensile strength curve to 1000°C. A temperature of 400°C was chosen for calculations of strength at low temperatures, which falls on the horizontal portion of the temperature-strength curve.

Ultimate tensile strength at 400°C - 74,290#/sq.in.

Allowable tensile strength at 400°C -

$$\frac{74,290}{5} = 14,860\#/\text{sq.in.}$$

Lamé's equation:

$$p = s_t \frac{r_2^2 - r_1^2}{r_2^2 + r_1^2} = 14,860\left(\frac{1.50^2 - 1.33^2}{1.50^2 + 1.33^2}\right) =$$

$$= 1770\#/\text{sq.in.}$$

A list of symbols is shown in the appendix.

Use maximum working pressure of 1700#/sq.in. at 400°C

Maximum working pressure at 1000°C - 140#/sq.in.

The bottom of the cylinder, for calculations, was considered a flat circular plate, not rigidly fixed at the

edges. The equation is:

$$s_t = p\left(\frac{r}{t}\right)^2$$

or

$$t^2 = p\,\frac{r^2}{s_t}$$

Using tensile strength at 400°C,

$$t^2 = 1700\,\frac{1.5^2}{14{,}860} = 0.258$$

$$t = 0.508''$$

Referring to the drawing of cylinder details (Fig. 2), a half inch fillet weld was used for the plate and cylinder. This is a much larger weld than necessary for strength, but is used to supply a large area of contact for current flow from plate to cylinder, thus reducing resistance. A half inch fillet weld is also specified for the inside bottom of the cylinder, the weld to be turned smooth. This was done to facilitate cleaning of the cylinder. There is a possibility that a weld cannot be placed on the inside bottom of the cylinder due to its depth and possible difficulty in welding this type of metal. If it is found too difficult to weld the inside, it will be omitted.

The top flange is to be of the same material. The sealing joint will be of the tongue and groove type, 1/4 inch wide, 1/8 inch deep, using an asbestos paper gasket. The top of the furnace is to be held in place by 3/4 inch stainless steel studs. The number of studs is calculated, using a working load of 2000 lbs.:

$$P = \pi r_3^2 p = \pi(1.875)^2(1700) = 18{,}900\#$$

Number of studs required is, then,

$$B = \frac{P}{2000} = \frac{18,900}{2,000} = 9.45$$

In order to prevent the building up of excessive pressures within the vessel, the number of bolts to be used was reduced to eight. In this manner the factor of safety for the top was reduced which would cause the bolts to fail before the remainder of the vessel. The top flange will be threaded for studs, the studs projecting 1/4 of an inch beyond the bottom of the flange, and tack welded in four places. (See Fig. 2)

The flange calculations were made, assuming that each section of the flange acted as a cantilever beam, fixed at one end. The area of this beam at the cylinder surface is:

$$A = 1/8\ \pi Dt = \frac{\pi(3.00)t}{8} = 1.18t$$

The maximum moment will be at the cylinder surface, the moment arm (Fig. 2) being 1-1/8 inches, and the load being one eighth of the total force on the flange:

$$\frac{P}{8} = \frac{18,900}{8} = 2360\#$$

in round numbers. The maximum moment is then:

$$M = 2360(1-1/8) = 2660\#"$$

The section modulus is found to be;

$$S = \frac{M}{s_t} = \frac{2660}{14,860} = 0.1791 \text{ in.}^3$$

and the section modulus is also:

$$S_m = \frac{Lt^2}{6} = \frac{At}{6} = \frac{1.18(t)}{6} = \frac{1.18t^2}{6}$$

$$t^2 = \frac{6S_m}{1.18} = \frac{6(0.1791)}{1.18} = 0.91$$

$$t = 0.95"$$

therefore use 1 inch thick flange. Calculations for shear showed that the 1 inch thickness is much greater than need be.

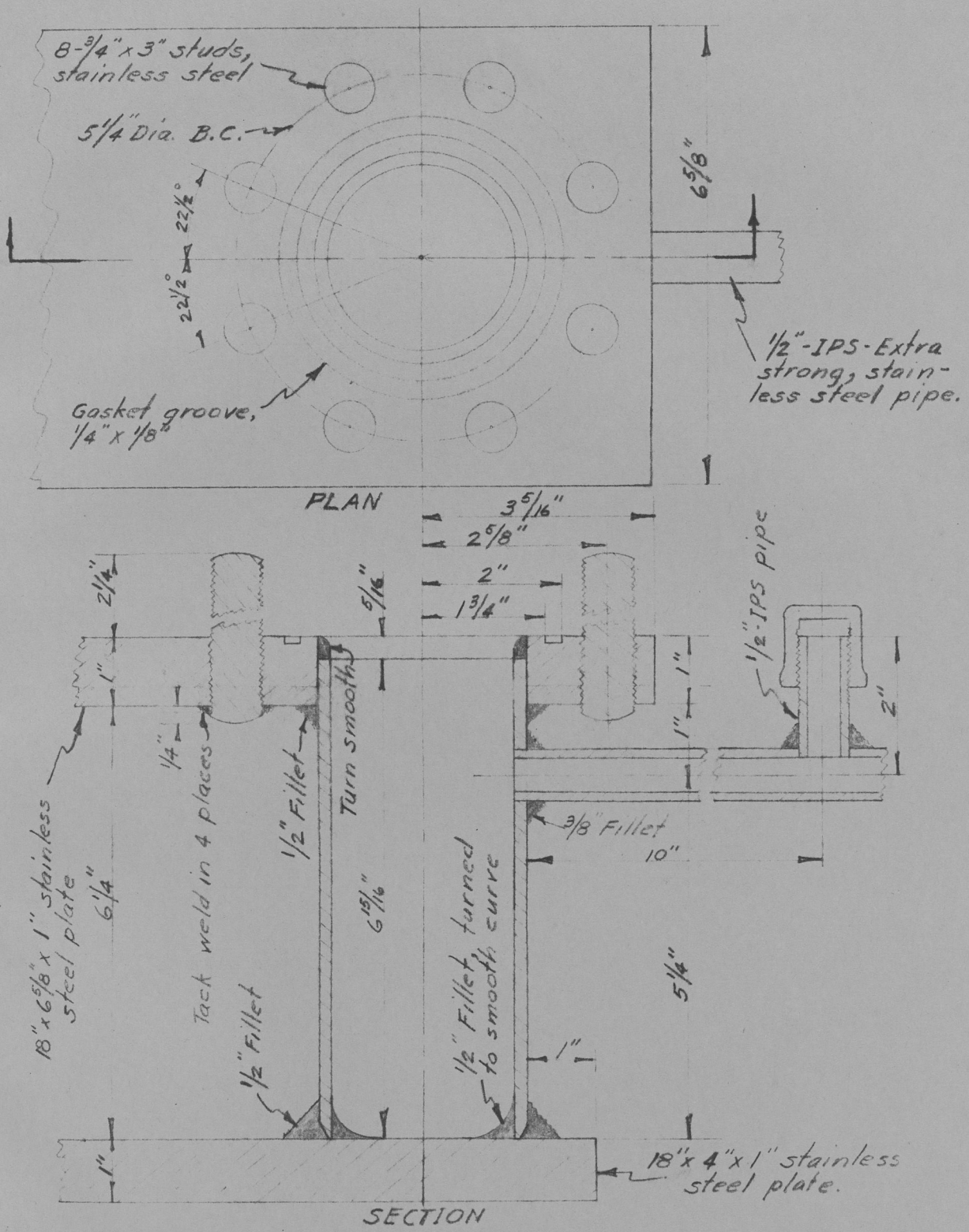
The top blank flange, by using the circular plate equation for a plate not fixed at the edge, was by calculation 0.9 inches. Therefore a 1 inch blank flange will be used. Details of this flange are shown in Fig. 3.

As can be detected in the foregoing, a good many of the equations used are empirical. For this reason, the design has been liberal insofar as weights and thicknesses of materials are concerned. Shear calculations indicated, in every case, that weights for tension were more than adequate shear strength.

The safety of operation is taken care of in two ways: one by under design of the number of studs holding the top blank flange, so as to cause stud failure before failure of any other portion of the furnace; and second, a blowout relief valve to be placed on the 1/2 inch IPS pipe nipple on the pipe which extends to the right of the cylinder (Fig. 2).

Fig. 4 shows details of heat insulation. This was troublesome due to the high temperature involved, and the number of projections in the way of plates and pipes. Johns-Manville, Sil-o-cel, C-22 (calcined) 2000°F brick was used to support the weight of the furnace within the transite container, and the lower of the electrical connection plates was bolted to an 8 inch channel to prevent twisting of the cylinder when tightening the flange studs. This latter will also partially support the weight of the furnace. The container, so

as to be removable, is split horizontally on three sides at the level of the upper electrical connection, and on the side in which the 1/2 inch pipe is taken out, it is split at the level of the pipe. This is done so that the cylinder is readily accessible. The top of this container is in two sections so that it will fit around the two vertical pipes. All of the space is filled and tamped with pulverized Sil-o-cel. Necessarily rough calculations showed that the temperature of the wall, for the worst condition (8 inches horizontal distance to the wall), would be about 120°F.



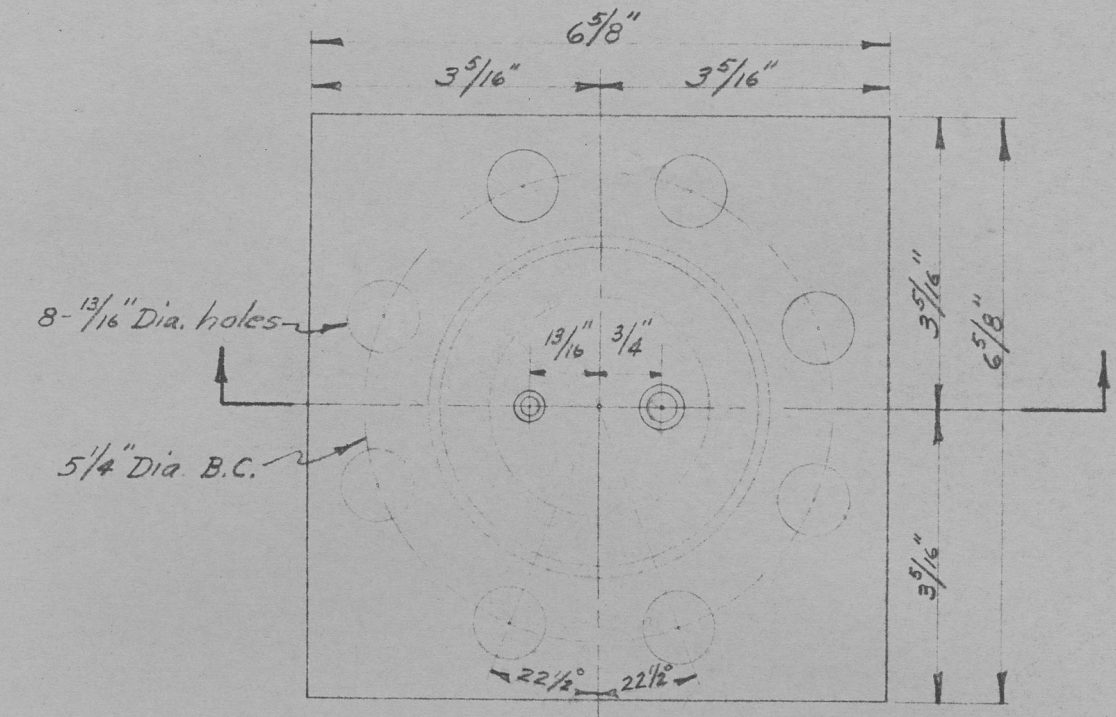
CYLINDER DETAILS

ELECTRIC RESISTANCE FURNACE

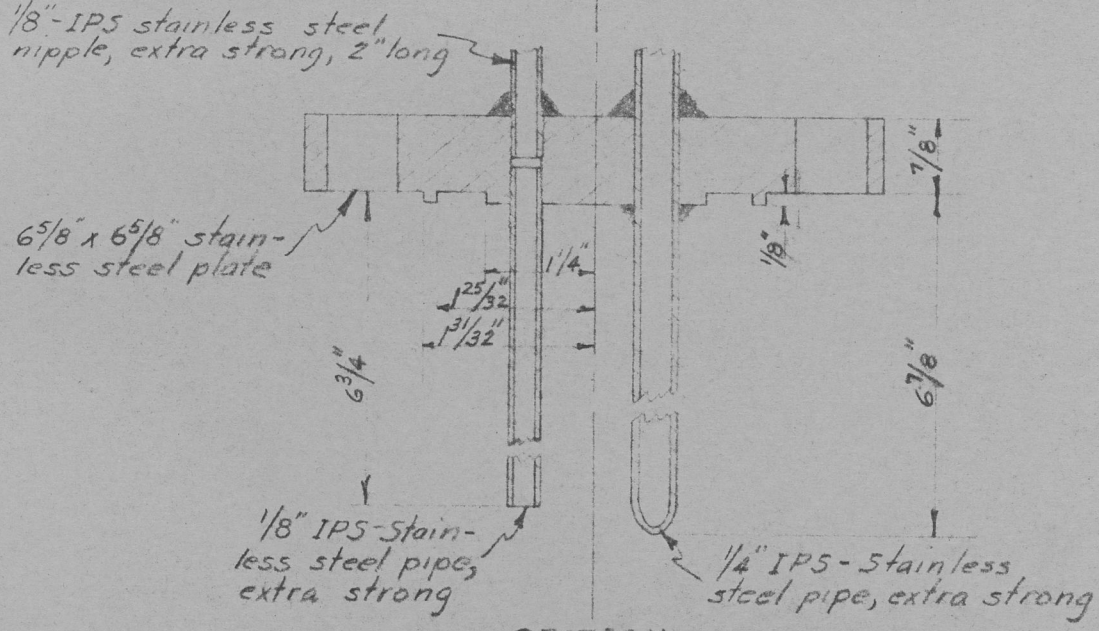
SCALE: Half Size

FIGURE 2

M. H.



BOTTOM VIEW



SECTION

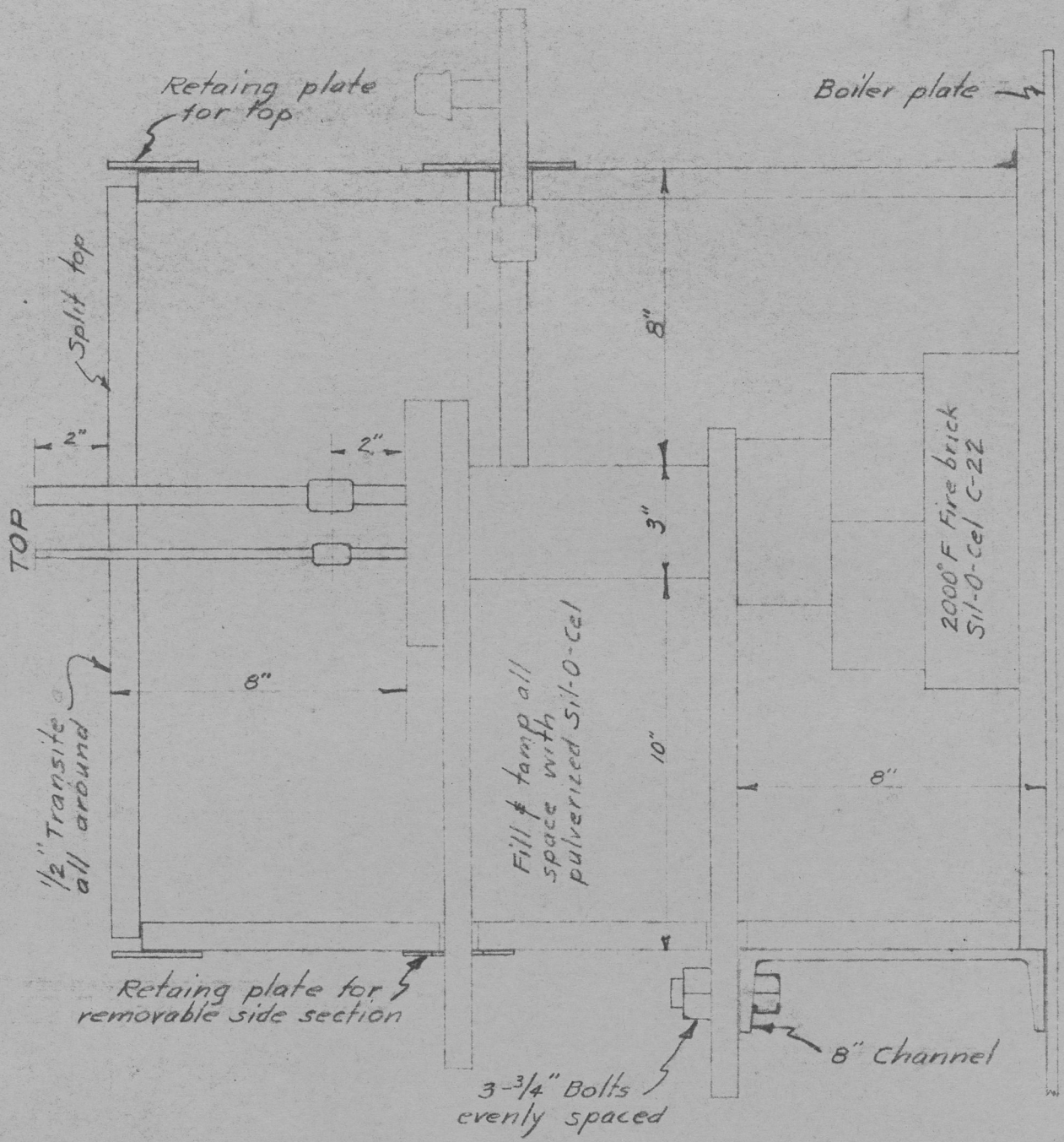
DETAIL OF TOP

ELECTRIC RESISTANCE FURNACE

SCALE: Half Size

FIGURE 3

M. H.



INSULATION DETAILS

SCALE: Quarter Size

ELECTRIC RESISTANCE FURNACE

FIGURE 4

M. H.

ELECTRICAL DESIGN

The cylinder designed in the previous section is to be used as a resistance and placed in the secondary circuit of a transformer; the temperature being controlled by varying the primary voltage and number of primary turns.

The electrical design of this furnace presented a number of difficulties, among them being the low resistance of the cylinder to be heated, and the small size of window in the transformer core obtained.

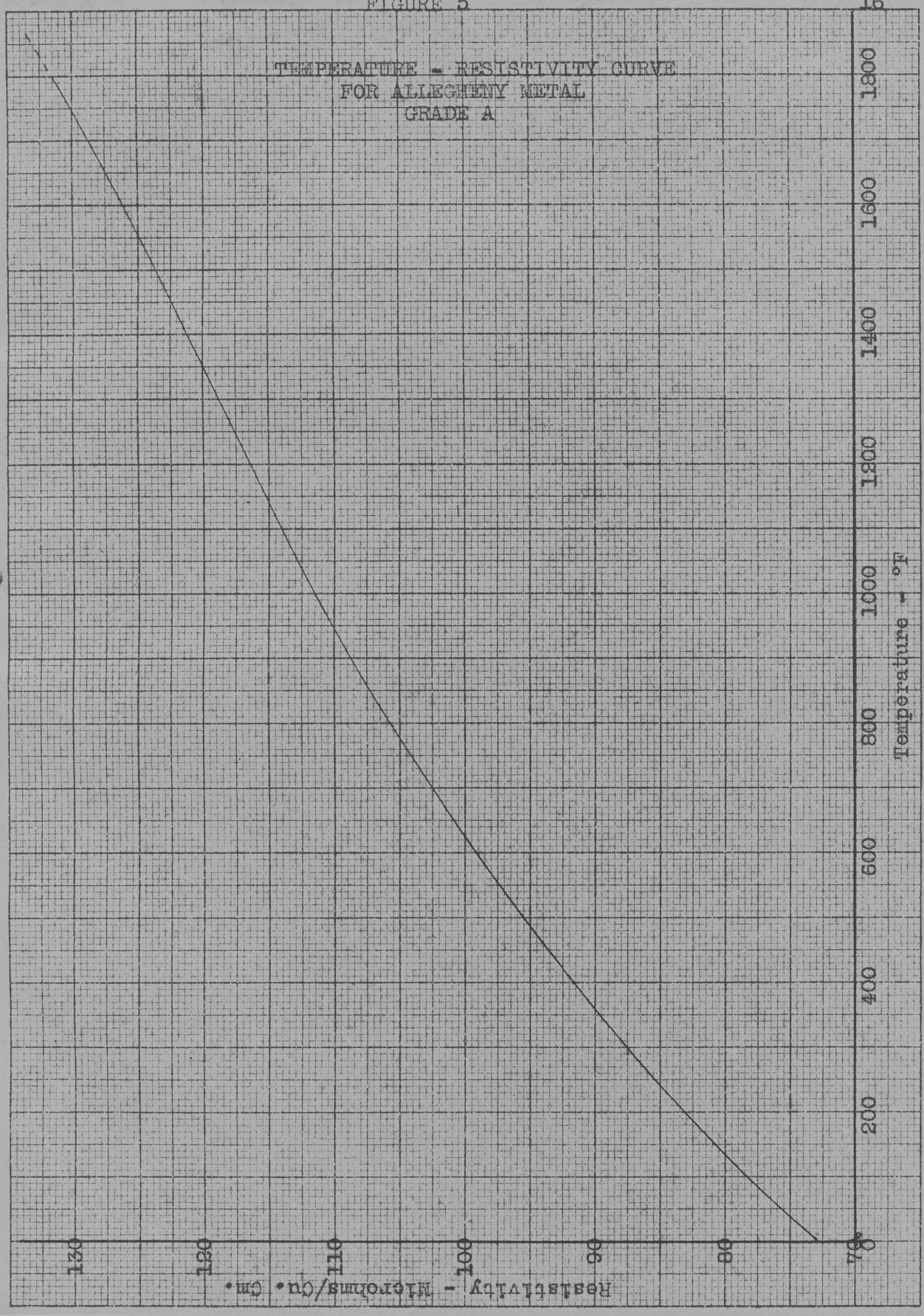
The resistivity of the tubing available is given in Fig. 5. As previously stated the outside diameter of the tubing is 3.00 inches, inside diameter 2.66 inches and the length available is 9.57 inches. The resistance of this tubing at room temperature is calculated as follows:

$$R = R_s \frac{L}{A} = (77 \times 10^{-6}) \times \frac{24.33}{9.78} = 192 \times 10^{-6} \text{ohms}$$

or resistance per inch of length is 20.0×10^{-6}ohms.
The resistance at 1000°C (1830°F) is found to be 34.4×10^{-6}ohms per inch length.

As a rough check on the manufacturer's values, the resistance of the tubing was measured with direct current and the results are given in the table.

FIGURE 5


TEMPERATURE - RESISTIVITY CURVE
FOR ALLEGHENY METAL
GRADE A
Resistivity - Microhms/Cu. Cm.
74
80
90
100
110
120
130
Temperature - °F
200
400
600
800
1000
1200
1400
1600
1800

Cylinder Resistance by Direct Current at Room Temperature.

I Amperes	E Milli-volts	R Ohms x 10^{-6}
106	22.0	208
152	33.4	220
193	42.6	221
	Average	216

or 22.6×10^{-6} ohms per inch length. As can be seen, this value is slightly higher than the manufacturer's value, but is expected due to the contact resistance of the voltmeter leads.

All calculations of energy required are made for the cylinder during the heating period, and the voltage of the circuit determined by taking into account, in the calculations, the total resistance of the circuit, so that the required current would flow.

It is not necessary to determine the heat losses, and therefore the heat supply to maintain steady state conditions, since the method of temperature control allows the heat supply to be adjusted to the losses.

The weight per inch length of the tubing is 0.426 pounds. Referring to Fig. 2., the effective length of cylinder is taken as 6 inches, or a weight of 2.60 pounds for this length.

The heat required for this cylinder at 1830°F is

$$H = T \times \text{Sp. ht.} \times \text{Wt.} = 1830(0.118)(2.60) =$$

$$= 561 \text{ BTU}$$

Assuming the heat efficiency as 50 per cent, the net heat required is 1120 BTU in round numbers. The output in kilowatt hours is then:

$$KWH = \frac{H}{3412} = \frac{1120}{3412} = 0.328 \text{ KWH}$$

or 328 watt-hours. For 100°C (212°F), the output is 38 watt-hours.

It is decided that the required temperature should be reached in 10 minutes; therefore the power required is:

$$W = \frac{\text{Output}}{10/60} = 328(6) = 1968 \text{ watts}$$

At 100°C, the power is 228 watts.

The average secondary current during the rise in temperature to 1000°C is (taking resistivity for 500°C):

$$I_{av} = \frac{W}{R} = \frac{1968}{(170 \times 10^{-6})} = 3400 \text{ amperes}$$

Average current during rise in temperature to 100°C is 1364 amperes.

The secondary copper area is based on 1000CM per ampere, and the total area required is:

$$A = \frac{I_{av}(1000)}{1.273 \times 10^{6}} = \frac{3400(1000)}{1.273 \times 10^{6}} = 2.67 \text{ sq.in.}$$

In order to determine the secondary voltage required, it is first necessary to calculate the resistance of the two long plates of the furnace which serve for transformer connections. Assuming an average temperature of 100°C, the total resistance of the two plates is 239×10^{-6} ohms.

The total resistance of the circuit (neglecting secondary resistance which is small) is the sum of the plate resistance and the cylinder resistance, or 409×10^{-6} ohms. The secondary voltage, is then:

$$E_s = IR = (3400)(409 \times 10^{-6}) = 1.39 \text{ volts}$$

The voltage required for 100°C is 0.469 volt.

The secondary will be one turn, because of large cross section required and low voltage.

The number of turns (for 1000°C) on the primary may now be determined for a one turn secondary:

$$T_p = \frac{E_p}{E_s} = \frac{110}{1.39} = 79 \text{ turns}$$

For 100°C, the number of primary turns is 234.

Based on the above ratio of turns, the primary current is:

$$I_p = \frac{E_s}{E_p} I_s = \frac{1.39(3400)}{110} = 43 \text{ amperes}$$

For 100°C, the primary current is 5.8 amperes. The size of wire on the winding for maximum voltage (maximum temperature), based on 1000 CM per ampere is 43,000 CM. No. 4 wire will be used which has an area of 41,740 CM.

The transformer core available is a core type, from an old 10 KVA transformer which did not have non-ageing iron. The actual area of the iron in the legs is 8.3 inches.

The total magnetic flux is given by the E.M.F. equation (for 1000°C):

$$E = 4.44T \, \phi_a f 10^{-8}$$

or

$$\phi_a = \frac{E \times 10^8}{4.44\ T\ f} = \frac{110(10^8)}{4.44(79)(60)} = 523{,}000 \text{ lines}$$

Flux density is:

$$B = \frac{\phi_a}{A} = \frac{523{,}000}{8.3} = 63{,}000 \text{ lines/sq.in.}$$

This maximum flux density is not excessive, and therefore this core will be used, even though the losses will be a little high due to the iron.

The magnetizing current of this transformer cannot be determined accurately, because the B-H curve for this iron is not available. Even if this curve had been available, it would more than likely have been in error because of the ageing of the iron. However, rough calculations, using an average value of ampere-turns for a flux density of 63,000 lines per square inch, and the worst condition of fewest effective turns in the primary, showed that the magnetizing current will be about 8 amperes.

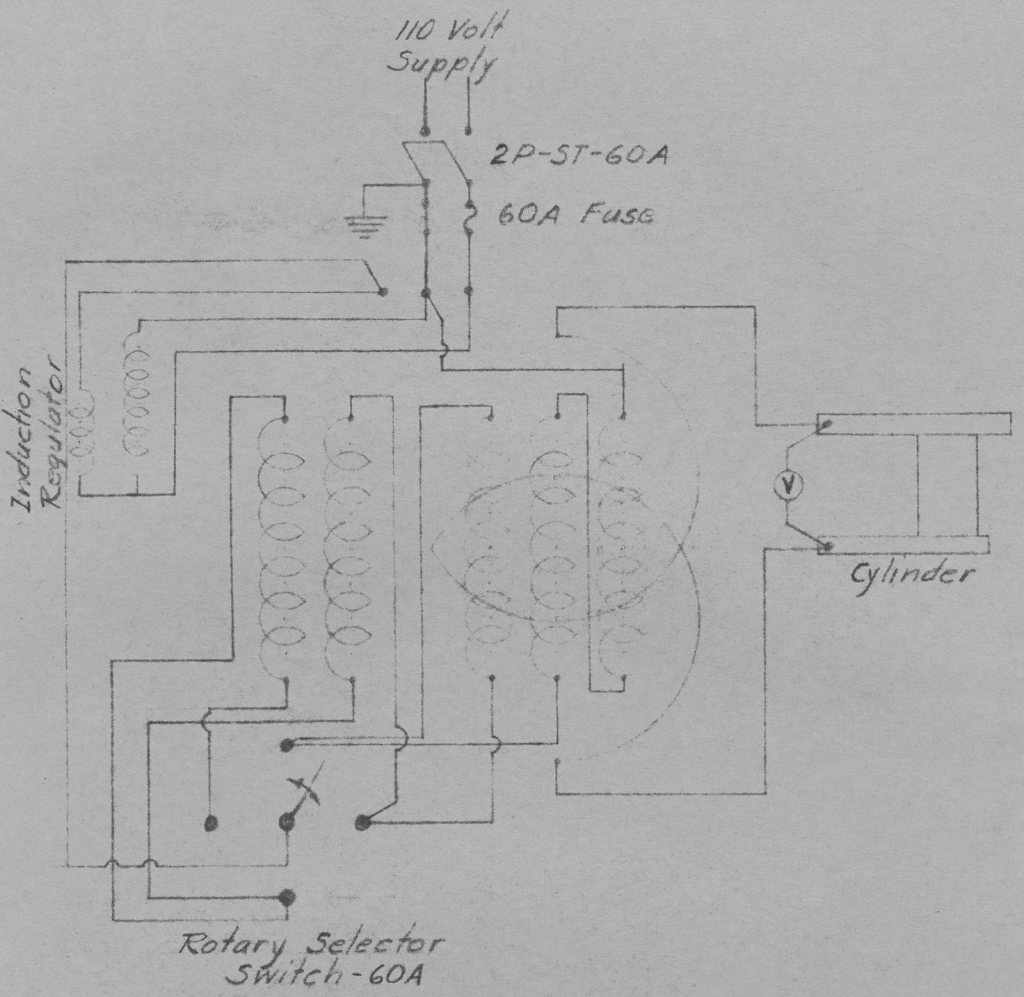
Referring to Fig. 6, the primary winding is made in 5 sections, three sections on one leg of the core, and two on the other leg. The secondary is a copper plate 1/4 inch thick and 12 inches wide, bent so as to almost close the turn.

The primary is of double cotton covered wire and on the leg with the secondary is made up of three layers of #4, 42 turns each, two of these in series giving the highest operating temperature. The two windings on the other leg are 58 turns of #6, and 80 turns of #8. This division of coils will allow the secondary voltage to be varied continuously

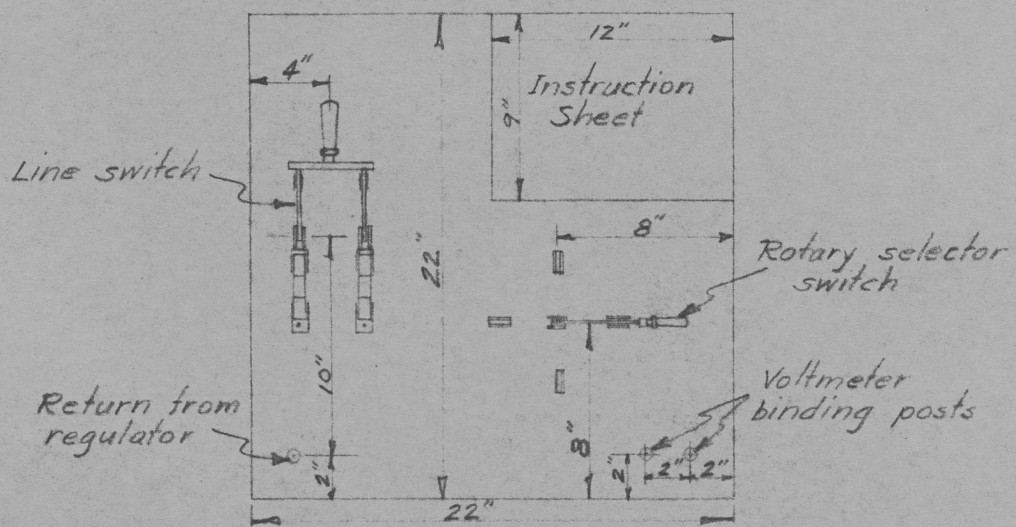
from the lowest to highest voltage by means of a 25 percent buck or boost induction voltage regulator in the primary. This regulator is available in the laboratory.

The form on which these are wound is of wood, and the coils will be wound and then placed on the core. The windings and wood will be painted with an air drying insulating varnish. The details of the form are shown in Fig. 7.

Fig. 8 shows details of the transformer connections. It will be noted that the top connection is made by means of two copper straps, while the bottom connection is made with 3 copper straps. This is done in order to give equal cross sections and area of contact in both cases.



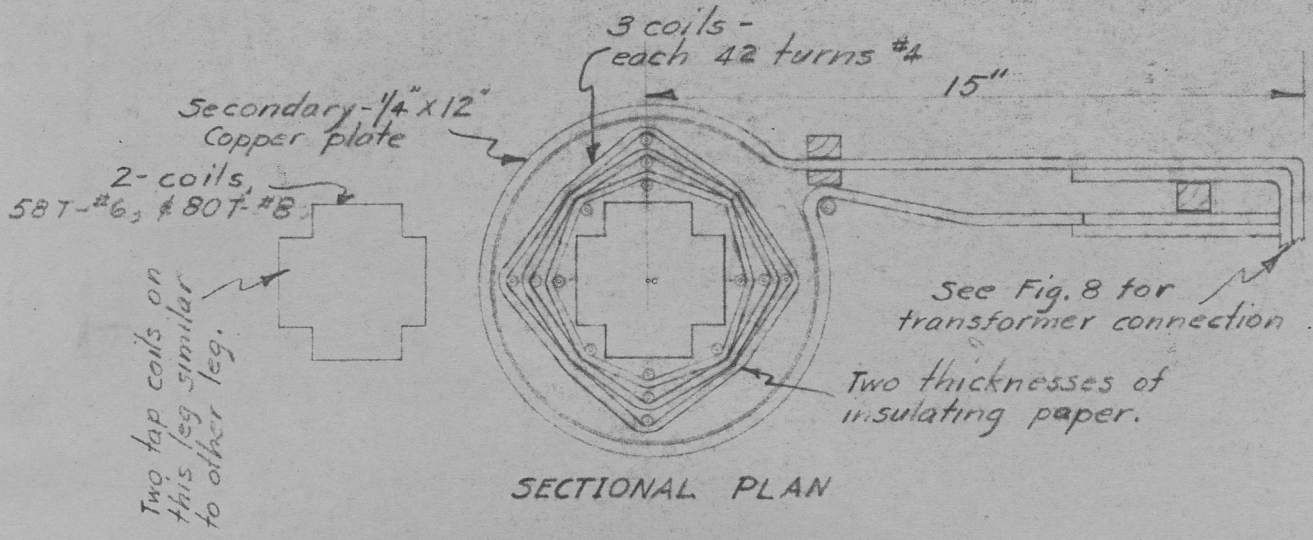
SCHEMATIC WIRING DIAGRAM



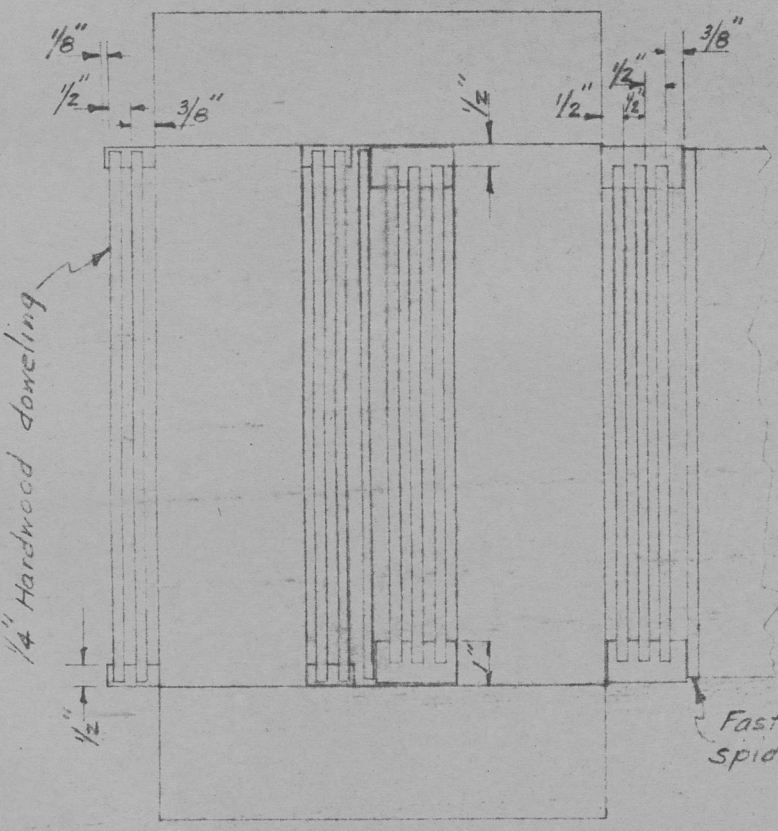
CONTROL PANEL
SCALE: 1" = 8"

ELECTRIC RESISTANCE FURNACE

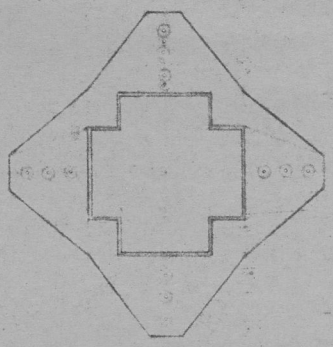
FIGURE 6



SECTIONAL PLAN



SECTIONAL ELEVATION
SECTION THRU CENTER
Primary omitted

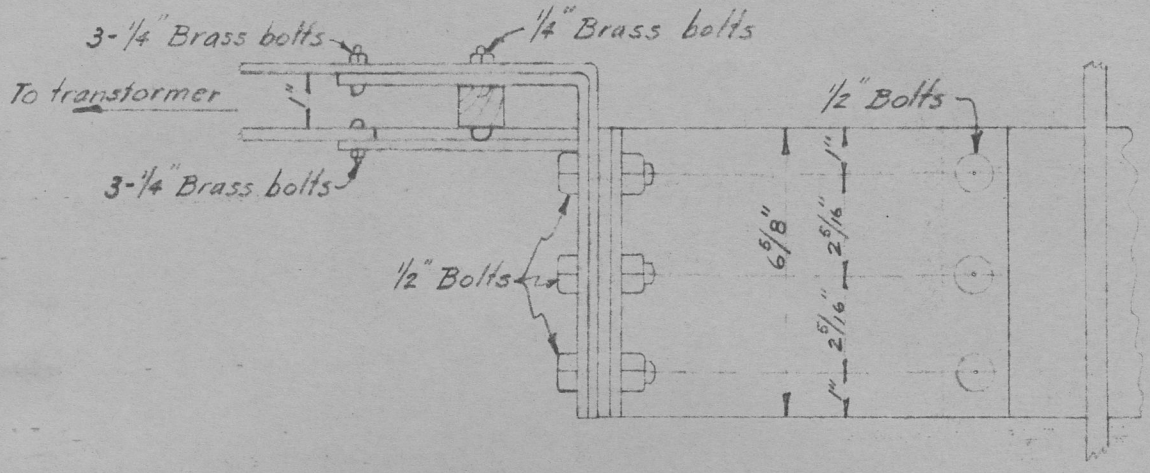


DETAIL OF SPIDER
Made in one piece

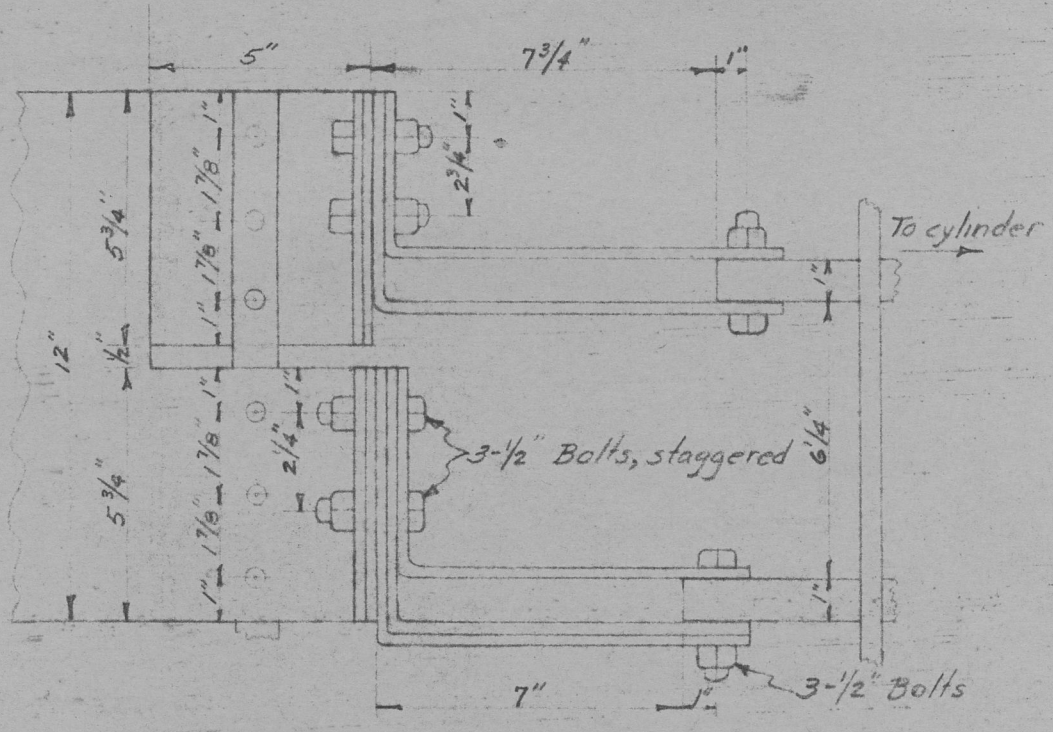
TRANSFORMER DETAILS

ELECTRIC RESISTANCE FURNACE
SCALE: Quarter Size

FIGURE 7



PLAN



ELEVATION

TRANSFORMER CONNECTION

ELECTRIC RESISTANCE FURNACE

SCALE: Quarter Size

FIGURE 8

M. H.

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LIST OF SYMBOLS

A = area.

B = total magnetic flux.

E = volts.

E_p = primary voltage.

E_s = secondary voltage.

H = heat in B. T. U.

I = Current in amperes, and moment of inertia.

L = length.

M = moment, pound inches.

P = total pressure in pounds.

R = resistance in ohms.

R_s = resistivity in ohms/cm^3.

S = section modulus.

T = temperature, or transformer turns.

T_p = number transformer primary turns.

W = watts.

p = pressure, #/sq.in.

r_1 = outside radius of cylinder.

r_2 = inside radius of cylinder.

r_3 = radius to center of gasket grove.

s_t = allowable unit tensile stress.

t = thickness.

ϕ = flux density, lines per. sq.in.

APPROVAL

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is to be understood that by this approval the undersigned does not necessarily endorse or approve any statement made, opinions expressed, or conclusions drawn therein, but approves the thesis only for the purpose for which it is submitted.

M. G. Northrop.

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Professor in Electrical Engineering