A HIGH FREQUENCY INDUCTION FURNACE

AND

HIGH-FREQUENCY, HIGH-VOLTAGE INDUCTION COIL.

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By

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PREFACE

The purpose of this paper is to treat the problems connected with the design and construction of an instrument capable of producing eddy-current heating, and high-voltage, high-frequency currents. The induction heating instrument was designed to be used for outgassing the electrodes of experimental vacuum tubes and for demonstrations in the physics class-room. Possibly it may find some applicationsin some research work regarding the effects of such high-intensity, high-frequency magnetic fields on plant and animal life.

The high frequency induction coil was designed to be a demonstration instrument to perform some of the very interesting and instructive demonstrations for which these currents are often used.

Obviously both of these functions require some type of high-frequency generator as the primary supply of energy. Since the frequencies involved are radio frequencies, a vacuum tube oscillator affords an efficient and convenient means of generating the energy required. Most of the first part of this paper will discuss the theoretical problems involved in the use of this energy by means of an efficient and convenient circuit. This theory will be divided into that concerning the induction furnace and that concerning the induction coil. The second part of this paper will describe the actual apparatus and give some details on the construction and performance of the instrument as it has been finished.

I want to acknowledge the help given me by Dr. Frank M. Durbin in this work.

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A. HIGH-FREQUENCY INDUCTION FURNACE.

I. Oscillator Circuit.

In general a vacuum tube oscillator requires a parallel tuned circuit arranged so that the plate current variations can excite it and so that some of this energy may be delivered to the grid circuit to control the plate current. The method of accomplishing this is shown in the following circuit (Figure 1a). In this circuit (called a Hartley oscillator) the current to the plate of each tube flows through one half of the oscillating coil N. Since the grid voltage must be less than the total oscillating voltage and 180 degrees out of phase, it is obtained by means of a tap fairly close to the center of the coil and on the opposite end of the coil from the tube it serves.

In such a circuit the impedance presented by the tuned circuit must be at least approximately correct for the vacuum tubes used. It can be shown that the impedance at resonance of a parallel circuit is

$$Z = L/CR \qquad (1)$$

where L is the inductance in henrys of the coil, C is the capacity in farads of the tuning condenser, and R is the apparent resistance of the coil. This R is not the actual resistance of the coil due to the coupled-in resistance of the loading device connected to it. The nature of this loading device will be discussed later.

In all following discussions where the symbol Z is used it means a complex impedance equal to $R + jX$, where R is the resistance and X is the reactance in the circuit and j is the

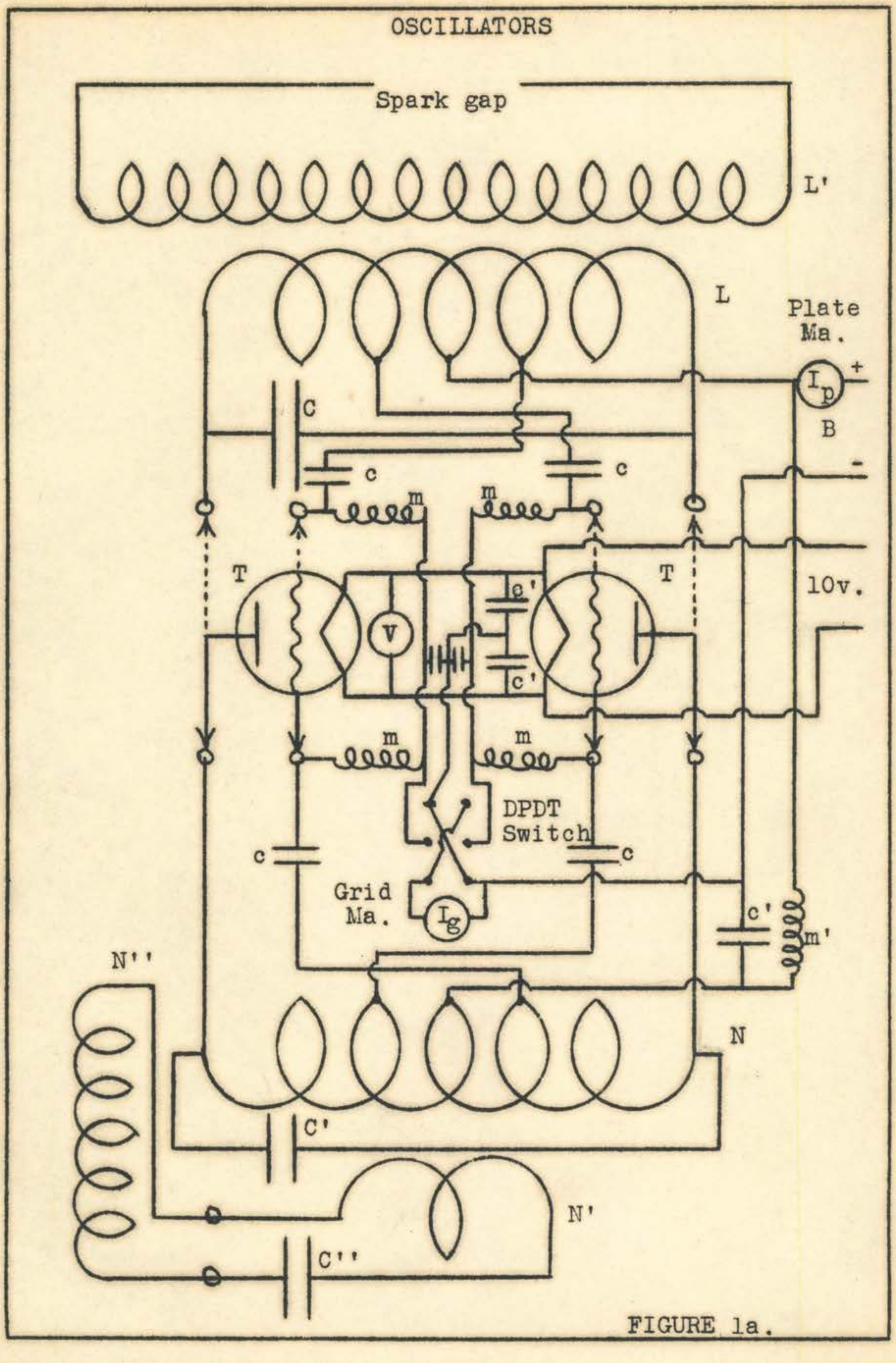
OSCILLATORS
Spark gap
L'
L
Plate
Ma.
I_p
+
B
-
C
c
c
m
m
T
T
10v.
c'
V
c'
m
m
DPDT
Switch
c
c
Grid
Ma.
I_g
c'
m'
N''
N
C'
N'
C''

FIGURE 1a.

POWER SUPPLY

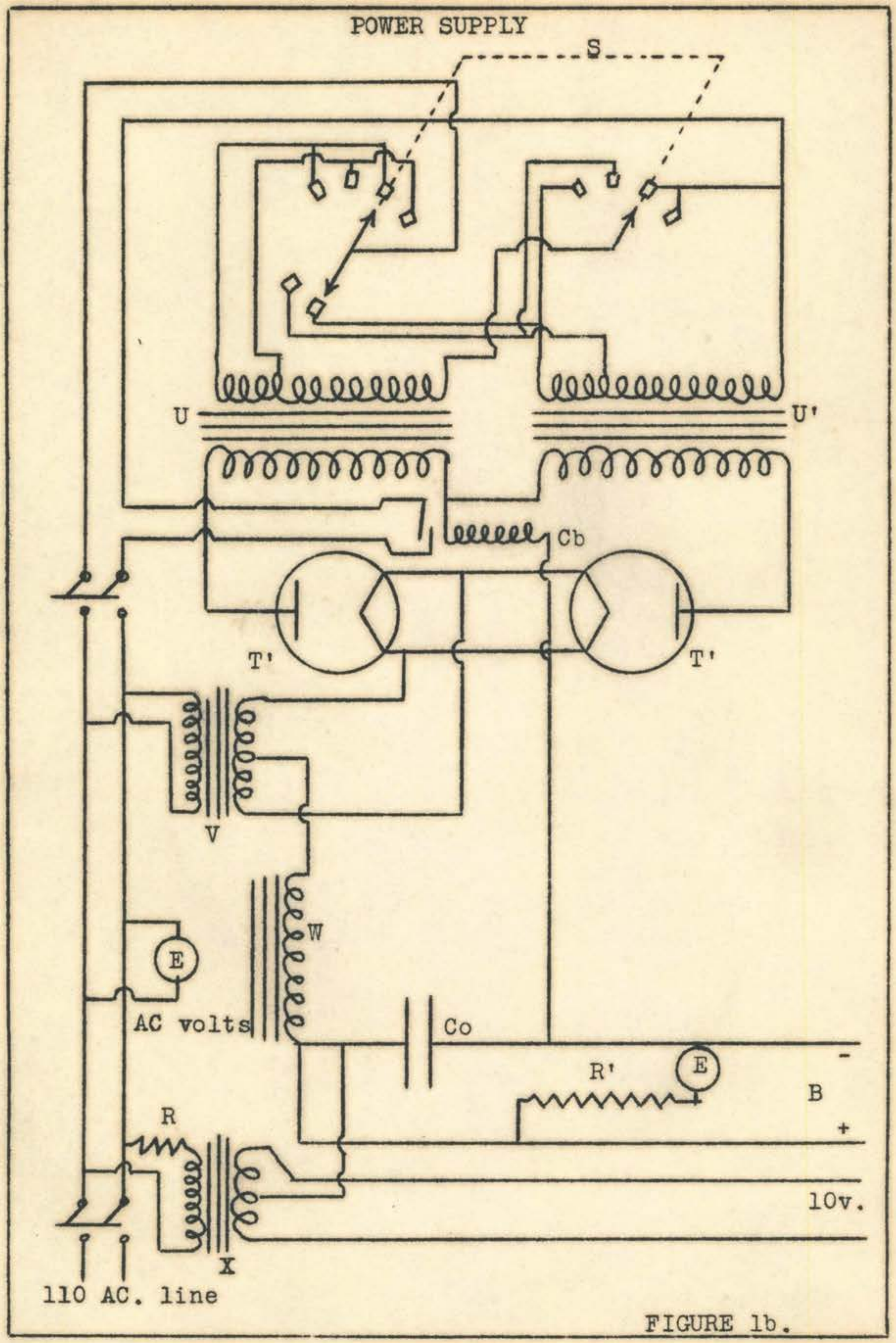

FIGURE 1b.

LEGEND

Figure 1a.

L'	High frequency induction coil secondary.
L	High frequency induction coil primary.
C	Tuning condenser for high frequency induction coil.
c	Grid blocking condensers.
m	Grid chokes.
T	Oscillator tubes.
c'	Bypass condensers.
m'	Plate choke for induction furnace.
N	Oscillator coil for induction furnace.
N'	Coupling coil for induction furnace.
N''	Induction furnace heating coil.
C'	Induction furnace tuning condenser.
C''	Series condenser for induction furnace heating coil.

Figure 1b.

S	Plate voltage switch.
U and U'	Plate supply transformers.
Cb	Overload relay.
T'	Rectifier tubes.
V and X	Filament transformers.
W	Filter choke.
Co	Filter condenser.
R	Filament rheostat.
R'	Plate voltmeter multiplier.

square root of minus one. Of course this can also be written in the polar form $Z\angle\theta$. In this form Z is $\sqrt{R^2 + X^2}$ and θ is arctangent X/R.

II. General Coupled Circuit Equations.

After this radio frequency power is generated by the vacuum tube oscillators it must be transferred to some other circuit to be used. This transformation is usually done by some type of inductive coupling. For such a coupled circuit as figure 2 it can be shown that [1]

$$Z'_{11} = Z_{11} - (Z_{12})^2/Z_{22} \tag{2}$$

where Z'_{11} is the apparent input impedance of the circuit,

Z_{11} is the self impedance of the primary,

Z_{12} is the transfer impedance between primary and secondary,

and Z_{22} is the self impedance of the secondary.

All of these impedances are taken without regard to the primary capacitance.

Usually the coupling will be to another resonant circuit, therefore Z_{22} will be a pure resistance. The transfer impedance Z_{12} will be purely inductive, therefore its square will have an angle of 180 degrees or be equal to a minus quantity at zero degrees. From these relationships the amount of coupled-in resistance added to Z_{11} to get Z'_{11} will be

$$R_1\ (\text{added-in}) = X_m{}^2/R_2 \tag{3}$$

where X_m is the mutual reactance and R_2 is the secondary resistance. This added-in resistance is approximately equal

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[1] W.L. Everitt, <u>Communication</u> <u>Engineering</u>, P. 22.

GENERAL COUPLED CIRCUIT

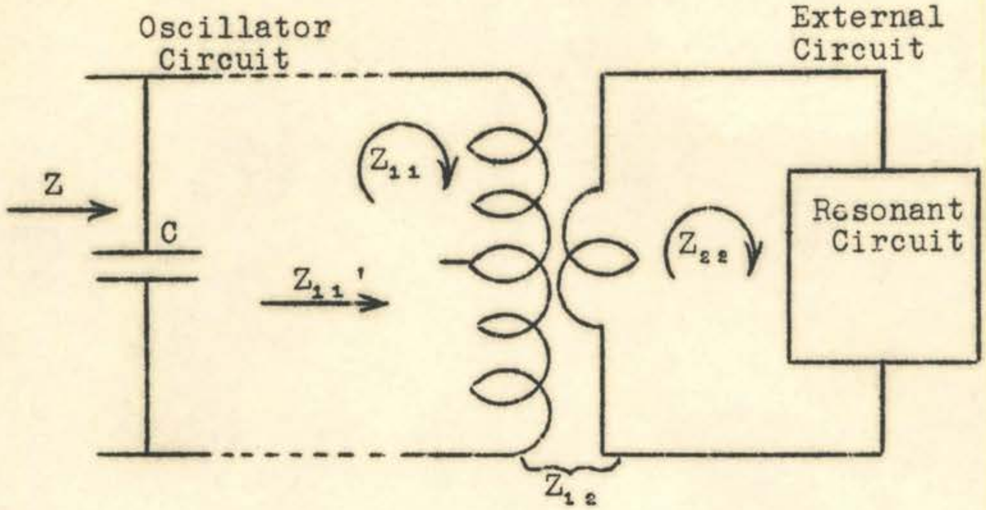

FIGURE 2.

PARALLEL RESONANT
HEATING CIRCUIT

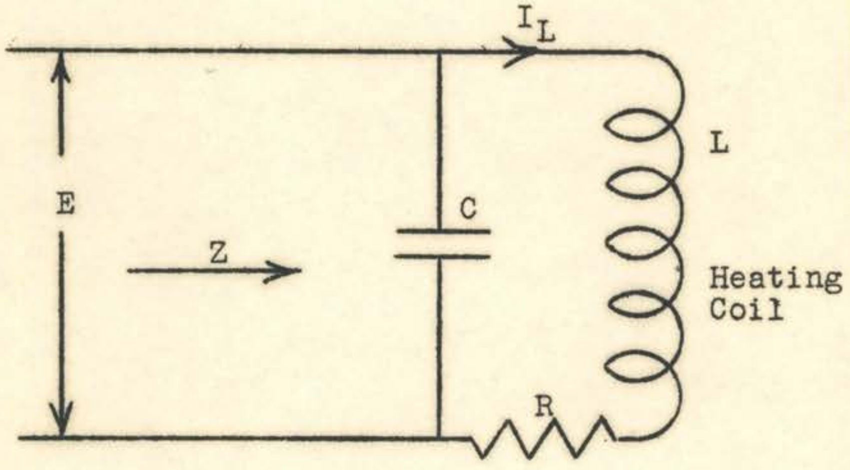

FIGURE 3.

to the total resistance of the primary due to the fact that the self resistance of the coil is very low. But the input impedance of the whole circuit including the primary capacitance has already been given as

$$Z = L/CR_1 \quad \text{but } R_1 = (X_m)^2/R_2 \text{, therefore } Z = LR_2/CX_m^2. \quad (4)$$

This last expression gives the impedance of the primary circuit with the secondary coupled to it. From it one can see that a decrease of R_2 (increased loading) would lower Z, and an increase of X_m (closer coupling) would lower Z. These four values must be adjusted so that sufficient power will be transferred to the secondary and so that the impedance of the circuit will be at least approximately correct for the tubes being used as oscillators. It is rather difficult to assign definite values to all of the constants in practice but they can be approximated by the standard inductance and capacitance formulae and any adjustments made experimentally. For instance X_m (the mutual reactance) can best be determined experimentally by either varying the distance between the primary and the coupling coil or by changing the number of turns on the coupling coil. In this particular case two turns around the primary coil were found to be sufficient for maximum power transfer.[2] This coupling coil is easily seen in picture number 2. The oscillator coil and its coupling coil are on the left in the picture.

[2] W.L. Everitt, Ibid, pp. 49 and 248.

III. Parallel Resonant Heating Circuit.

The relationships involved in the actual heating circuit of the induction furnace will now be considered. In other words the following relations deal with the circuit to which the oscillating circuit is coupled.

In the first place when one is dealing with high-frequency alternating currents he naturally thinks of two fundamental circuits, namely parallel resonant and series resonant circuits. The relations involved in the use of a parallel resonant circuit for induction heating will be considered first.

In a circuit such as figure 3 the input impedance, Z, as in equation (1), is L/CR, and the current through the inductance is

$$I_L = E/2\pi fL \qquad (6)$$

where the frequency, f, is determined by the LC circuit so that

$$f = 1/2\pi\sqrt{LC}\ . \qquad (7)$$

Therefore the current through the inductance becomes

$$I_L = E\ \sqrt{C/L} \qquad (8)$$

It is well known that at low frequencies, the eddy current heating W due to an alternating magnetic field is proportional to

$$W \propto B^2 f^2 \qquad (9)$$

where B is the flux density and f is the frequency. Assuming that this holds for radio frequencies and remembering that $B \propto NI$ and $L \propto N^2$, it can be shown that

$$W \propto N^2 I^2 f^2 \propto L(E^2C/L)1/LC \propto E^2/L \qquad (10)$$

and if the frequency is constant $W \propto E^2C$.

According to these relations the amount of eddy current heating, W, is proportional to the capacity in the circuit and inversely proportional to the inductance in the circuit, when E is constant.

If this parallel resonant circuit is in the plate circuit of the oscillator tubes, it can be shown that the voltage is practically constant as long as the tubes oscillate efficiently.[3] The above equation for eddy-current heating requires that L be small and C large while on the contrary L must be large and C small to meet the conditions of correct load impedance for the oscillator tubes as shown in equation (1). Obviously these two conditions are directly opposed to each other.

It is possible, electrically, to overcome these objections by a correctly designed coupling network but when this is done there are some other objections introduced. For instance such a network would probably require a coupling coil coupled to the oscillator coil, a transmission line to deliver the power to the heating coil, and the heating coil itself with its high-voltage, high-capacity condenser in parallel with it. Such a circuit, while perfectly possible and quite efficient, would be rather hard to adjust and inconvenient to handle. High-voltage, high-capacity condensers such as would be necessary in such a circuit are rather heavy and bulky. This would make the heating coil very inconvenient to move from one position to another and would render it practically immobile while being used.

[3] Peters, Thermionic Vacuum Tube Circuits, pp. 82 and 91.

SERIES RESONANT
HEATING CIRCUIT

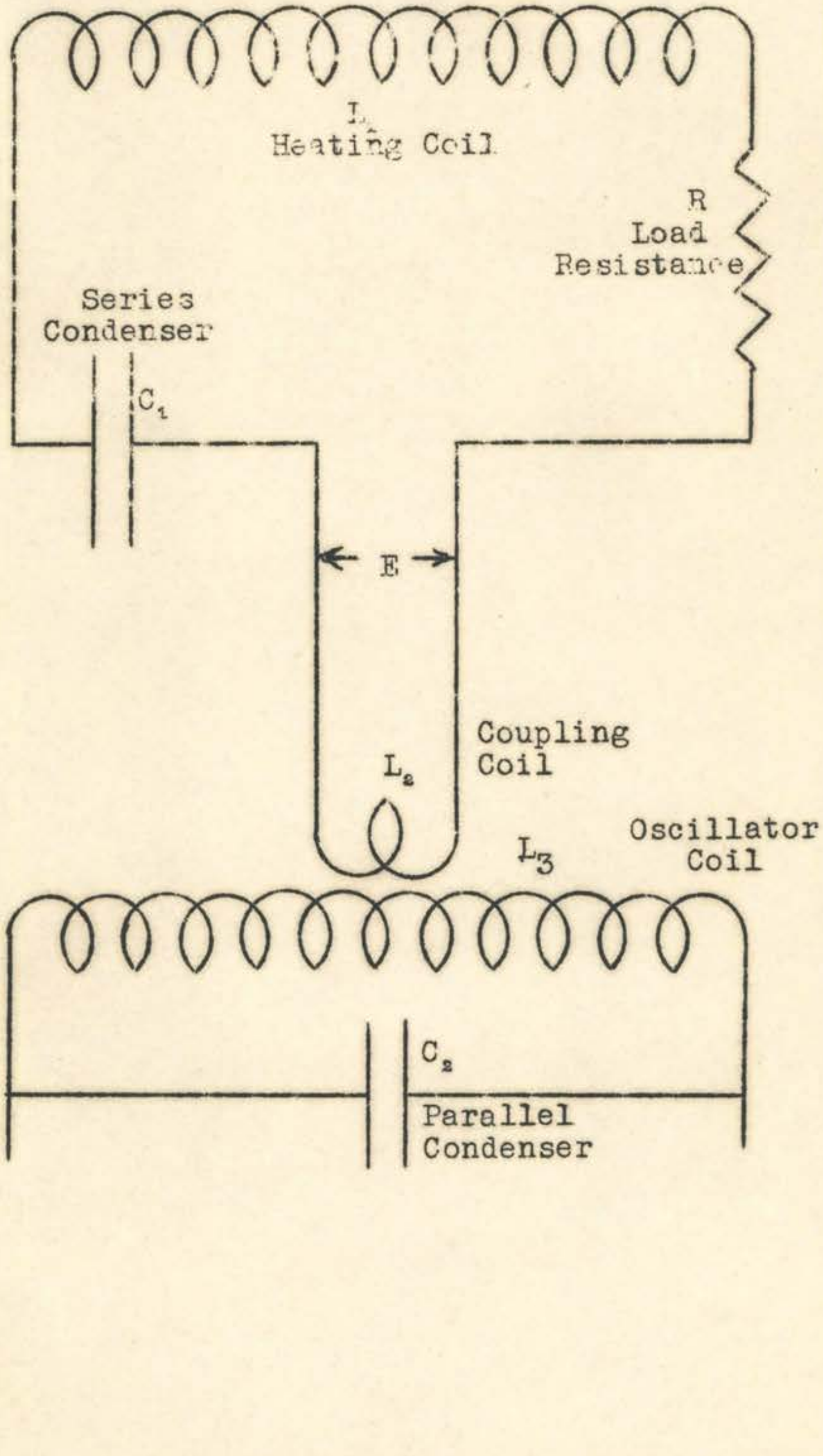

FIGURE 4.

IV. Series Resonant Heating Circuit.

The preceeding considerations leave much to be desired in the way of convenience and efficiency for an induction heating circuit. One would naturally turn from here to the series resonant circuit for a possible solution of this problem.

Consider the circuit diagram of figure 4 where the symbols have the following meanings:

L_1 is the induction heating coil. (N" in figure 1_a)
L_2 is the coupling coil. (N' in figure 1_a)
L_3 is the oscillator coil. (N in figure 1_a)
C_1 is the series capacity. (C" in figure 1_a)
R is the effective load resistance.

The impedance of a resonant circuit consisting of an inductance, capacitance, and resistance in series can be shown to equal R. Also at resonance the inductive reactance is equal to the capacitive reactance so that

$$2\pi fL = 1/2\pi fC \qquad \text{or} \qquad f = 1/2\pi\sqrt{LC} \tag{11}$$

The impedance, R, can be easily matched by a correct choice of the number of turns on L_2 or by varying the coupling between L_2 and L_3. The conditions for impedance match are also given in the reference 2, Page 7.

Since the impedance of this series resonant circuit is equal to R, the current through the circuit is E/R. In practice R can be made very low, therefore, while E is not extremely large, the current is rather high compared to the currents ordinarily obtained in radio frequency circuits of moderate power. As before the eddy current heating

$$W \propto B^2 f^2 \propto N^2 I^2 f^2 \text{ .} \tag{13}$$

$$\text{But } I = E/R \qquad L \propto N^2 \qquad \text{and} \qquad f \propto 1/\sqrt{LC} \text{ .} \tag{14}$$

$$\text{Therefore} \quad W \propto L(E^2/R^2)\, 1/LC \propto E^2/R^2C \propto LE^2/R^2 \tag{15}$$

for a given frequency.

According to this relation for the eddy current heating the inductance should be large and the capacitance small. This is a condition easily met in practice since the impedance of this resonant circuit does not depend on the inductance or capacitance in the circuit.

The size of the inductance is determined largely by the use that is going to be made of it because the use will approximately determine the length, diameter and the size of copper tubing of which it must be made. Since such coils are usually wound of copper tubing, these heating coils cannot have a large number of turns. The condenser must be able to withstand high voltages since a series resonant circuit usually has much higher voltages across each of the elements than the actual applied voltage. The actual physical sizes which are practical will approximately determine the frequency of operation by

$$f = 1/2\pi\sqrt{LC} \text{ .} \tag{16}$$

Low frequencies can be used by making the capacitance and inductance high, but high capacitance condensers have correspondingly higher losses than low capacitance condensers due to the dielectric loss at high frequencies and due to the relations derived above. Obviously there will be some optimum value of the frequency but these considerations are not very critical as can be seen from the reasons for giving any optimum value at all. An efficient circuit could probably be arranged operating at frequencies from a few hundred kilocycles to 10 or 20 megacycles. The present apparatus operates around 1 or 2 megacycles. This is not proposed as an optimum value, it has merely seemed to be convenient to design the elements to such a frequency.

V. Performance.

Using the circuit described above this instrument has been found to be very convenient and efficient. The leads used for the heating coil are number 00 arc welding cable which is very efficient and at the same time flexible enough to facilitate moving of the coil. The heating coil most commonly used is 3 inches in diameter and consists of 15 turns of 5/16 inch copper tubing.

With these circuit elements the instrument will heat, in free air, an iron cylinder (1/2 inch in diameter, 3 inches long and 1/32 inch thick) to a dull red with an actual power input of less than 200 watts. (This iron cylinder is a neon sign electrode). With 800 to 1000 watts input to the oscillator tubes, the instrument will heat 6 inches of a 3/4 inch solid iron rod to a red heat. Similar objects require proportionate amounts of energy.

It is advisable to use as small a coil as possible for the heating coil in order to concentrate the flux around the object to be heated. For this reason it is convenient to have several sizes and shapes of coils on hand for different applications. For instance a spiral or "pancake" wound coil might be useful when heating some small object or a localized region, while a large-diameter, cylindrical coil might be necessary if the object to be heated happened to be either large or enclosed in a large glass vessel. Since this apparatus was designed to out-gas the elements of experimental vacuum tubes, all such conditions are often encountered.

B. HIGH-FREQUENCY, HIGH-VOLTAGE INDUCTION COIL.

I. Parallel Resonant Secondary Circuit.

The high-frequency, high-voltage induction coil consists of an oscillatory circuit connected in the plate circuit of the vacuum tube oscillators and this coil in turn coupled inductively to a long coil of many turns in which is induced the high-frequency, high-voltage currents.

It can be shown that the secondary current I_2 of a coupled circuit such as figure 5 is given by[4]

$$I_2 = \frac{-EZ_{12}}{Z_{11}\ Z_{22} - (Z_{12})^2} \qquad (17)$$

where E is the primary voltage, Z_{12} is the mutual impedance which is equal to $-jwM$ when M is the mutual inductance, Z_{11} is the self impedance of the primary without C, and Z_{22} is the self impedance of the secondary including its inductance, effective resistance, and distributed capacitance. The voltage E_2 across the secondary coil is then $wL_2 I_2$ or

$$E_2 = \frac{E\ (jwM)\ (jwL_2)}{Z_{11}\ Z_{22} + (wM)^2} \qquad (18)$$

$$\text{But } Z_{22} = R_2 + j(wL_2 - 1/wC_2) \quad \text{and } w = 2\pi f \qquad (19)$$

$$\text{Therefore} \quad E_2 = \frac{-E\ w^2\ ML_2}{Z_{11}\ (R_2 + j(wL_2 - 1/wC_2)) + (wM)^2} \qquad (20)$$

For E_2 to be maximum $wL_2 = 1/wC_2$ and M should be just large enough for maximum power transfer. (Reference 2)

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[4] W. L. Everitt, Op. Cit., pp 221.

HIGH-VOLTAGE HIGH-FREQUENCE INDUCTION COIL

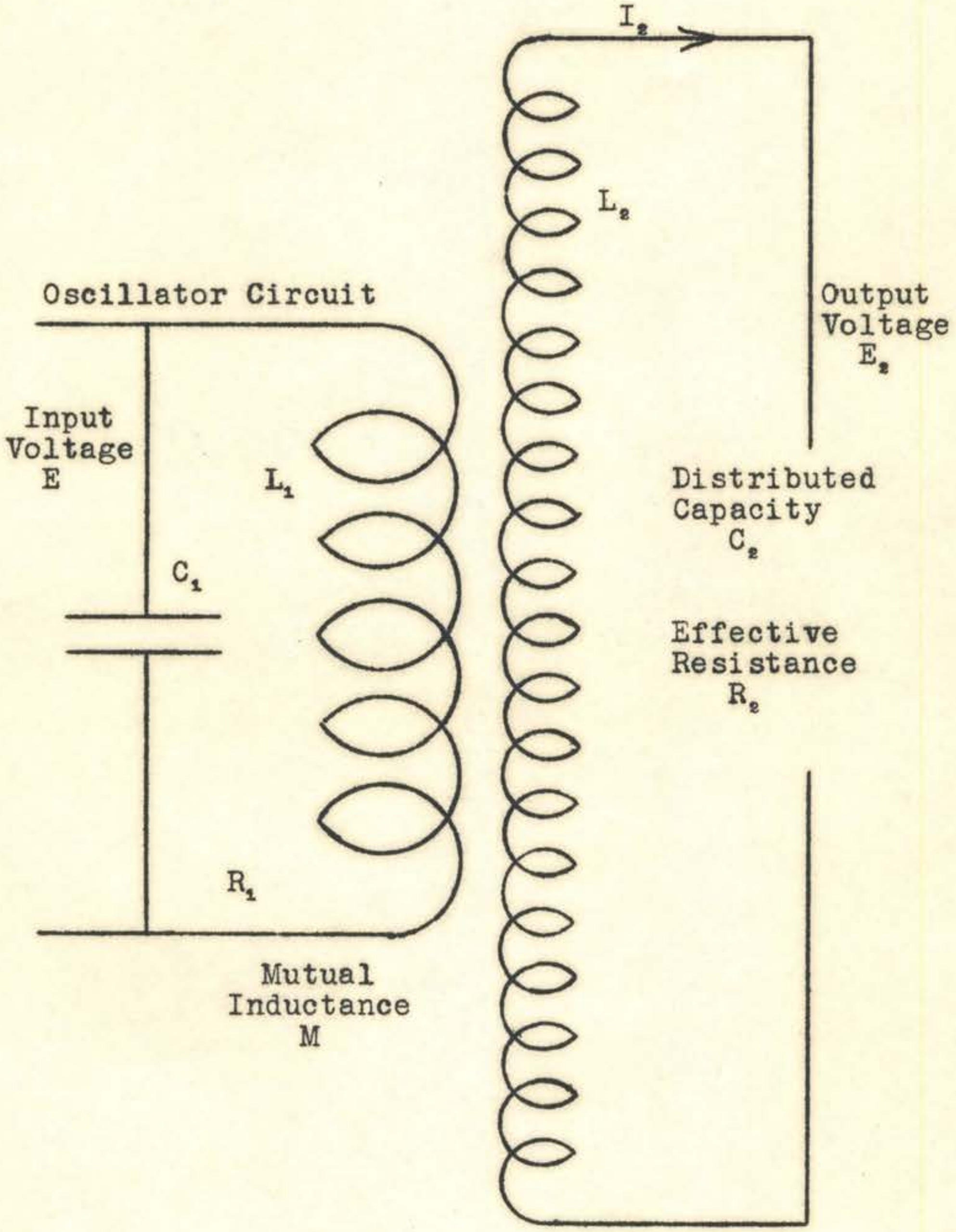


FIGURE 5.

Z_{11} must have a definite value in order to present the correct load impedance to the tubes used according to the relation L/CR. For the oscillating circuit which is a resonant circuit $wL_1 = 1/wC_1$ and since it has already been shown that $wL_2 = 1/wC_2$ then

$$L_1C_1 = L_2C_2 \tag{21}$$

The ratio between the primary and secondary voltages can be shown to be approximately

$$E_1/E_2 = k\sqrt{L_1/L_2} \tag{22}$$

when the primary and secondary are both parallel resonant at the same frequency.

In order to obtain a high voltage E_2, this equation says that L_2 should be high compared to L_1. But according to equation (21) C_2 would then have to be small compared to C_1. It must be remembered, however, that L_1 must not be too small compared to C_1 because of equation (1). The above conditions are not hard to meet because C_2 is the distributed capacity of the secondary and is, therefore, quite small. Similarly L_2 is a long coil of many turns of small wire and consequently it has a rather large inductance compared to L_1.

II. Series Resonant Secondary Circuit.

A series resonant circuit coupled to a vacuum tube oscillator might also be used to produce these high-voltage, high-frequency currents, as will be seen by the following relationships. The current in such a series resonant circuit as figure 6 is very high as has been shown by equation (12). Therefore the voltage across any one element of the circuit

SERIES RESONANT CIRCUIT FOR
PRODUCTION OF HIGH VOLTAGES

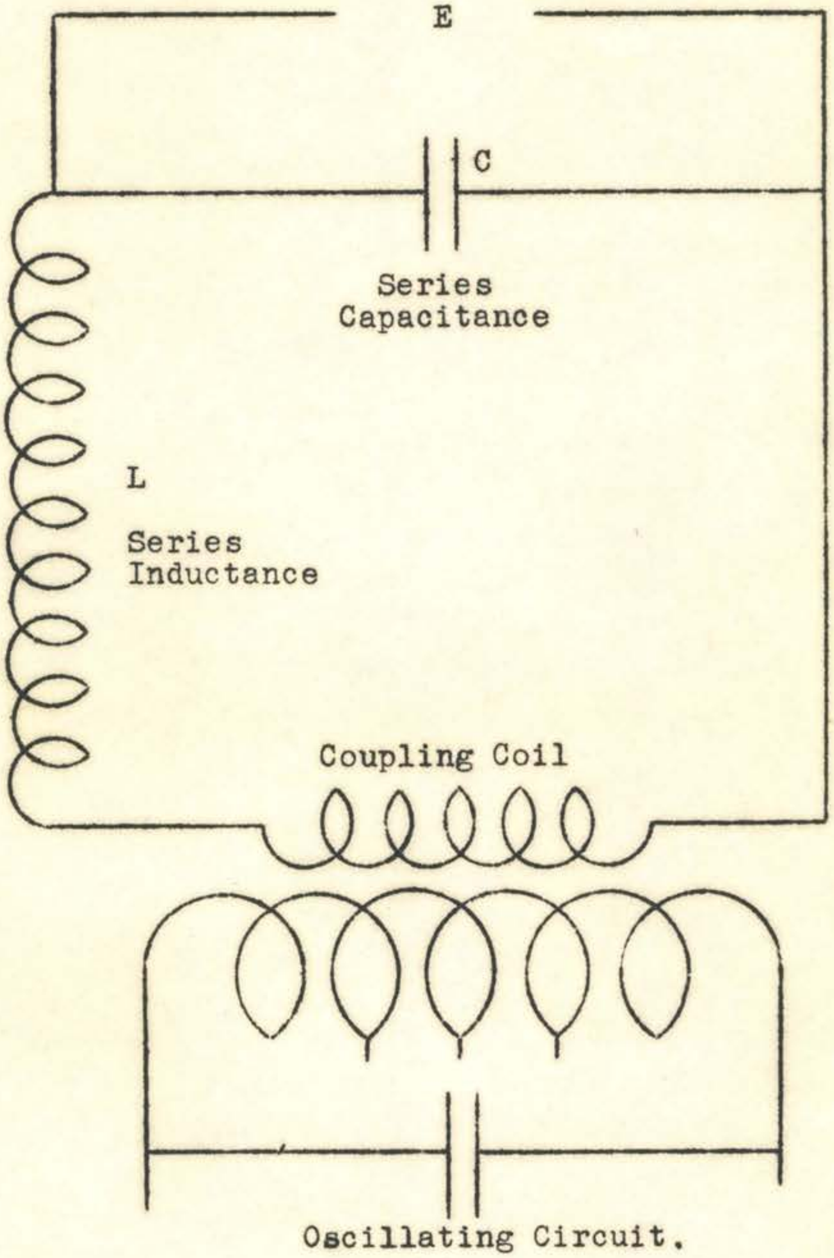


FIGURE 6.

is correspondingly very high. For instance the voltage across the condenser is

$$E = I/2\pi fC, \qquad (23)$$

which is seen to be greatest for low frequencies and low capacities. However, a low frequency and low capacity would necessitate a very high inductance. As an illustration consider a 100 $\mu\mu$f condenser at a frequency of 200 kilocycles. For these values X is about 8,000 ohms. Therefore, to obtain a voltage of about 200,000 would require a resonant current of approximately 25 amperes. With a circuit having a Q [5] of 100 this would require almost 2000 volts input to the series circuit. In such a case the power loss in the circuit would be 50,000 watts, which is much more than that available in the present apparatus. If an inductance having a Q of 1000 or more could be designed, a series resonant circuit might prove useful here. Otherwise such a circuit is quite impractical.

III. Frequency Used.

It has been found that the amount of energy dissipated in the corona discharge increases as the frequency increases. This makes it necessary to use low frequencies in order to obtain high potentials. On the other hand it is expected that this instrument will be used to show that high frequency currents have no harmful effects on the human body. To meet this last requirement the frequency must be greater than 100 to 150 kilocycles. With this in mind this instrument was

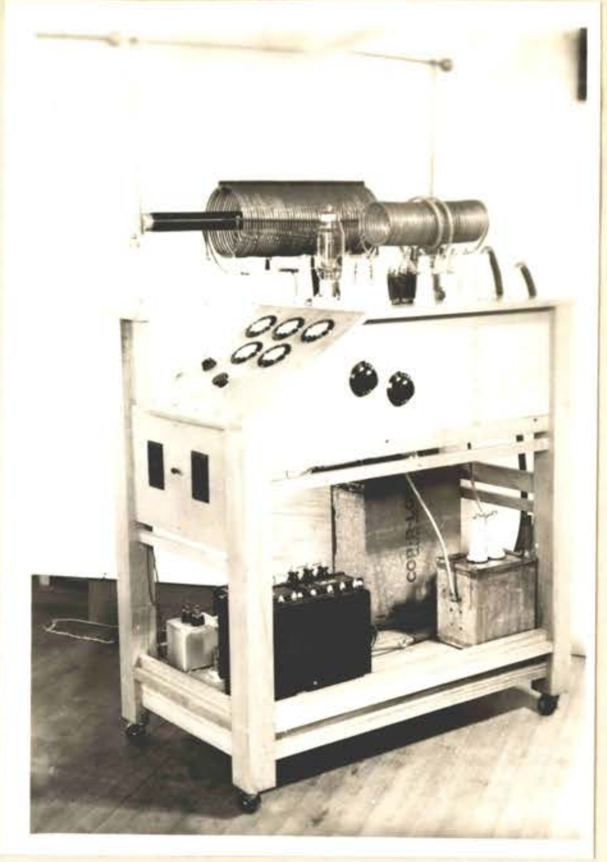
[5] W.L. Everitt, Ibid., pp. 65.

designed to operate on a frequency of approximately 300 kilocycles. The only sensation that can be observed when this current is allowed to flow through the body is one of warmth where the current enters the body. In all respects this choice of frequency has proven quite satisfactory.

IV. Performance.

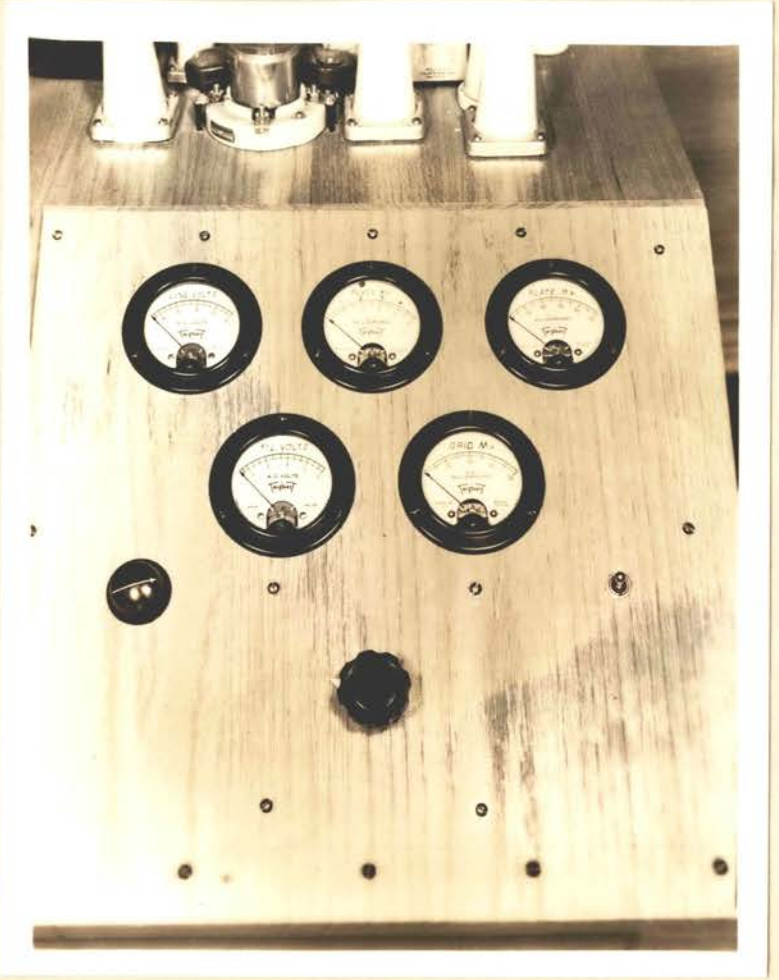
Operating at a frequency of around 300 kilocycles, this instrument will produce a corona discharge at the electrodes which appears to the eye to have 6 or 8 "fingers" about 6 inches long. It is capable of producing a spark 10-12 inches long which appears to be 1/4 to 1/2 inch in diameter. 1/4 inch iron rods were used for the electrodes because either the corona discharge or the spark has energy enough to keep the points at a red heat. Care must be taken in the design of the supports for the high voltage coil to prevent corona discharge from forming on sharp corners of it. It must have very smooth, round corners and the ends of the wire on the coil must be carefully protected to prevent the corona discharge from burning them in two.

This instrument has been found to be very satisfactory for the many interesting and instructive demonstrations that are usually performed with high-frequency, high-voltage currents.



Picture Number 1.

Picture Number 2.



Picture Number 3,

Picture Number 4.

C. DESCRIPTION OF INSTRUMENT

I. General Layout.

As can be seen from the photographs, this instrument was built on an oak table about 42 inches long, 24 inches wide and 42 inches high. This table has two under-shelves to hold some of the heavier and more unsightly equipment, and a sloping panel at one end for the necessary instruments and control apparatus. The bottom shelf supports the two power transformers, rectifier tubes, filament transformers, filter choke, and filter condenser at the end next to the panel. At the other end of this shelf are the series condenser for the induction furnace circuit and the larger condenser for the induction coil primary circuit. The second shelf holds the tuning condensers for both circuits and a few other small items. The tuning knobs for these condensers are on the right side of the table when one faces the instrument panel.

On top of the table is mounted the two oscillator tubes, the two oscillator coils and the respective grid chokes and blocking condensers. The tubes are in the center with the induction furnace coil on the right and the high frequency induction coil on the left. Provision is made to switch the tubes from one circuit to the other by means of "banana" jacks in the top of porcelain stand-off insulators.

The instrument panel consists of 5 meters which read the following: Plate current in milliamperes, plate voltage in kilo-volts, grid current in milliamperes, filament volts, and line volts, A rotary switch to change the plate voltage, a switch to change the grid meter from one tube to the other, and a filament rheostat are also mounted on the sloping instrument panel. On the vertical panel just below the meter panel is mounted ON and OFF switches for both filament and plate circuits and an overload relay to protect the power supply.

As far as the actual arrangement of parts on the table, this short description and the pictures on the preceeding pages should be quite sufficient. However, some further details on the design and construction of some of the component parts might be of interest.

II. The Series Resonant Condenser For The High-Frequency Induction Furnace.

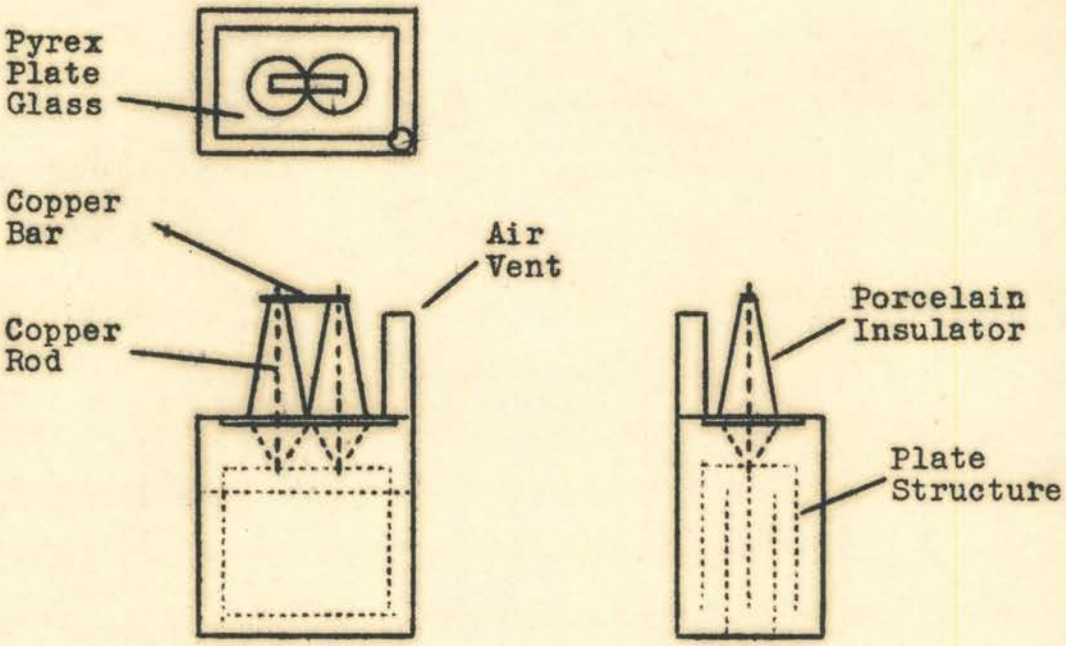
It can be shown from the preceeding theory and equations (12) and (21) that this condenser must be able to withstand about 50,000 volts. From experience it has been found that 1 inch of space in oil is necessary to give sufficient insulation. This would correspond to 300,000 volts insulation for direct currents but radio frequency currents require much more insulation.

This condenser was built of 18 gauge galvanized iron. The main box is 9 inches high, 6 inches wide, and 8 1/2 inches long. Vertically in the bottom of the box there are two plates 6 inches high welded to the ends of the box and spaced 2 inches apart. The top of the box consists of a metal rim holding a piece of pyrex plate glass with 2 lead-through insulators mounted on it. On the bottom of these insulators is mounted a three plate structure designed to fit between the box and the two welded-in plates and leave 1 inch space on all sides and ends. The drawing of figure 7 might help to clarify this description. The connections to this condenser are made to the top of the insulators and to the box itself as shown in picture 4. The circuit was so arranged that the box could be at low potential.

This condenser is filled with distillate which seems to be a very good dielectric at the frequencies in use. There have been no objectionable losses observed in it due to either dielectric loss or to the resistance loss in the iron. Assuming a current of 25 amperes in this circuit (which is surely much too low) a resistance of only 0.6 ohm would account for 1000 watts of power absorbed. Therefore the resistance of this condenser is probably of the order of a few hundredths of an ohm since very little power loss is observed.

It is very interesting to note that just any dielectric is not suitable for this application even if it does have a dielectric strength high enough. One has to give the dielectric loss and dielectric constant just as much consideration as the dielectric strength. For instance glycerine with a dielectric constant of 56 and a dielectric strength of probably 100,000 volts per centimeter is absolutely no good for a condenser operating at radio frequencies. In some experiments with glycerine a small condenser with 2 inches of plate area and 1 1/2 inch spacing was connected across the oscillator coil of the induction

SERIES CONDENSER FOR INDUCTION FURNACE



Scale 1/8 inch = 1 inch

FIGURE 7.

PARALLEL CONDENSER FOR INDUCTION COIL

Plate Structure

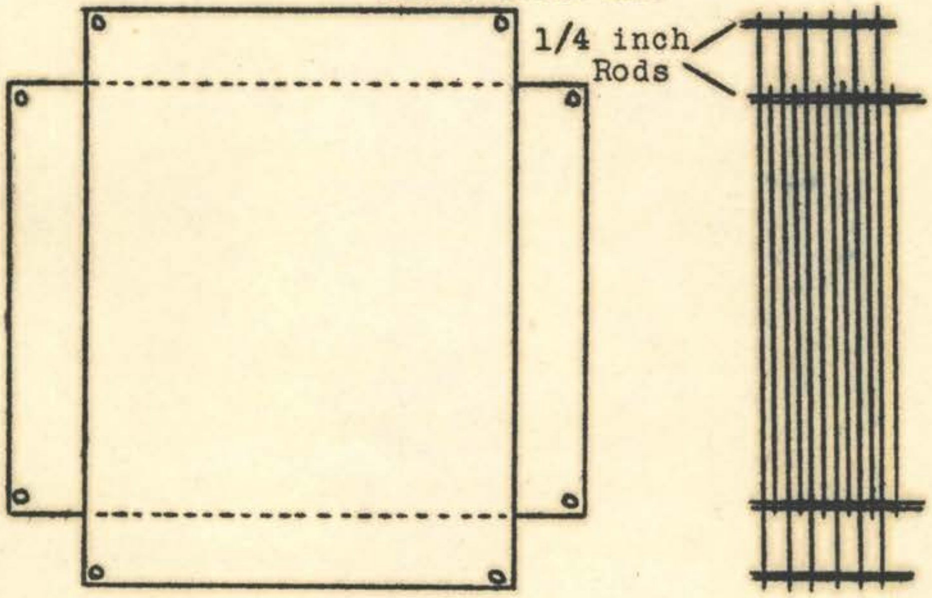


FIGURE 8. Scale 1/4 inch = 1 inch

furnace. This small condenser had almost enough loss to stop the tubes from oscillating. About 100 cubic centimeters of glycerine became hot to the touch in a few seconds of operation. Glycerine is an extreme case but similar trouble was observed with many other substances which were tried. In general a substance with a dielectric constant greater than 4 or 5 will have a high loss in the radio frequency region.[6]

III. Parallel Condenser for the High Frequency Induction Coil.

This condenser operates at a much lower voltage and must have a much higher capacitance than the other one. It is built, as shown in figure 8, of 11 or 12 plates spaced 1/4 inch and 9 inches by 12 inches in area. These plates are supported by 1/4 inch bolts through holes in the corners of the plates using nuts as spacer. Alternate plates are laid across the plate next to it thus dividing the plates into two sections as shown in the left view of figure 8. This whole assembly is supported in a tank of oil by means of small stand-off insulators and two small lead-through insulators are used for connections. As in the previous condenser the oil used is distillate.

The variable condenser for this circuit is on the second shelf and is also mounted in a tank of distillate. It is a standard small transmitter type of condenser.

[6] E.J. Murphy and S.O. Morgan. The Dielectric Properties of Insulating Materials. The Bell System Technical Journal, Vol. XVI October 1937 (640-670) and Vol. XVII October 1938 (493-513).

IV. The High-Frequency Induction Coil Primary.

This coil was wound from 100 feet of 1/4 inch copper tubing. It was first shaped to size on a glass battery jar of convenient proportions then threaded on the three bakelite strips. The bakelite strips have holes drilled in them at equal intervals to hold the tubing rigid and evenly spaced. This looks like a rather tedious process, but it eliminates the necessity of bolts or slotted strips and their necessary limitations.

V. The High-Frequency Induction Coil Secondary.

The secondary coil of the high-frequency, high-voltage induction coil consists of 5,000 turns of number 34 enameled wire wound on a 50 millimeter pyrex glass tube three feet long. The winding was done on a machine lathe using the lead screw to space the wire evenly 140 turns per inch. The coil is mounted on two 6 inch pyrex stand-off insulators so as to be in the center of the primary coil. This arrangement is clearly seen in pictures number 1 and 2. The high potential electrodes are also easily seen in the pictures. The air gap is readily adjusted by sliding the electrode having the long, hard-rubber handle.

D. CONCLUSION.

It is concluded that it is possible to build a simple and comparatively inexpensive instrument capable of performing the two functions that were originally desired. In the present instrument there is enough power available to do most of the jobs of induction heating that are encountered in the physics laboratory. At the same time the apparatus is simple enough to operate to afford quick and efficient application.

The high-frequency induction coil delivers enough power at a sufficiently high voltage to enable one to perform the standard demonstrations with such currents. On the other hand it lacks the element of danger so often observed in the case of spark-gap operated induction coils. With vacuum tube oscillators one does not have to worry about the frequency being too low due to failure of the gap to operate properly or due to the improper adjustment of the coil or condenser.

This type of apparatus is more expensive than some other types, but it is believed that the increased efficiency, ease of operation, and safety is well worth it.

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