A STUDY OF MAGNETOSTRICTION AND THE DESIGN AND CONSTRUCTION OF A MAGNETOSTRICTION OSCILLATOR

by

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INTRODUCTION

Magnetostriction is the name given to the elongations and contraction of a material when it is magnetized and demagnetized. That is, when rods of certain metals are placed in a magnetic field they will either expand or contract depending on the properties of the metals. It has been found by research that almost practically pure nickel, which is only slightly magnetic, has very strong magnetostrictive properties, while on the other hand iron and steel rods, which are strongly magnetic, show very little magnetostrictive response. There is also a reciprocal relation in which the magnetic properties of a rod in a magnetic field can be changed by applying a mechanical stress. Burrows in a Bureau of Standards bulletin says, "There is one and only one set of physical and chemical properties corresponding to a given set of magnetic characteristics, and that conversely there is one and only one set of magnetic properties corresponding to a given set of physical and chemical characteristics." That is, if a ferromagnetic rod increases its length when placed in a magnetic field then by applying a mechanical pull to the rod, while it is still in the magnetic field, its permeability will be increased to a larger value.

HISTORY

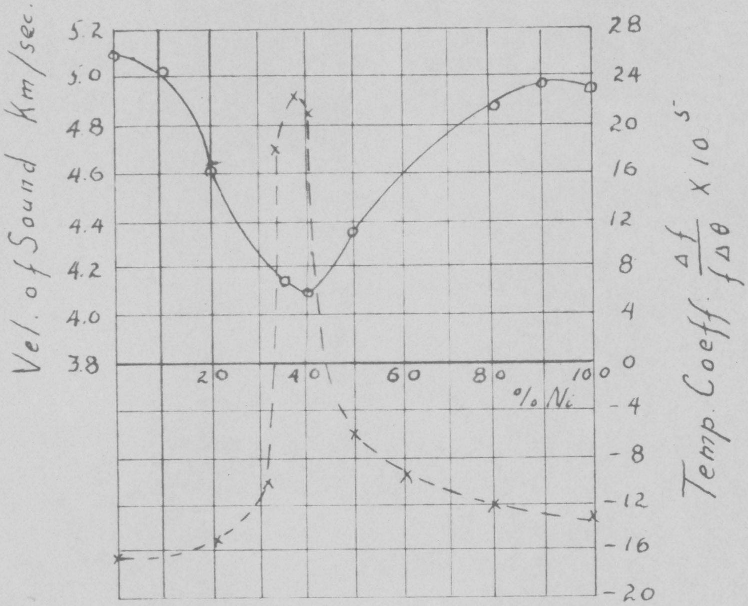
The first experiments recorded that had any relation to magnetostriction was made by C. G. Page at New Haven in 1837. He hung a horseshoe magnet over a spiral wound conductor, and by connecting and disconnecting a voltaic cell to the terminals of the spiral he obtained a characteristic sound. The magnetic field set up by the spiral was induced and removed in the horseshoe magnet and thus caused changes in dimensions which in turn produced the sound. Others, such as G. Wertheim, Delezenne, J. P. Marrian, W. Beatson, and C. Matteucci carried out similar experiments by changing slightly the size and shape of material, the magnetizing coil, and the method of support.

In 1842 James Prescott Joule wrote a paper in which he described a means of measuring very small linear displacements which he had used in proving that an iron rod expanded along the axis of magnetization and contracted at right angles to the axis for the relatively small magnetic fields that he was able to produce. Joule also found that by applying tension to the iron rod the magnetization was increased in the given magnetic field. Joule made his measurements with an extensometer which consisted of two levers in tandem, the outer end of the second lever being amplified by a microscope. He obtained very accurate results in this way.

In the Joule effect, the linear change in length, due to a longitudinal field, is very small and great care must be taken so no outside force will effect it. First the uniformity of the magnetic field must be considered, and means of keeping it uniform over a length of time must be devised. Also the rod must be placed in the solenoid in a symmetrical position, and it should be separately suspended from the coil. Then other magnetic fields such as the earth's field and the fields of permanent and electro magnets must be taken into account. The most important factor of all is the temperature. Great care should be taken in maintaining a constant temperature throughout a series of experiments. This effects not only iron rods, but also rods of nickel, cobalt, and alloys of the three metals. G. W. Pierce has done some work in this field and found that different percentages of metals in the alloys effected the temperature coefficient.

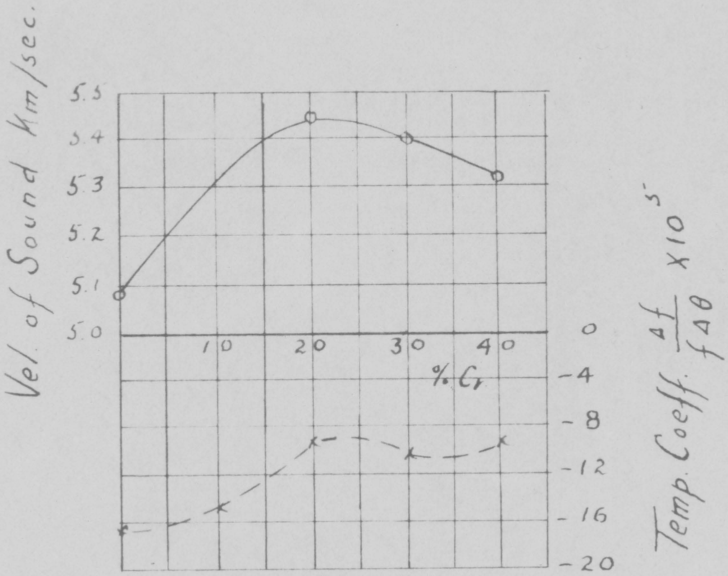
Figures 1, 2, and 3, taken from some of Pierce's work show the relation of the temperature coefficient and the percentage of nickel and chromium in iron rods. Pierce also has found the velocity of sound in the different rods and plotted it against the percentage of nickel and chromium in the iron rods. Figure 1 shows the percentage of nickel in iron. It is seen that the temperature coefficient has a maximum value and the velocity of sound has a minimum value at about 36% to 40% nickel. Figure 2 shows the same relations for the various percentages of chromium in iron. This gives slightly different results in that the temperature coefficient is a maximum and the velocity of sound is also a maximum at 20% to 25% chromium. Pierce said that this possibly suggests a law "that in a binary metallic alloy the temperature coefficient of frequency is a maximum or minimum at the composition at which the velocity is a maximum or minimum, or the reverse." Figure 3 shows the effect of introducing a third element of 5% silicon in the chromium-iron rods. The curves with and without silicon are compared on the graph, and it is found that at 20% chromium, 5% silicon, and 75% iron, there is a large minimum value of velocity. The effect of adding the silicon also obeys the law of Pierce stated above.

Curves Showing Results for Velocity and Temperature Coefficient of Various Alloys of Iron



Nickel-Iron Alloys

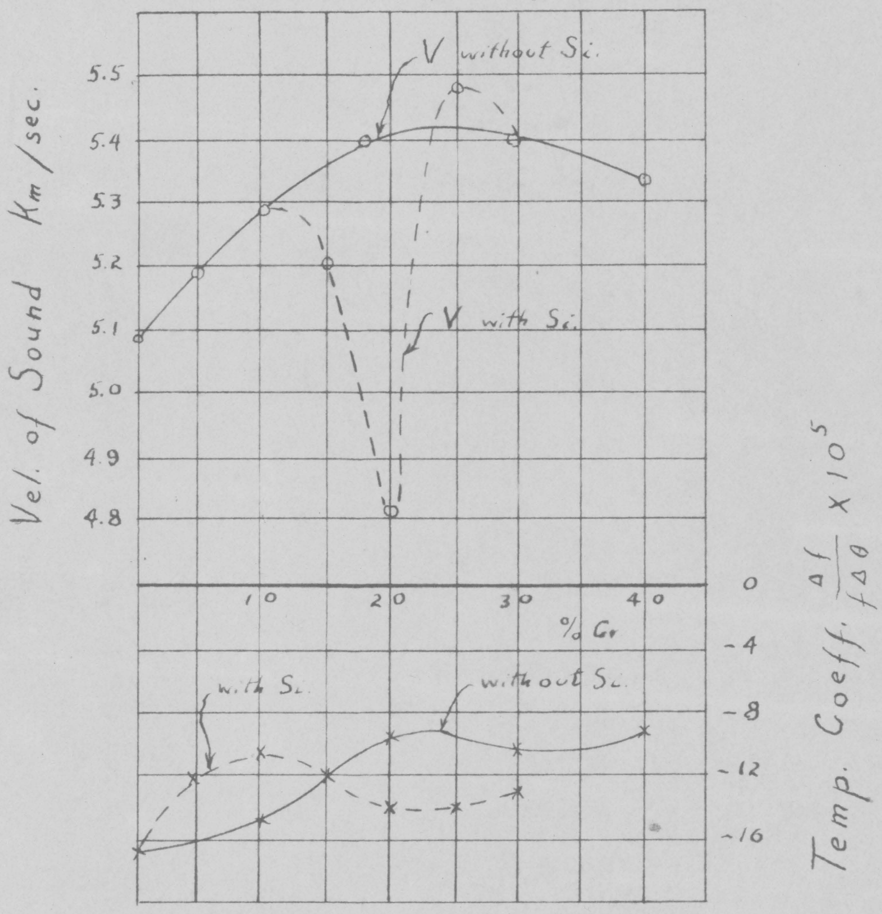
Figure 1.



Chromium-Iron Alloys

Figure 2.

Curves Showing the Effect of Silicon in Chromium - Iron Alloys



Chromium-Silicon-Iron Alloys

Figure 3.

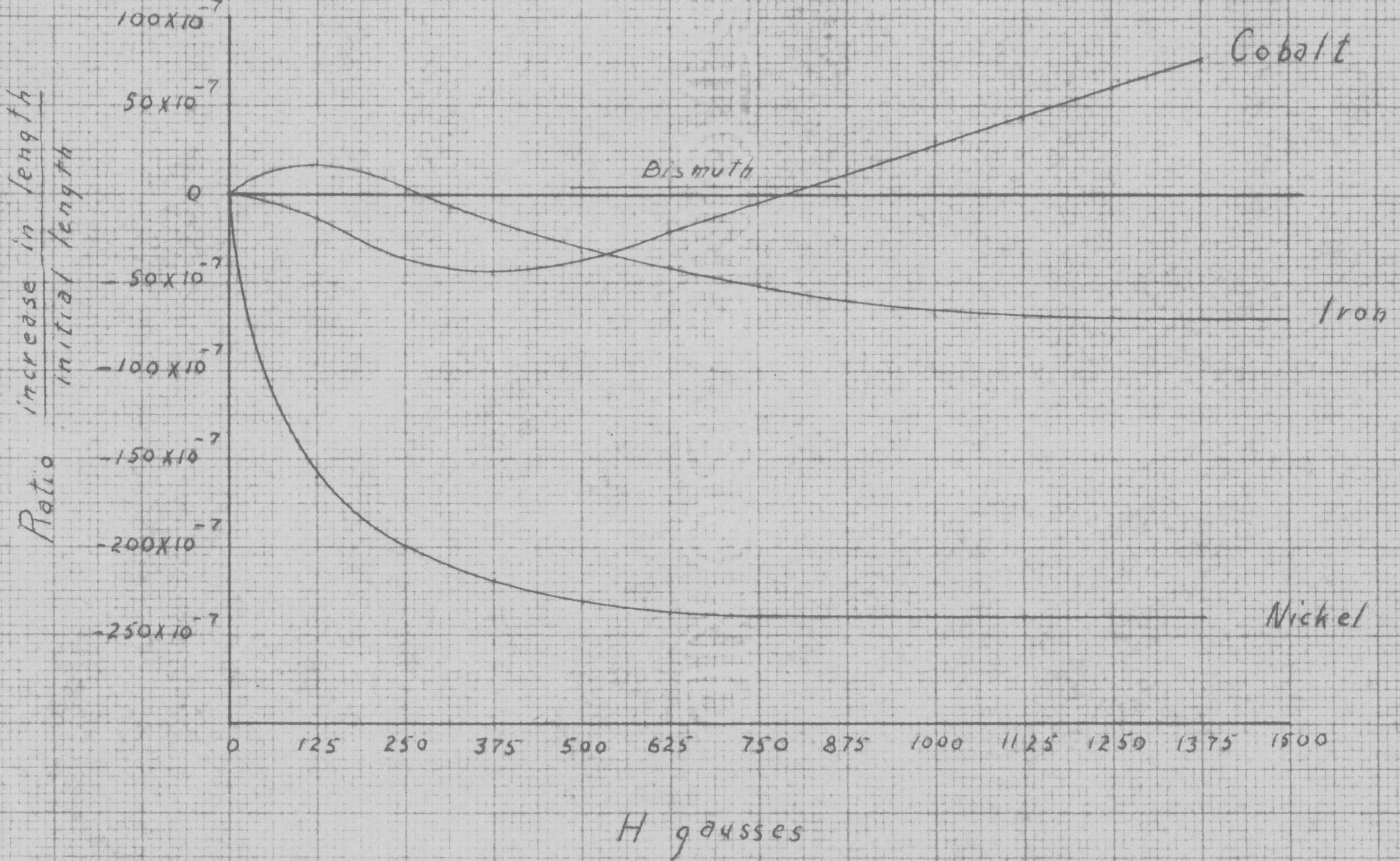

100X10^{-7}
50X10^{-7}
0
-50X10^{-7}
-100X10^{-7}
-150X10^{-7}
-200X10^{-7}
-250X10^{-7}
Ratio increase in length / initial length
Cobalt
Bismuth
Iron
Nickel
0
125
250
375
500
625
750
875
1000
1125
1250
1375
1500
H gausses

Figure 4.

Shelford Bidwell carried out some very thorough investigations on magnetostriction about 1890 in which he used an optical lever to measure the change in length of a rod. He was able to detect with accuracy a change of 10^{-7} times the length of his specimen. Bidwell tested nickel, cobalt, and bismuth besides iron rods in very strong magnetic fields as well as weak fields. His results are shown in figure 4. For iron it is seen that for value of the magnetizing force between zero and 270 gausses, the rod increases or expands with a peak or maximum value at 125 gausses. At a magnetizing force of 270 gausses, the rod neither shortens nor lengthens. Then if the magnetizing force is made greater than 270 gausses the iron rod tends to decrease in length and it continues to do so. The effect of magnetizing force on cobalt is opposite to that of iron. For magnetic fields up to 750 gausses the cobalt rod shortens in length with a minimum shortening at 375 gausses, and for values over 375 gausses the cobalt rod increases in length. The nickel rod acts differently from either of the other two in that it shortens or decreases in length for all magnetizing values. As can be seen from the graph, the change of magnitude is about five times as great as for either the iron or nickel. Bidwell found that the change in length of a bismuth rod was very small when magnetized as shown on the graph.

The reverse of the Joule effect or the changes in magnetic induction due to longitudinal stresses was first mentioned by Matteucci. Villari devised a much better method and found that when the rod is stretched in a fairly weak magnetic field, the magnetic induction is increased; but, if the rod is stretched in a strong magnetic field, the magnetic induction will decrease. This is known as Villari effect, and the point where stretching or compression does not effect the magnetic induction is called the Villari reversal point. The character of the Villari effect as in the Joule effect is greatly determined by heat treatment, stresses, and magnetization of the rod.

Mayer, in 1873, repeated some of Joule's experiments and found that steel rods, after being expanded in weak magnetic fields, and then being contracted in strong fields had become shorter than they were originally. He also observed that the length of a magnetized rod depended somewhat upon whether the applied field had reached the momentary value by an increase from a smaller value, or by a decrease from a higher value. This was a lag or hysteresis effect.

Beatson as early as 1846 made observations on rods when a circular magnetic field and a longitudinal magnetic field were both impressed on an iron rod at the same time. The resultant of these two fields gave one along a helix of the rod, which caused a twist in the rod. The stress in the rod would then be nonhomogenous; that is, there would be more change in a small volume near the surface than in a small volume close to the axis. Because the small twist could be more easily measured than the small linear expansions, work was done first on this effect of torsion. Then Wertheim in 1852 found that when a magnetized wire was twisted there was a transient difference in electrical potential between its end. Later Wiedemann, in 1860, published a report on the two effects. These effects still bear his name. That is, the direct Wiedemann effect is the twist due to the interaction of the circular and longitudinal fields, and the inverse Wiedemann effect is the axial magnetization of a rod or wire subjected to an axial torque and an electric current at the same time. Wiedemann, Smith, Groesser, and others have also observed that when a permanent torsion is set in a rod and a longitudinal magnetic field imposed on it that the rod will untwist. It was found that the direction of the magnetic field had nothing to do with the untwisting. They concluded that the twisted crystals in the rod along the permanent set would tend to become parallel to the imposed magnetic field and thus untwist the rod.

As there was a reverse of the Joule effect, there is also a reverse of the Wiedemann effect which is longitudinal magnetization due to twisting a circularly magnetized rod. The circular magnetization was produced by an electric current flowing lengthwise of the rod. Then when the rod was twisted, a transient current was set up in the coaxial coil, which indicated longitudinal magnetization.

In the Wietheim effect of circular magnetization due to twisting a longitudinally magnetized rod, the two terminals of a ballistic galvanometer were connected to the ends of the rod which had been longitudinally magnetized by a solenoid. When the rod was twisted, an electric current flowed along the rod and deflected the galvanometer which indicated that circular magnetization had been produced in the rod.

The Guillemin effect of bending of a rod due to a magnetic field was observed by Guillemin in 1846. He fastened one end of a rod one centimeter in diameter and twenty-five centimeters long in a clamp and put a weight on the other end so that it was slightly bent. When current was supplied to a solenoid which surrounded the rod, a magnetic field was set up. This caused the free end of the rod to lift slightly. Wertheim, Honda, Shimizu, and others studied this effect. In the Guillemin effect the upper half of the rod is in tension while the lower half is in compression; and some think that the bending is caused by this tension and compression when the Joule effect takes place. Others have the theory that the fibers of the bar along the axis tend to set themselves parallel to the field.

The change in volume due to a magnetic field is known as the Barrett effect. Joule, in 1847, looked for volume changes by placing the specimen in a liquid and looking for a slight movement of the liquid in a capillary which was placed on the tube containing the liquid. Joule didn't find any movement due mainly to the fact that his specimen had not been magnetized to the saturation point. Barrett was the first to really detect any change of volume caused by a magnetic field. Barrett used a rod of nickel instead of iron as the nickel gave him greater change in dimensions. Knott also did some work along these lines, but he worked with hollow iron, steel, and nickel tubes.

The Nagaoka - Honda effect is the reverse of the Barrett effect, that is the change in magnetic intensity due to volume changes. Yeh has made some very careful experiments along this line at much higher pressures than Nagaoka and Honda used.

Some magnetic effects which might be due to magnetostriction are as follows: Changes in thermo emf due to a magnetic field. If a thermocouple of copper and iron, when maintained at a constant temperature, is subjected to a magnetic field, the magnitude of the emf is changed slightly. This seems to have a relation similar to the Joule effect. Lord Kelvin observed that a magnetized piece of iron showed a thermo emf when joined to an unmagnetized piece of iron. Smith has studied the effect of tension on thermo emf by a magnetic field in both nickel and iron. He found that tension on nickel increased the thermo emf for strong fields and decreased the thermo emf for weak fields.

Electromotive force due to magnetization is obtained by placing two pieces of iron in an electrolyte and magnetizing one of the pieces. An emf was set up between the iron pieces before either was magnetized, then when one piece was magnetized a change in the emf could be noticed. Usually the unmagnetized piece is negative and the magnetized piece is positive. For nickel the magnetized piece is always positive while bismuth is just the reverse.

When a rod of any substance is magnetized, it has a change in electrical resistance. This is very noticeable in bismuth, which is used in measuring magnetic field strengths by its change in resistance. As seen earlier in the paper, bismuth has very little or no magnetostrictive response; and, therefore, the change in resistance is not caused by changes in dimension. Williams and others have stated in their work that there is a relation between the change in length and the change in resistance in steel.

There are changes in the frequency of vibrating bodies when they are magnetized. This effect is true for either a tuning fork or a steel rod clamped at the center. The angle at which the tuning fork makes with the magnetic field also has an effect on the frequency.

A click or tick is emitted when a rod is magnetized. This may be due to effect of both the electric current and the magnetic force, or some think it is due to the sudden expansion or contraction of the rod when magnetized.

Barkhausen, by connecting in a radio amplifier a coil of many turns, placing a metal strip in coil, and applying a magnetic field observed that a murmuring could be heard in the telephone receiver. It seems that the magnetization takes place in jumps rather than continuously. In magnetizing silicon-steel the crystals change their length in jumps; therefore, there may be a relation due to magnetostriction.

Theories of Magnetostriction

Thomson's Theory

Attention was called to some relations of the changing in length of a wire and the magnetizing force by J. J. Thomson, in 1886. He said the two effects of the change of length of a rod when magnetized and the changing of magnetization of a wire in a magnetic field by varying its length, must be dependent upon each other. Thomson's theory does not take into account the magnetic hysteresis and, therefore, only holds in cases where hysteresis is unimportant. If the sign of any effect is known, then Thomson's theory can be used in determining the sign of the reciprocal effect, that is, in nickel, which always contracts when magnetized, we will know that tension tends to decrease and compression will tend to increase the magnetization along the axis of the stress in the rod.

Ewing's Theory

Ewing's theory of ferromagnetism depends on the behavior of the molecules of the element in a region on an atomic scale. Using this basis, Williams and others summarized the principle features of magnetostriction by calling them theories of maneuver. They concluded that the changes in dimensions were due to gradual rotation of non-spherical elements which are atoms or groups of atoms, and the atoms were thought of as undergoing simultaneous equal changes in magnetization. Ewing's theory offers no explanation of the peculiar way in which permallory acts. In alloys it would not be expected that the individual atoms were symmetrically surrounded by their neighbors, as in pure metals, but Ewing does not mention this at all. Ewing's theory makes it necessary that every atom be symmetrical with respect to every other atom.

Atomic Orientation

By referring all of the various magnetostrictive effects to a common cause, orientation of the magnetic axis of the atoms, the conception is greatly simplified. Magnetic saturation corresponds, in a way, to the parallel orientation of all the atomic axis; and it can be effected only by very strong magnetic fields. Different magnetic materials require different strengths of fields. Tension orients the magnetic axis of the atoms parallel to the line of pull in a material which elongates when magnetized. If no magnetic field acts to determine the cause of orientation, then the polarity produced is indeterminate, and the magnetization due to tension alone is zero. In a homogenous cubic crystal, hydrostatic pressure should have no orienting effect on the atom. A transverse magnetic field is produced by an electric current in a wire. This has different directions at different points in the cross-section, and thus causes torsion which produces tension and compression in the wire which changes both in direction and magnitude.

Atomic Magnetostriction

Intra-atomic changes are changes which occur wholly within the single atom. It is assumed to be governed by quantum dynamics and that the principle changes in the magnetic moment of any single atom are considered as being abrupt. The abrupt change in the magnetic moment of an atom is accompanied by a change in that atom which is independent of the environment around it. Another assumption is that the magnetic hardness and hysteresis are due mostly to inter-atomic changes which are changes that involve more than one atom. This depends on the mechanical properties of the material and also on the type of atom. In magnetically hard materials, the changes involved in atomic magnetostriction meet large resistance which requires large amounts of energy from the strong magnetic field. In magnetically soft materials the same changes meet with small resistance which can be produced by weaker magnetic fields.

The above theories can be easily explained by considering a single annealed crystal of nickel with no field applied. The magnetic axis would then be most probably in a number of direction, and the net magnetization in any volume containing a number of atoms is zero. Each atom in a nickel crystal is surrounded by twelve other atoms, and if there is any magnetostriction effect at all, it would seem that the direction of the twelve atoms would depend somewhat on the direction of the magnetic axis of the atom in the center of the group. Thus there is an inter-atomic relation between the center atom and its neighbors. Each of the atoms is in equilibrium, but the stability of orientations is different for different atoms. The stability may be large if a change in orientation of the atom requires large displacement of the neighboring atoms, and there will not be much stability if there is not only a small change in displacement due to orientation of the atom.

If a magnetic field is applied, the stability of orientation is raised nearly parallel to the line of the magnetic field and the stability of other orientations is lowered. Then as the field is increased, the orientation of single atoms at different points becomes unstable and there will result sudden changes in orientation. There will be at least twelve correspondingly sudden changes due to inter-atomic forces, and they will set up vibrations in the crystal.

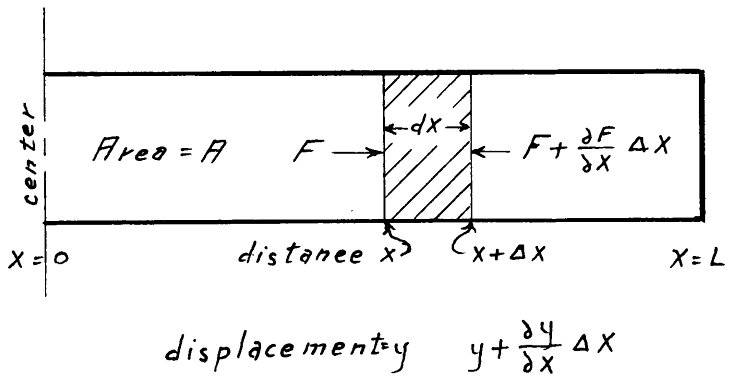
These vibrations are converted into heat and the dissipated energy is used to explain hysteresis effect. It is convenient to assume, as in all atomic events, that unless the change in potential energy for a change in conditions, such as a change in orientation of the atomic axis with respect to the applied magnetic field, is sufficient to supply the energy to be dissipated in the accompanying event, the change will not occur.

Another effect is obtained as each atomic axis is placed more nearly parallel to the applied field by the previously existing local stresses until there is a large number of atoms oriented. In this effect the resultant strains remain almost entirely local and the external dimensions change very little or none. The nature of the local strains is such that at first the stability of incorrect orientation of atoms is increased by correct orientataion of the neighboring atom. Then by events occuring at non-adjacent points in the crystal, the magnetization tends to build itself up. As magnetization increases there will come a time when the local strains begin to overlap and the local stresses to diminish. This allows a rapid increase of magnetization and a more rapid change in external dimensions, which shows the atomic magnetostrictive effect. Large scale instability may occur and a large number of atoms may change their orientation simultaneously. This was the case in the Barkhausen effect.

The same process takes place in iron and cobalt although the final state of strain due to magnetostriction and the type of local stresses will be different in each metal. For weak fields the magnetostrictions of iron and nickel are opposite in effect, iron expands and nickel contracts along the line of magnetization. Therefore, it is expected that in alloys of these two metals the local stresses set up by the magnetization of a nickel atom will be partly relieved by the magnetization of an adjacent iron atom. Magnetization of a properly proportioned alloy of these metals should become magnetized to saturation by a weak field. The proportions of iron and nickel should be such that the magnetostriction of the alloy should vanish, and the hysteresis will be small, because of the simultaneous magnetization of small groups of iron and nickel atoms in such proportions that the changes in the forces exerted by the group on its neighbors is a minimum. Such changes require very little energy. It has been found by McKeehan that the magnetostrictive effect of a nickel-iron alloy changes sign when the percentage of nickel is about 81. This is almost the composition of permallory which is composed of 78.5% nickel and 21.5% iron.

Equation of Motion of the Magnetostrictive Rod

One half of the magnetostrictive rod is considered as shown below.



Let Δx be a small element of the rod.

x = distance from the center of the rod to any point

L = length of one-half of the rod

A = area of cross-section of the rod

F = force acting at x to the right on element Δx

$F + \frac{\partial F}{\partial x} \Delta x$ = force acting at $(x + \Delta x)$ to the left on the element Δx

y = displacement at x of the element Δx to the right at the time (t)

$y + \frac{\partial y}{\partial x} \Delta x$ = displacement at $(x + \Delta x)$ to the right

The displacement of both y and $y + \frac{\partial y}{\partial x} \Delta x$ is to the right or in the x direction.

The force in the x direction is equal to the mass of the little element (Δx) times the acceleration of the small volume.

$$F = m a$$

$$\left[F - \left(F + \frac{\partial F}{\partial x} \Delta x\right)\right] A = \Delta x p A \frac{\partial^2 y}{\partial t^2}$$

which by simplifying becomes

$$-\frac{\partial F}{\partial x} = p \frac{\partial^2 y}{\partial t^2} \quad \text{------------------------------------(1)}$$

where p is the density of the material of the magnetostrictive rod.

The force (F) is composed of several forces, such as, forces due to viscosity (Fv), forces due to elasticity (Fe), and forces due to magnetostriction (Fm). These various forces are due to the pressures formed by the expansion of an element to the left of that shown in the figure. The total force (F) is equal to

$$F = Fv + Fe + Fm \quad \text{--(2)}$$

Force due to viscosity

$$Fv = -G \frac{\partial}{\partial t} \left(\frac{\partial y}{\partial x} \right) \quad \text{------------------------------------(3)}$$

where (G) is the coefficient of viscosity in c. g. s. units and is positive.

$\left(\frac{\partial y}{\partial x} \right)$ is the ratio of the increase of volume to the volume of the element.

Force due to elasticity

$$Fe = - E \frac{\partial y}{\partial x} \text{ ---(4)}$$

where (E) is Young's modulus of elasticity in dynes per square inch.

$\left(\frac{\partial y}{\partial x} \right)$ is again the ratio of the increase of volume to the volume of the elements.

Force due to magnetostriction

This magnetostrictive force is due to a perodic magnetic induction (B), which is composed of two parts, magnetic induction due to the periodic current (B_r) and magnetic induction due to the distortion of a small element caused by the magnetostrictive effect (Bm). G. W. Pierce separates magnetostriction into two laws. In the first law he assumes that the magnetostrictive force (Fm) caused by the perodic induction (B) is proportional to B.

$$Fm = a\,B \text{ ---(5)}$$

where (B) is the magnetic induction at (x) that produces (Fm).

(a) is the coefficient relating the expassion pressure of magnetostriction in dynes per square cm. to magnetic induction (B).

(a) is positive for some magnetostrictive metals and negative for others. It is also not exactly constant, for it varies with (B), but where (B) is a small induction added to constant large inductance, it is considered as a constant.

By substituting equations (3), (4), and (5) in (2) the total force is obtained.

$$F = - G \frac{\partial^2 y}{\partial t \partial x} - E \frac{\partial y}{\partial x} + a\,B \text{ ---------------------(6)}$$

In a substituting equation (6) in (1) we get

$$p \frac{\partial^2 y}{\partial t^2} = G \frac{\partial^3 y}{\partial t \partial x^2} + E \frac{\partial^2 y}{\partial x^2} - a \frac{\partial B}{\partial x} \text{ ------------------(7)}$$

In considering the magnetic induction (B), that produces the magnetostrictive force (Fm), it is found that it is composed of magnetic induction due to the variable current (i) in the windings plus an additional magnetic induction caused by the magnetostrictive effect when the rod is distorted. The total magnetic induction is therefore,

$$B = Bi + Bm$$

where

Bi = magnetic induction due to the current (i)

Bm = magnetic induction due to the expansion of the element Δx. It is, also, a function of the total length of the rod.

The second law of magnetostriction states that when the rod of original length (2L) is stretched an amount (2y) there is an induction (Bm) produced that is proportional to y/L

Thus Bm is proportional to the increase of length of the element (Δx) divided by the original length of the elements, thus

$$Bm = am \frac{\partial y}{\partial x} \text{ --(8)}$$

where am is a coefficient magnetostriction

$\frac{\partial Bi}{\partial x}$ is regarded as equal to zero

Then

$$\frac{\partial B}{\partial x} = \frac{\partial Bm}{\partial x} + \frac{Bi}{x} = \frac{\partial Bm}{\partial x}$$

but since

$$Bm = am \frac{\partial y}{\partial x}$$

$$\frac{\partial B}{\partial x} = am \frac{\partial^2 y}{\partial x^2} \text{ ------------------------------------(9)}$$

Substituting equations (8) and (9) in (6) and (7) and let $(E - aan) = E^1$ we get

$$F = -G \frac{\partial^2 y}{\partial t \partial x} - E^1 \frac{\partial y}{\partial x} + aBi \text{ ---------------------------------(10)}$$

$$p \frac{\partial^2 y}{\partial t^2} = G \frac{\partial^3 y}{\partial t \partial x^2} + E^1 \frac{\partial^2 y}{\partial x^2} \text{ ------------------------------(11)}$$

Equation (11) has a solution of the form

$$y = R \, \varepsilon^{-jkx - bt} \text{ ---(12)}$$

where R = constant

k = wave-length constant

$b = \alpha + jw$

where α = attenuation constant (with time)

$w = 2\pi f$ frequency constant

From the solution (12)

$$\frac{\partial y}{\partial t} = - bR \, \varepsilon^{-jkx} \cdot \varepsilon^{-bt}$$

$$\frac{\partial^2 y}{\partial t^2} = b^2 R \, \varepsilon^{-jkx} \cdot \varepsilon^{-bt} = R\,(\alpha^2 + 2j\alpha w - w^2)\, \varepsilon^{-kx - bt}$$

$$\frac{\partial y}{\partial x} = - jkR \, \varepsilon^{-jkx - bt}$$

$$\frac{\partial^2 y}{\partial x^2} = - K^2 R \, \varepsilon^{-kx - bt}$$

$$\frac{\partial^3 y}{\partial t \partial x^2} = K^2 b R \varepsilon^{-kx - bt} = RK^2 (\alpha + jw) \varepsilon^{-kx - bt}$$

Substituting the above equations in equation (11) and then equating the real and imaginary parts.

$$p\alpha^2 - pw^2 + j^2\alpha wp = GK^2\alpha - E^1K^2 + jGK^2w$$

$$p\alpha^2 - pw^2 = K^2(G\alpha - E^1)$$

and

$$2\alpha p = GK^2$$

$\alpha = GK^2/2p$ Attenuation constant ----------------------------(13)

also

$$G^2K^4/4p - pw^2 = K^2(G^2K^2/2p - E^1)$$

$$pw^2 = K^2(G^2K^2/4p + E^1 - G^2K^2/2p)$$

$$w^2/K^2 = E^1/p - G^2K^2/4p^2$$

$C = w/K = \pm\sqrt{E^1/p - G^2K^2/4p^2}$ wave velocity

since

$$w = 2\pi f$$

$$C = 2\pi f/K$$

$$K = 2\pi f/C$$

The wave-length constant

$$pw^2 = E^1K^2 - G^2K^4/4p$$

$$K^4 - 4pE^1K^2/G^2 - 4p^2w^2/G^2 = 0$$

$$K^2 = 2p/G^2 \left[E^1 \pm \sqrt{E^{12} + w^2 \quad G^2} \right]$$

The solution then becomes

$$y = R\,\varepsilon^{-jkx - bt}$$

$$y = R\,\varepsilon^{-jkx} \cdot \varepsilon^{-\alpha t} \cdot \varepsilon^{-jwt}$$

$$y = R\,\varepsilon^{-QK^2t/2p} \left(\varepsilon^{-jkx} \cdot \varepsilon^{-jwt} \right)$$

$$y = R\,\varepsilon^{-QK^2t/2p} \left[(\text{Cos } Kx - j \text{ Sin } Kx)\ (\text{Cos } wt - j \text{ Sin } wt) \right]$$

$$y = R\,\varepsilon^{-QK^2t/2p} \left[\text{Cos } (Kx - wt) - j \text{ Sin } (Kx\ wt) \right]$$

Considering only the longitudinal vibrations

$$y = R\,\varepsilon^{-QK^2t/2p} \quad \text{Cos } (Kx - wt) \text{ ------------------------- } (14)$$

To determine the constant A, we consider the equation (10). The boundary conditions are at $x = L$, the force $(F) = 0$

$$\therefore \quad 0 = - E^1 \frac{\partial y}{\partial x} - G \frac{\partial^2 y}{\partial t \partial x} + a\, Bi \text{ ---------------------- } (15)$$

Then from

$$y = R\,\varepsilon^{-QK^2t/2p} \quad \text{Cos } (Kx - wt)$$

$$y = R\,\varepsilon^{-QK^2t/2p} \quad \text{Cos } Kx \text{ Cos } wt + R\,\varepsilon^{-QK^2t/2p} \text{ Sin } Kx \text{ Sin } wt$$

$$\frac{\partial^2 y}{\partial x \partial t} = R\,\varepsilon^{-QK^2t/2p} \quad \text{Cos } (Kx - wt) + RQK^2/2p\ \varepsilon^{-QK^2t/2p} \text{ Sin } (Kx - wt)$$

$$\frac{\partial y}{\partial x} = -R\,\varepsilon^{-QK^2t/2p} \text{ Sin } (Kx - wt)$$

Substituting the above equations in equation (15) and rearranging we obtain a value for R

$$R\ \varepsilon^{-QK^2t/2p} = \frac{a\ Bi}{G\ \mathrm{Cos}\ (KL - wt) + E^1 - GQK^2/2p\ \mathrm{Sin}\ (KL - wt)}$$

which is the value of the constant

$$R\ \varepsilon^{-QK^2t/2p}$$

Substitute this value in equation (14)

$$y = \frac{a\ Bi\ \mathrm{Cos}\ (Kx - wt)}{G\ \mathrm{Cos}\ (KL - wt) + (E^1 - GQK^2/2p\ \mathrm{Sin}\ (KL - wt)} \quad \text{-------------}(16)$$

which is the equation of motion of the rod.

The Magnetostriction Oscillator

Theory

If an alternating current be passed through a coil of wire, it will produce magnetizing effects at the peak of each half cycle. If a rod with good magnetostrictive properties, such as nichrome steel, be placed in the coil, the rod will be magnetized each half cycle, and it will expand and contract along its length each half cycle. Therefore, the rod will vibrate longitudinally with a frequency equal to twice that of the alternating current. If, on the other hand, the rod is at the same time subjected to a steady magnetizing force greater than the peaks of the alternating force, the net magnetization will not reverse its polarity, and the rod will rise and fall with the alternating current wave. The rod will then vibrate with the same frequency as the alternating current. These forced vibrations are imparted to the surrounding air and they can be heard if the frequency is in the audible range.

G. W. Pierce discovered, that instead of forcing the rod to vibrate in step with an impressed frequency, that he could use the rod to control the oscillation of a vacuum tube to a single frequency or to harmonics of the frequency. The frequency with which the tube will oscillate is determined by the natural frequency of the rod, which depends on its length and the velocity of sound in the rod. The frequency (F) is equal to the velocity of sound in the rod (V) divided by twice the length (L) of the rod.

$$V = 2\,L\,F$$

For a given material, the velocity of sound (V) is a constant, and

A Simple Circuit of a Magnetostriction Oscillator

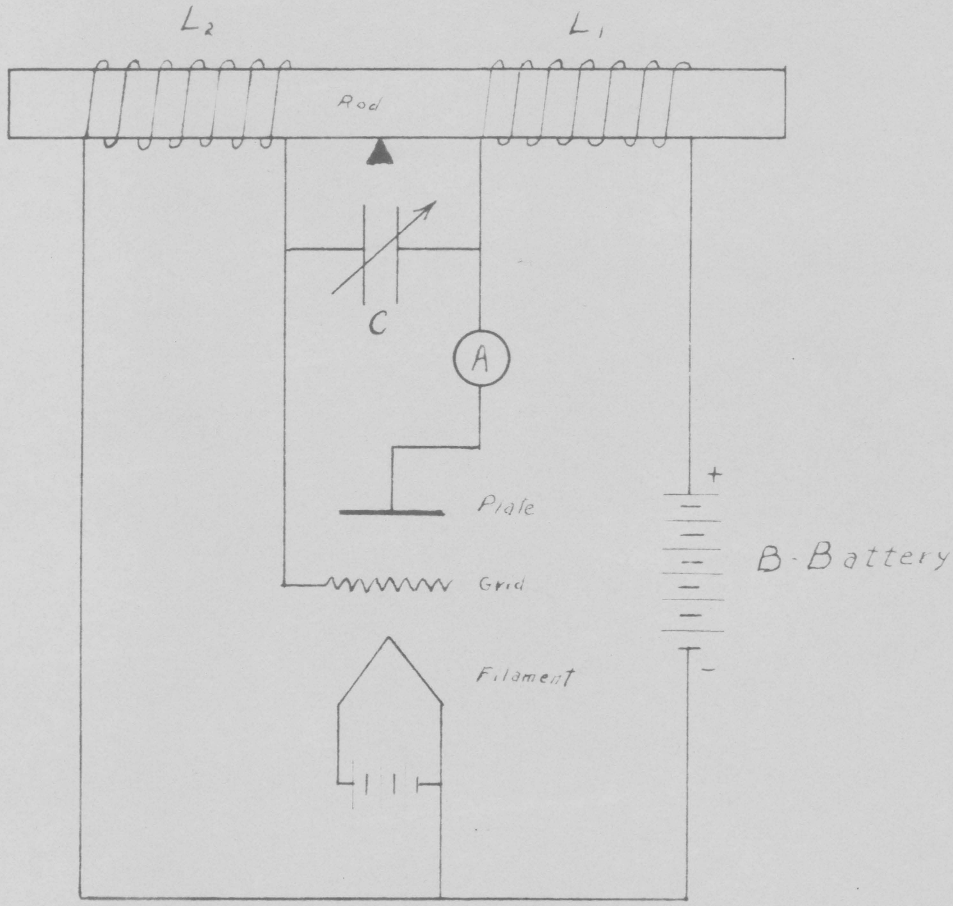


Figure 5.

is dependent of the length (L) and the frequency (F).

The oscillations of the tube are controlled by using two identical coils. (See figure 5) One coil is placed in the plate circuit and the other is placed in the grid circuit. A variable air condenser (C) is placed across the plate and grid so that the total reaction of the coils may be resonated to the natural frequency of the rod. The magnetostrictive rod is placed through the centers of both of the coils and put in such a position that it does not touch either. It is balanced or clamped at the center. The direction of winding of the coils is such that the filament emission currents flowing in the plate and grid circuits will magnetize the rod with the same polarity. This is exactly opposite of the Hartley oscillator circuit. A is a d. c. milliammeter giving the plate current, and it serves to indicate the resonant tuning of the circuit as the condenser C is varied. When such a circuit is tuned by means of C, until resonance with the natural frequency is approached, the reading of the plate current A rises sharply to a maximum as the rod goes into vibration. After the rod goes into vibration the condenser C may be varied over a considerable range while the frequency of oscillation does not change. Thus the circuit is stabilized at the natural frequency of the rod.

The effect of the magnetostrictive rod in a circuit may be explained as follows: We know that an iron rod will expand when magnetized, and, also, that there is a reverse effect of changing the magnetization when a magnetized rod is stretched. In the circuit of figure 5, a magnetostrictive rod is placed in the center of two coils (L_1 and L_2) which are in the place and grid circuit respectively. Now, any small change of current in the plate coil L_1 will change the magnetization of the rod and thus the rod will be changed in dimensions, either expanded or contracted. It should be remembered that the rod is deformed along its whole length and as a result the state of magnetization is changed and consequently an emf has been induced into the grid coil (L_2). This change in the grid causes an amplified change of current in the plate circuit and in the coil (L_1). This process continues and the oscillating current builds up large amplitudes with a frequency determined by the longitudinal vibration of the rod.

Frequencies of the Magnetostriction Oscillator

By using rods of different lengths and materials, frequencies from a few hundred cycles per second to about 300,000 cycles per second can be obtained. Frequencies up to several million may be had by using the harmonics of the above frequencies. It has been stated that the length of the rod times the frequency is equal to twice the velocity of sound in the rod. Then by controlling the length of the rod and the material of the rod, a series of vibrators of different frequencies can be made. A final adjustment may be made by grinding away a little of the length; this increases the frequency. The frequency can be lowered by grinding a little from the girth of the rod. Low frequencies say 1,000 cycles per second, can be obtained by using a nickel tube filled with lead, since lead has a low velocity of sound. High frequencies may be obtained in several ways: first, by the use of very short cylinders, placed within the coil, with their axes parallel to the magnetic field of the coil; second, by using rods which have been notched to about half its diameter for the whole length of the rod; and, third, by placing flat strips or sheets of magnetostrictive material between the plate and grid coils.

The Stabilizing Effect

It is known that in any self-oscillating vacuum tube circuit that accidental changes in various factors will change the frequency of the circuit. The most troublesome difficulty arises from the fact that the generated frequency depends somewhat on the internal impedance of the tube. Changes in the internal tube impedance may arise from many sources, such as changes in plate potential, changes in the mean grid potential, changes in the filament potential, and changes in spacing of the tube element. In using the magnetostrictive rod as a stabilizer, we do not have to worry with some of the above factors. It is found that after the circuit has started to vibrate at the natural frequency of the rod, then the plate potential may be varied from 150 volts to 230 volts, that the filament potential may be varied from practically zero emission to destruction of the filament, and that the tuning condenser may be varied over a considerable range without appreciably changing the frequency of the circuit. A reasonable control of these variables gives a much more precise standardization of the frequency. The set may continue oscillating for days without the frequency changing.

Materials Used for Magnetostriction Vibrators

G. W. Pierce has made some study of materials which may be used for magnetostriction vibrators. He found that large magnetostrictive effects and constancy of mechanical frequency in spite of changes of temperature and magnetization are required for good vibrators. He discovered that pure nickel was a good vibrator but did not have much stabilizing power, and that pure iron or iron with carbon content, had very little magnetostrictive effect. On the other hand, alloys of the two in the correct proportion are good vibrators. Invar and Stoic metal of about 26% nickel and 64% iron are good examples of the above. Also, alloys of chromium, nickel, and iron, such as nichrome steel make good vibrators. Monel metal, which is composed of 68% nickel, 28% copper, and small amounts of iron, silicon, manganese, and carbon, is a good oscillator, but usually it has to have some means of separate polarization. Tubes of nickel make good oscillators for demonstration purposes, but they are not stable. Vibrators that are practically independent of temperature have been made by using a tube of nickel and placing in it a core of Stoic metal, which has an opposite temperature coefficient. Pierce has found that all of the rods are made more powerful if they are annealed.

Final Circuit of the Oscillator

In designing the magnetostriction oscillator, both triode and pentode tubes were tried. The 101-D, 240, 651, 6K7, and 6F6 are a few of the tubes that may be used. As the 6F6 seemed to give the best result, it was used. The final circuit of the power pack, the oscillator, and a one stage amplifier is shown in figure 6. The rectifier tube used was a 5Z4, which put out a little over 300 volts. A 6F6 was used for the oscillator. The plate coil L_1, and the grid coil L_2 each consisted of 1,800 turns of number 28 wire. R_1 is the resistance which supplies the grid bias. R_2 is the fixed resistance of 4,000 ohms which determines the screen voltage and keeps it constant at 135 volts. R_3 is a potentiometer rheostat of 3,500 ohms and is the means by which the plate voltage is varied. A is a 50 millimeter which reads the plate current. C_1 is a variable air condenser of 500 micro micro farads. By means of a set of switches, a series of fixed condensers can be placed in parallel with the variable condenser C_1.

Final Circuit of Magnetostriction Oscillator

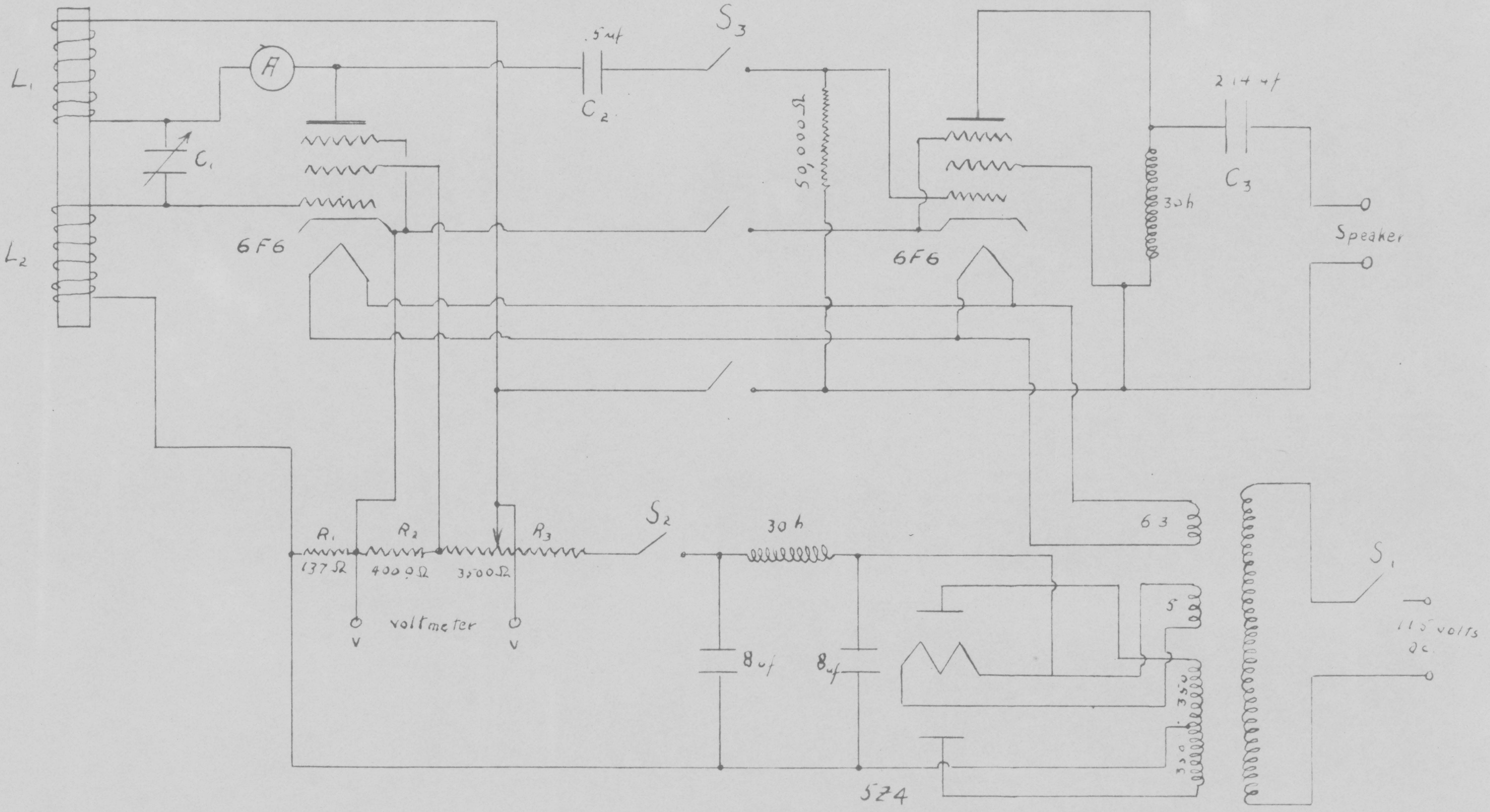
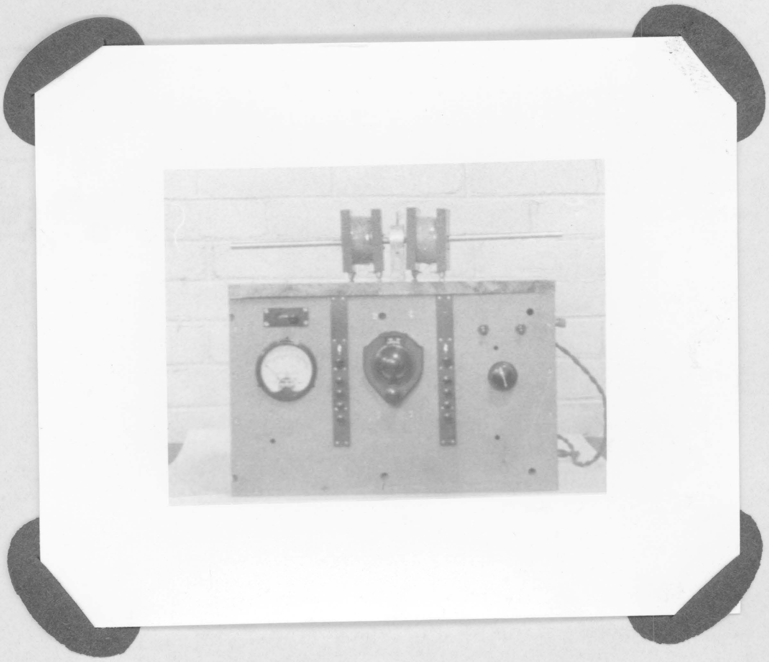


Figure 6

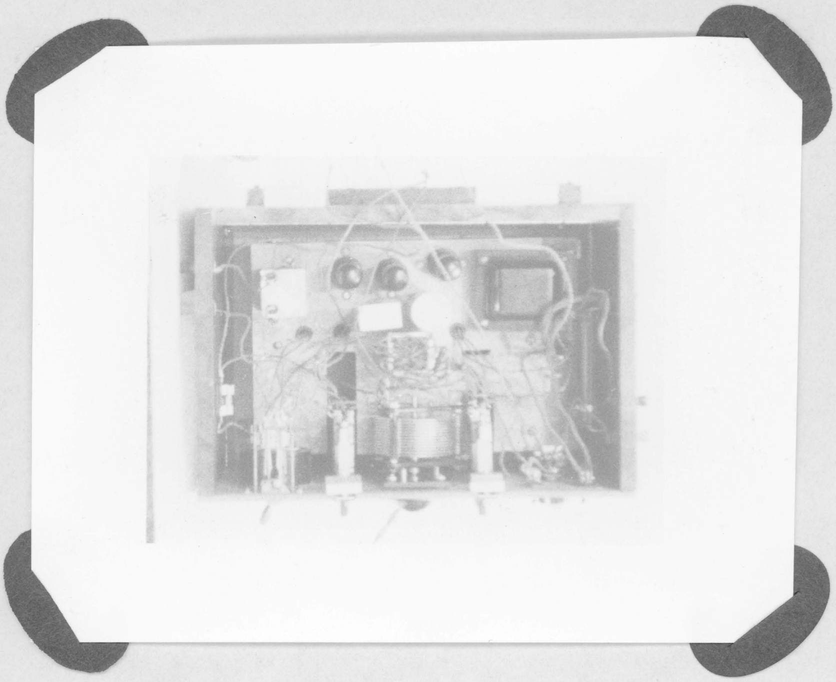
The amplifier is connected to the oscillator by means of a switch S_3 so that when it is not in use its load can be taken off the transformer. A 6F6 is used as the amplifier tube. It is coupled to the oscillator by condenser C_2 of .5 micro farads. The amplifier tube has its plate and screen grid connected to the plate of the oscillator. The cathodes of both the oscillator and amplifier are connected together. The grid lead is a 50,000 ohm resistor. The plate circuit of the amplifier contains a speaker filter unit which consists of a 30 henry audio choke, and the output terminals are connected through a 2.14 micro farad condenser C_3.

Switch S_1 is in the primary of the transformer, and switch S_2 is in the output of the rectifier. When S_1 is closed it heats the filaments of all three tubes. After the tubes become hot, switch S_2 can be closed which permits the current to pass through the oscillator. The terminals V-V are connected so that a voltmeter can be used to determine the plate voltage of the oscillator.

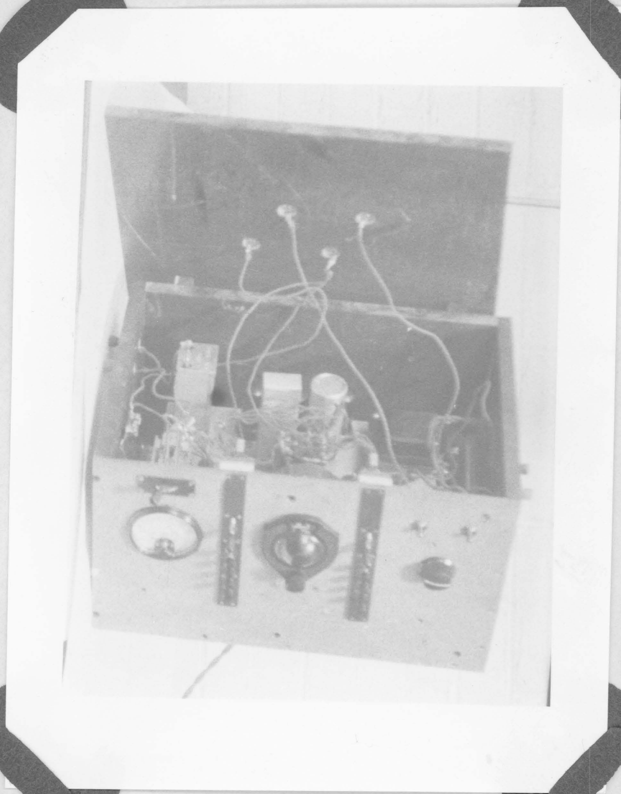
The coils L_1 and L_2 are wound on wooden frames. At the base each end of the coil is connected to a banana plug. The sockets in which the coils fit are placed on top of the set. The clamp which holds the rod is between the two coils, as shown in the pictures. The coils are provided with banana plugs and socket so that coils of different inductances and different size cores may be inserted in the plate and grid circuit with ease. Different views of the oscillator are shown on pages 33, 34, and 35.



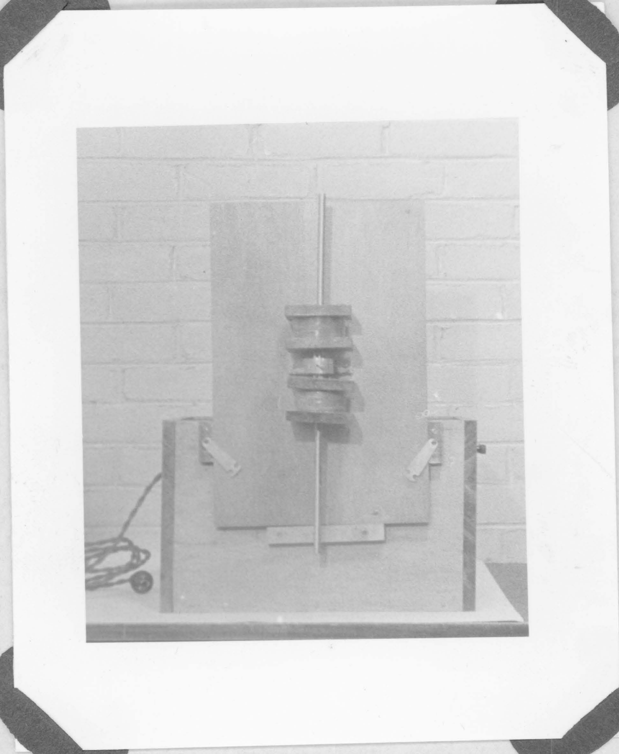
Front view of oscillator

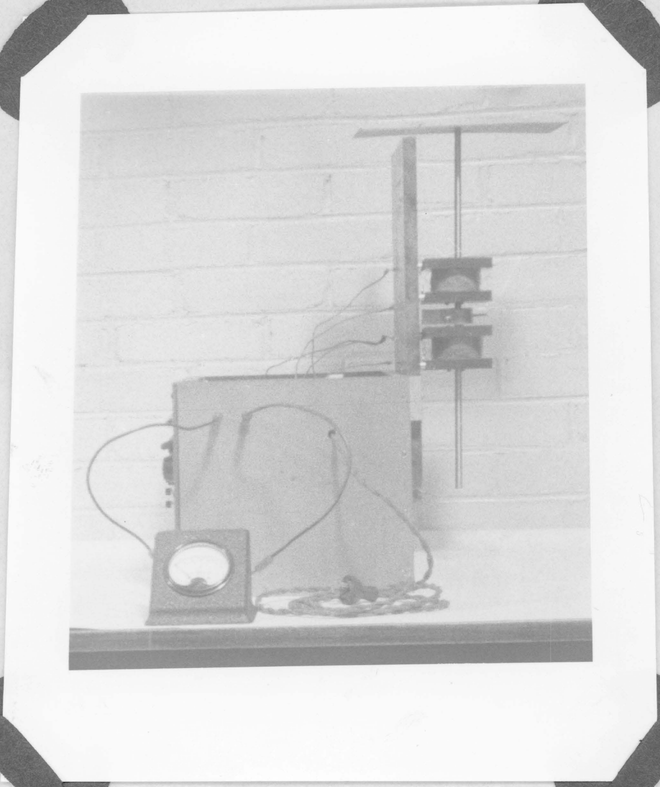


Top view of oscillator showing the
arrangement of parts



View showing the front and the
inside of the oscillator.





Back and side views showing the method of holding the magnetostrictive rod for vibrating the various plates.

EXPERIMENTAL RESULTS

In running test on the oscillator it was found that it took quite a while for the set to heat up and that the plate current and plate voltage would change in value. A series of readings were taken of the plate current and plate voltage as the set heated up, and it was found that approximately three hours were taken for the oscillator to reach a constant value of plate current and plate voltage. The relation of the plate current and plate voltage with respect to time can be seen in figures 7 and 8. A curve was also plotted of the plate current against the plate voltage; this seems to be a straight line relation. The condenser dial was set at zero and left there. The plate voltage was set at 150 volts as quickly as possible after the set was turned on. It was found that the plate reached a constant value of 18.9 milliamperes in three hours and that the plate voltage increased from 150 volts to 175 volts, a change of 25 volts in three hours. The data is found in table I.

TABLE I

Date for Figures 7, 8, and 9

Time	Ep Volts	Ip Ma	Time Min.	Time	Ep Volts	Ip Ma	Time Min.
2:32	0	0	0	3:115	162	16.8	39.5
2:325	150	12.0	.5	3:225	165	17.1	50.5
2:33	150	13.1	1.0	3:29	165.5	17.2	57.0
2:335	150	13.9	1.5	3:42	166	17.5	70.0
2:34	150	14.1	2.0	3:48	167	17.8	76.0
2:345	150	14.3	2.5	3:53	168	17.9	81.0
2:35	150	14.7	3.0	3:555	169	18.	83.5
2:36	150	14.9	4.0	4:05	169.5	18.	93.0
2:37	150	15.0	5.0	4:20	170.1	18.1	108.0
2:42	153	15.3	10.0	4:25	172	18.2	113
2:435	153	15.5	11.5	4:42	174	18.7	130
2:45	154	15.5	13.0	4:53	174.5	18.8	141
2:465	155	15.8	14.5	5:00	175	18.9	148
2:50	156	15.9	18.0	5:15	175	18.9	163
2:54	157	16.	22.0	5:32	175	18.9	180
3:00	158	16.2	28.0	6:42	175	18.9	250
3:055	160	16.5	33.5				

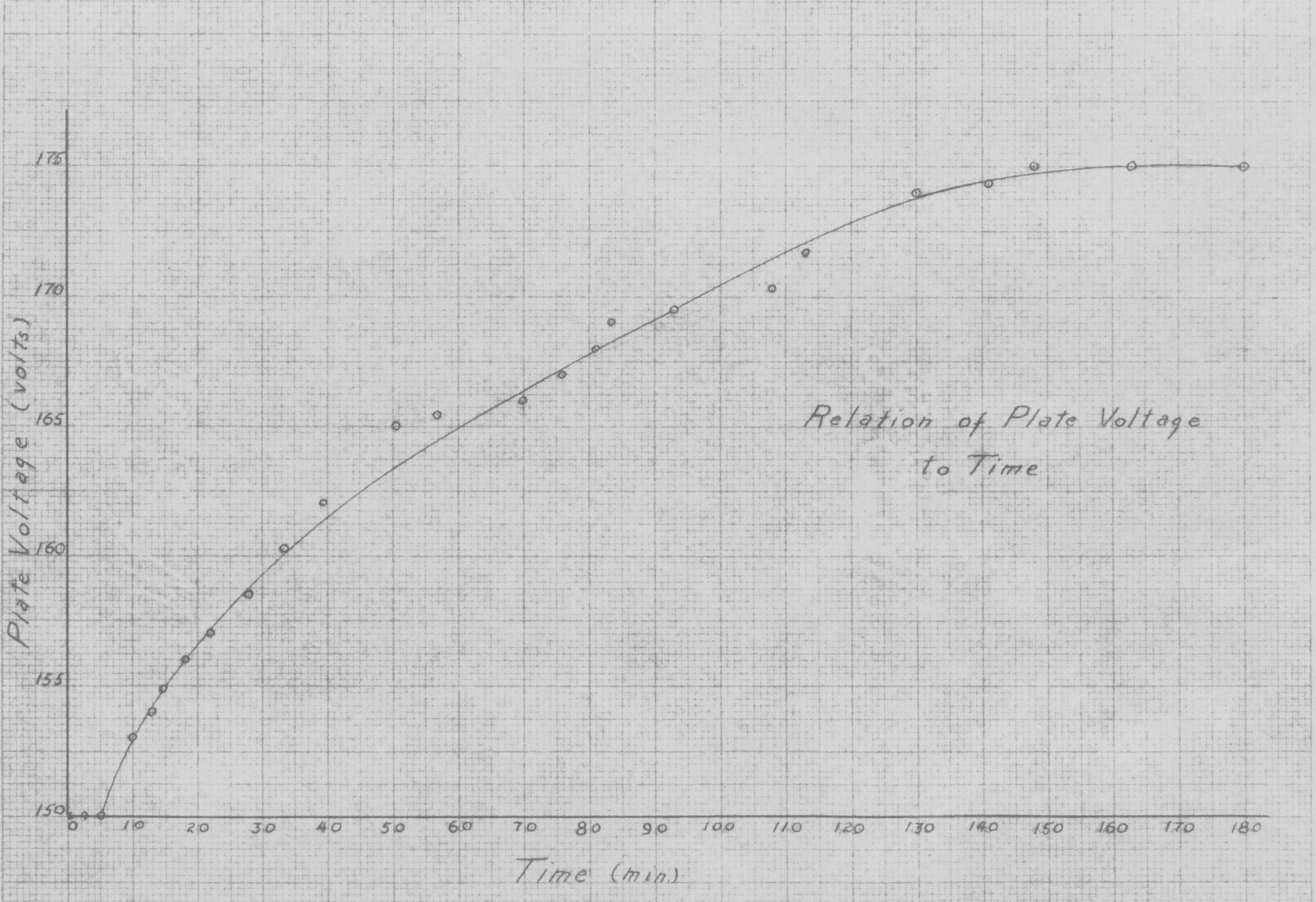

Relation of Plate Voltage
to Time
Plate Voltage (volts)
150
155
160
165
170
175
Time (min.)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180

Figure 7.

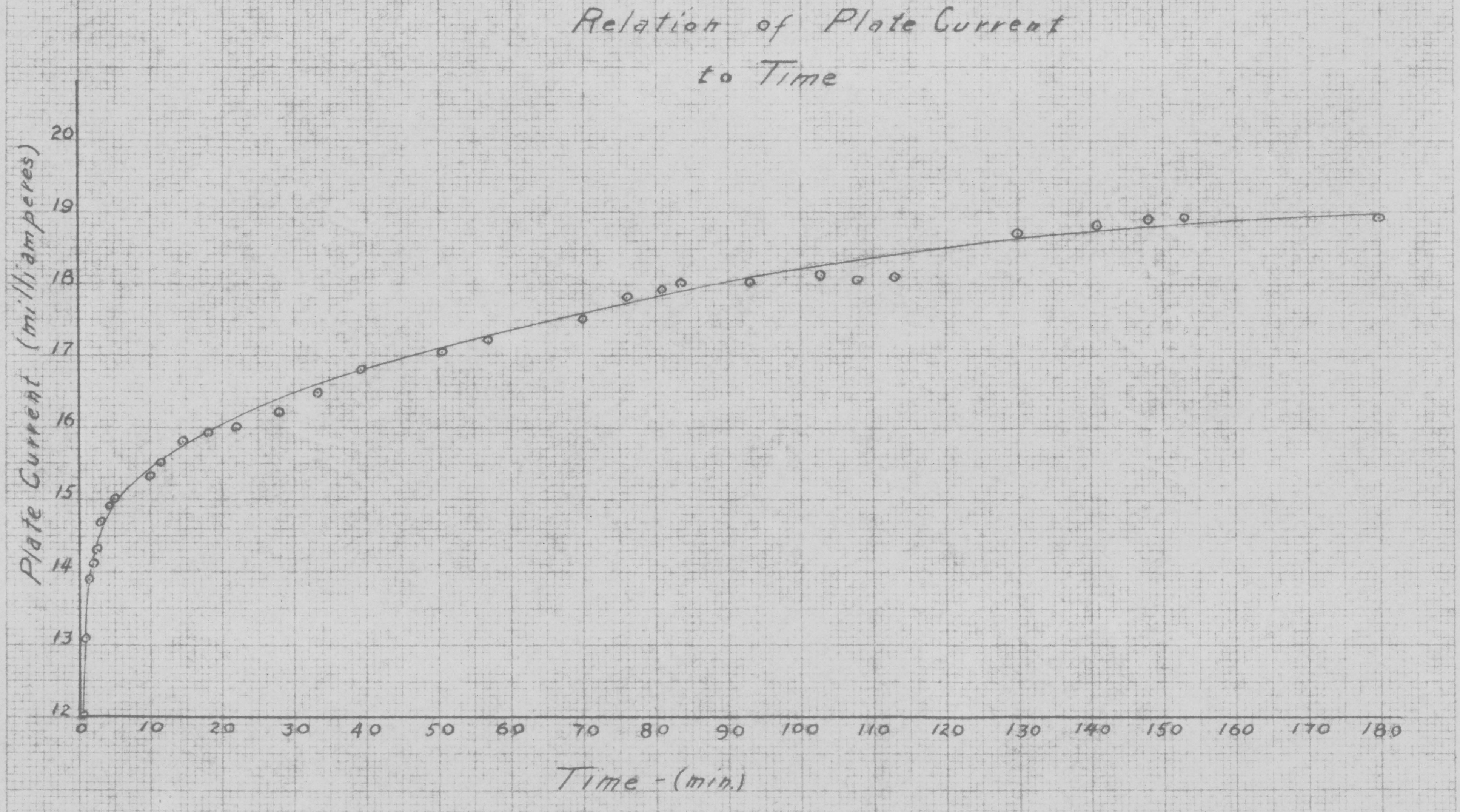
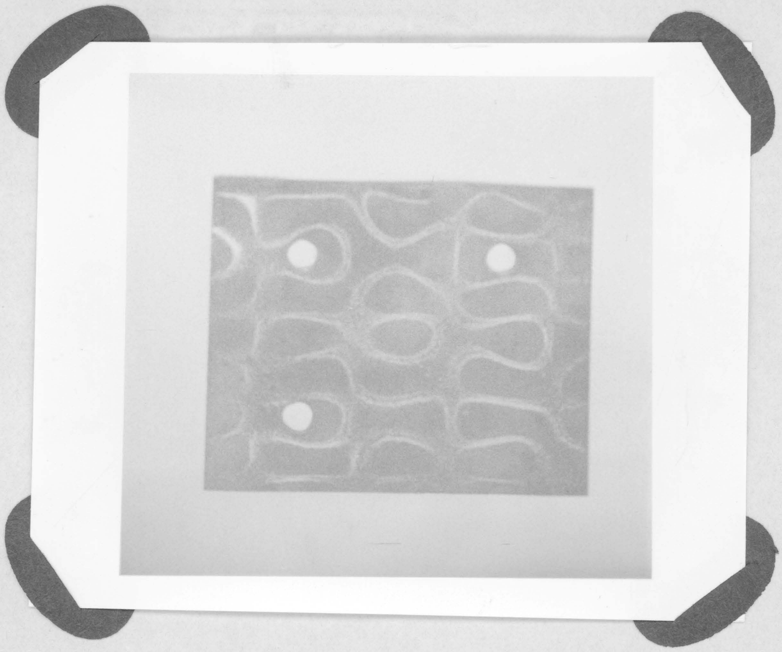
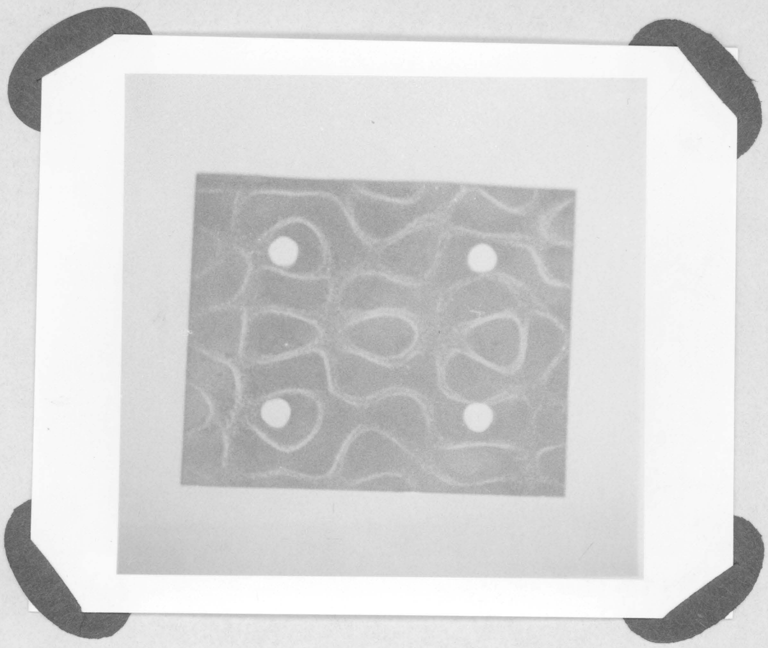

Relation of Plate Current
to Time
Plate Current (milliamperes)
20
19
18
17
16
15
14
13
12
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Time - (min.)

Figure 8.



The same plate with another 3/8" hole $1\frac{3}{4}$" along the other diagonal with the rod in the center.



The same plate with four 3/8" holes $1\frac{3}{4}$" along the diagonals from each corner with the rod in the center.

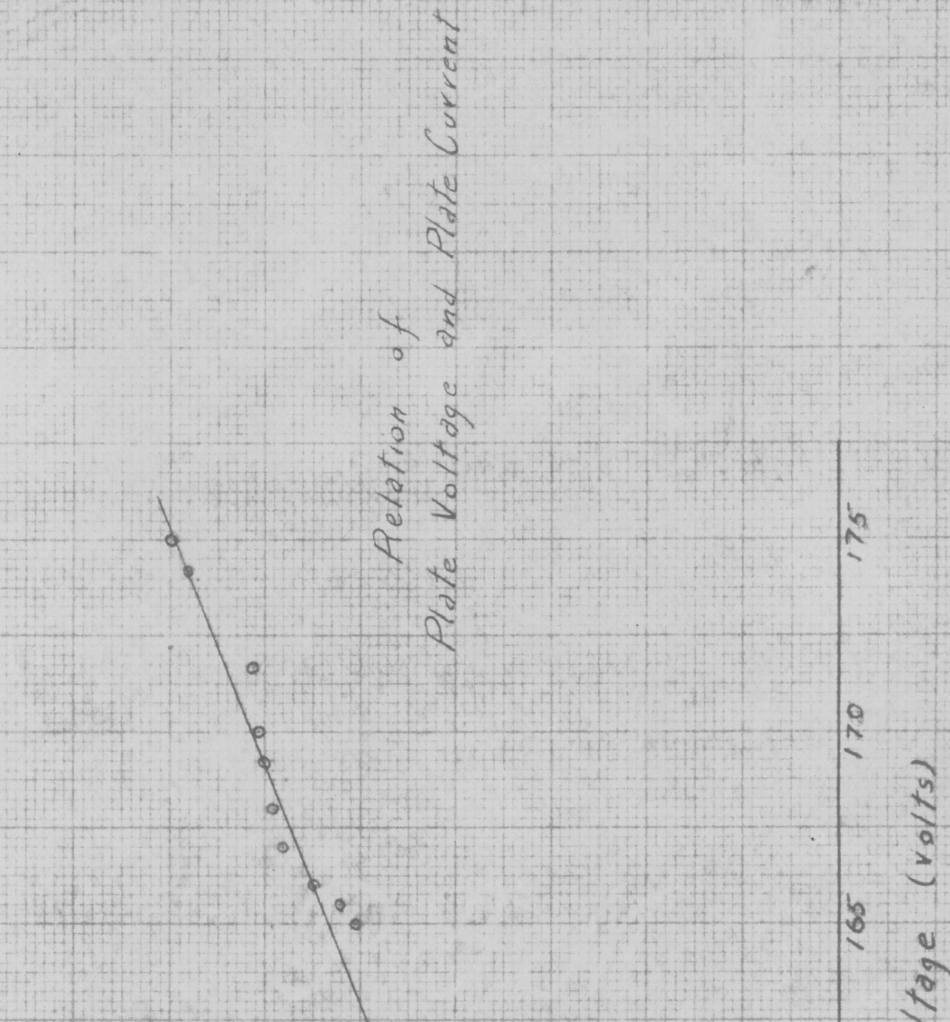
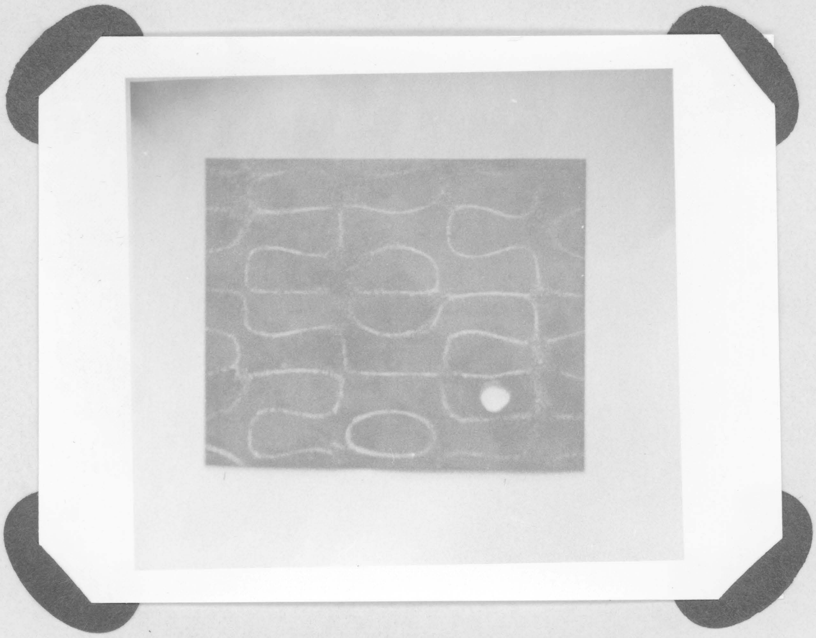

Relation of
Plate Voltage and Plate Current
Plate Current (m.a.)
20
19
18
17
16
15
14
13
12
150
155
160
165
170
175
Plate Voltage (volts)

Figure 9.



The negative was reversed when printed.

A 4"X5"X0;014" plate of stove iron with a 3/8" hole $1\frac{3}{4}$" along the diagonal from the upper right hand corner with the rod in the center.

The same plate with another3/8" hole $1\frac{3}{4}$" along the diagonal from the lower left hand corner with the rod in the center.

After the oscillator had heated up for over three hours a set of readings were taken of the condenser dial settings and the plate current with a plate voltage at a constant value of 150 volts. The readings were taken first on increasing the condenser dial from 0 to 100 and then decreasing it from 100 to 0. Next similar sets of readings were taken for plate voltages of 175, 200, 225, 250, and 275 as shown in Table II. The curve for each voltage is plotted of plate current against condenser dial settings in figure 10. Referring to the 150 volt curve, it is seen that the current starts at 18 ma. and follows a smooth curve until the condenser setting of 44 is reached. The current then drops to 17.8 ma. and stays at 17.8 ma. until the condenser setting is 50. It then jumps back to 18.15 ma. and continues to increase along a smooth curve to 18.5 ma. at a condenser setting of 100. As the condenser settings are decreased, the current follows the same curve that it did when the condenser was increased. Then as the condenser setting reached 47, the current again jumped down to 17.8 ma. and continued at 17.8 ma. to a value of 38 on the condenser dial. In each case the rod went into vibration when the plate current decreased and continued to vibrate until the current jumped back to its original value. The rod could be heard to vibrate by means of a sounder, which was a piece of spring steel placed against the end of the rod. The rod becomes magnetized and holds the spring against it. As the rod goes into vibration, it kicks the spring, and it can be heard as it hits against the rod. After the rod once starts to vibrate, the condenser can be moved from 38 to 51 division without affecting the frequency.

The curve for a plate voltage of 175 acts in a similar manner as can be seen from the graph. When 200 volts is put on the plate, the current acts entirely different. The curve increases along a smooth curve until the condenser setting is 43.5, then the current instead of decreasing as in the other two curves, it increases all of a sudden from 20.1 to 20.5 ma. It then decreases along a smooth curve to 20.1 ma. at 51.1 on the condenser dial, where it stops vibrating. The current then increases to 20.8 ma. at 100 on the dial. As the condenser is decreased, the current follows the same curve until a condenser value of 46 is reached. Here the rod starts to vibrate, and the current increases from 20 to 20.3 ma. and stays at this value until a reading of 37 on the condenser dial is reached; the rod then stops vibrating and the current drops to 20.1 ma. The current follows the curve back to the starting point after the vibration in the rod stops.

The current for the other values of plate voltage 225, 250, and 275 behaves in a similar manner of that of 200 plate volts, only the amount of change in plate current increases as the plate voltage increases. In the 275 volt curve the plate current jumps from 30 to 33.5 ma., and the rod vibrates over a range of condenser settings from 65 to 91. The rod was found to vibrate at approximately 6,400 cycles per second.

TABLE II

Date for Figure 10

Ep Volts	Ip Ma	Condenser Setting
150	18	0
	18.15	38
	18.15	39
	18.15	40
	18.15	42.5
	17.80	44
	17.80	51
	18.15	51
	18.50	90
	18.50	100
	18.15	47
	17.80	46
	17.80	38
	18.15	38
	18.00	0
175	19.0	0
	19.1	38.5
	19.1	40.0
	19.1	43.0
	18.8	43.2
	18.8	50
	19.1	50

Ep Volts	Ip Ma.	Condenser Setting
175	19.5	100
	19.1	45.5
	18.8	45
	18.8	36
	19.1	36
	19.0	0
200	19.9	0
	20.0	20
	20.1	38.8
	20.1	39.1
	20.1	40.0
	20.1	43.5
	20.5	43.5
	20.3	49.0
	20.0	50.0
	20.1	51.1
	20.5	70.0
	20.8	100.0
	20.1	46
	20.0	44.5
	20.3	44.5
	20.1	37.0

TABLE II CON'T

Ep Volts	Ip Ma.	Condenser Setting
200	20.1	37.0
	19.9	0
225	21.5	0
	22.0	32
	22.2	43
	22.2	49
	23.2	49
	23.7	53
	23.7	58
	23.2	61
	22.6	61
	23	100
	22.6	57
	22.6	56
	22.2	51.5
	22.2	50.5
	23.5	50.5
	23.0	46.5
	22.2	45.5
	22.2	44.5
	22.0	32.0
	21.5	0
250	23.5	0

Ep Volts	Ip Ma.	Condenser Setting
250	24.0	16
	24.5	30
	25.0	45
	25.2	54
	25.3	60
	27.0	60
	27.5	67.5
	27.0	73
	26.0	73
	26.5	100
250	26.0	70
	26.0	68
	26.0	65
	26.0	64
	25.8	63
	25.8	62
	27.5	62
	27.0	57.5
	26.5	56
	25.6	55
	25.6	51
	25.0	45
	24.5	22

TABLE II CON'T

Ep Volt	Ip Ma.	Condenser Setting
250	24.0	10
	23.5	0
275	27.0	0
	27.5	11
	28.0	18
	28.5	27
	29.0	34
	29.5	48
	29.9	67
	29.9	74
	33.2	74
	33.5	76
	33.2	86
	32.0	89
	31.0	91
	30.8	93
	30.8	100
	30.8	91.5
	30.5	80
	30.8	84
	30.3	77
	33.5	77
	33.0	70

Ep Volt	Ip Ma.	Condenser Setting
275	30.2	65
	30.0	59
	29.5	48
	29.0	34
	28.0	18
	27.5	11
	27.0	0

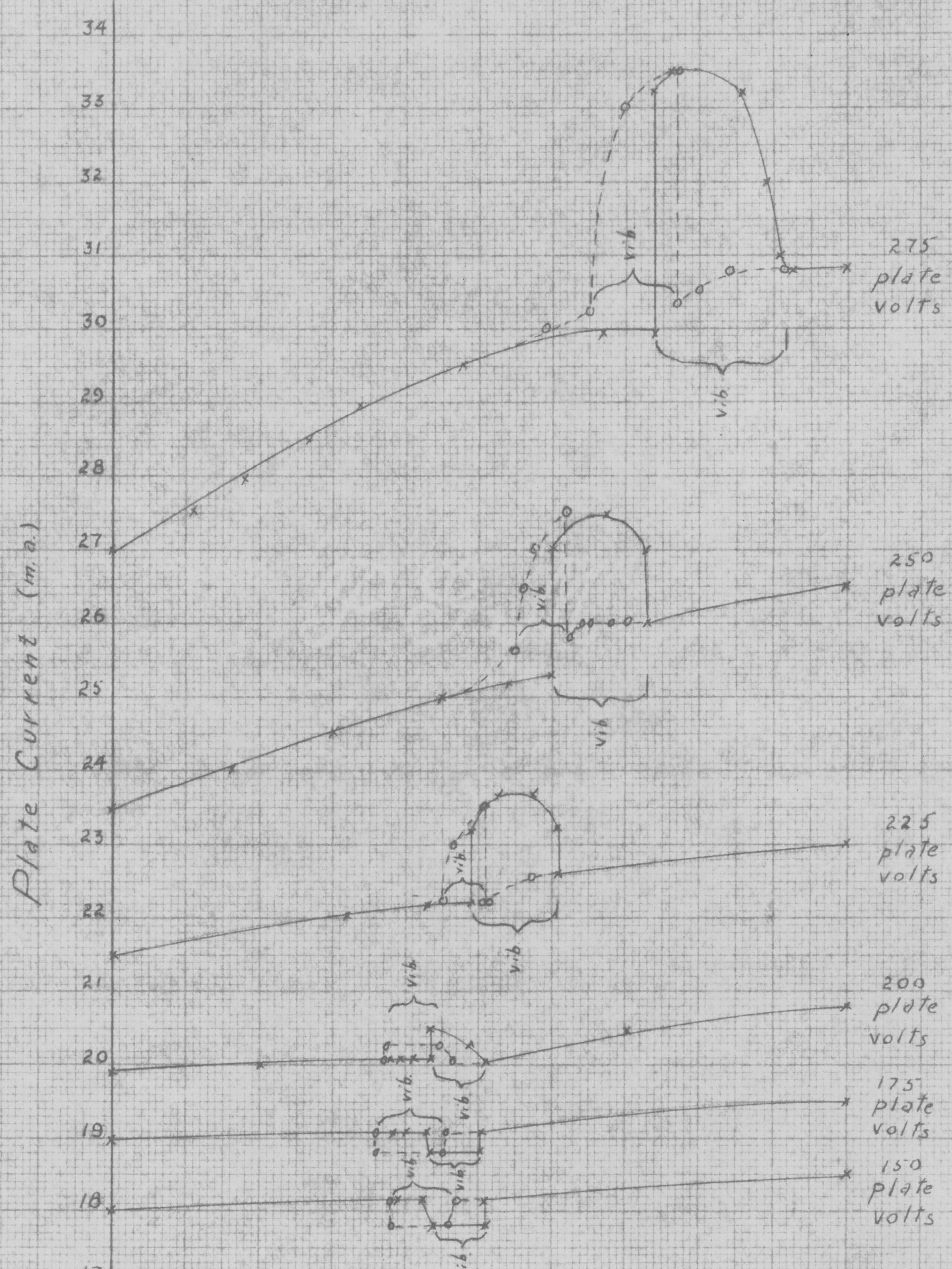

34
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
Plate Current (m.a.)
0 10 20 30 40 50 60 70 80 90 100
Condenser Dial Setting
275 plate volts
250 plate volts
225 plate volts
200 plate volts
175 plate volts
150 plate volts
vib
vib
vib
vib
vib
vib
vib
vib
vib
vib
vib

Figure 10.

Next, the condenser was set at 40 and the plate voltage was varied from 150 to 275 volts. Readings of the plate voltage and plate current were taken as the voltage was increased from 150 to 275 volts and back again. This gave the smooth curve shown in figure 11. When the condenser was set at 50, a smooth curve was not obtained (see figure 12). As the rod went into vibration, the current increased from 21.8 ma. at 220 volts to 23.9 ma. at 233 volts. The current then dropped to 23.2 ma. at 233 volts. For decreasing the plate voltage the current behaved in a smilar manner but not at the same values. The values that the rod vibrated between are marked on the graph. For condenser settings of 55 and 65 similar results were obtained, as shown in figures 13 and 14. In all the curves the full lines are for increasing values and the dotted lines are for decreasing values.

TABLE III

Data for Figures 11, 12, 13, and 14

Condenser Setting	Ep Volt	Ip Ma.
40	140	17.5
	145	18.0
	157	18.7
	173	19.0
	192	20.0
	207	20.7
	218	21.2
	225	22.1
	235	23.0
	240	24.0
	250	25.2
	260	27.0
	270	29.0
	275	29.9
	254	26.0
	220	21.6
	210	20.8
	192	20.0
	156	18.5
	148	18.0

Condenser Setting	Ep Volt	Ip Ma.
50	150	18.2
	168	19.0
	192	20.0
	220	21.8
	222	23.1
	225	23.6
	233	23.9
	233	23.2
	238	24.1
	245	25.0
	253	26.1
	258	27.0
	265	28.2
	275	30.0
	258	27.0
	233	23.3
	230	23.9
	220	23.0
	212	22.1
	205	21.0
	193	20.1

TABLE III CON'T

Condenser Setting	Ep Volt	Ip Ma	Condenser Setting	Ep Volt	Ip Ma
55	150	18.2	65	150	18.2
	162	19.0		192	20.0
	206	21.0		210	21.0
	223	22.0		227	23.0
	234	23.5		233	23.5
	232	25.0		235	24.0
	240	26.0		242	25.0
	247	25.5		245	25.8
	251	26.0		248	26.0
	256	27.0		250	28.9
	269	29.0		265	29.5
	275	30.0		265	28.8
	245	25.0		275	31.0
	238	26.0		255	27.5
	230	25.0		250	28.5
	227	24.0		235	27.0
	112	22.0		230	25.0
	209	21.0		220	22.0
	162	19.0		192	20.0
	150	18.2		150	18.2

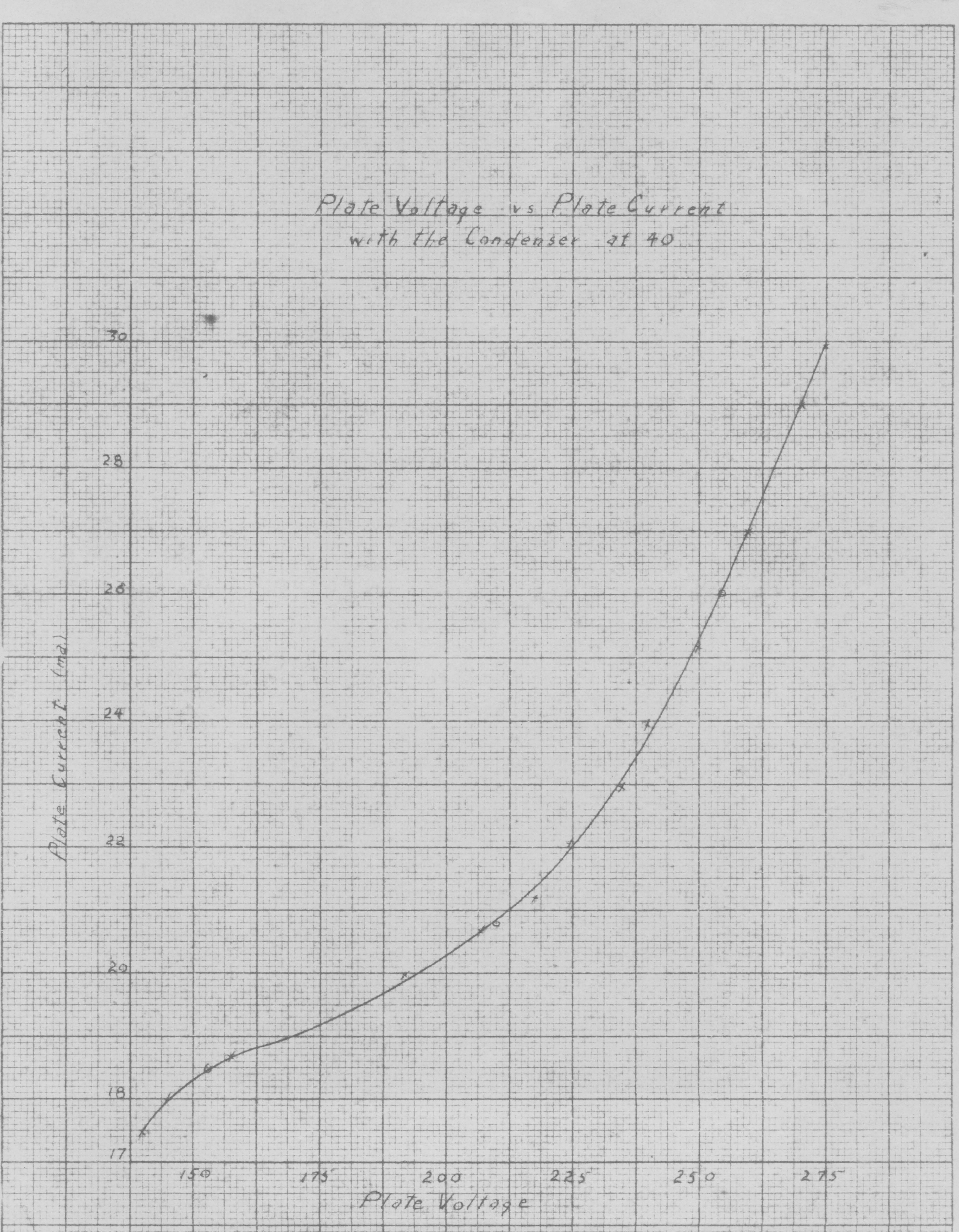


Plate Voltage vs Plate Current
with the Condenser at 40
Plate Current (ma)
30
28
26
24
22
20
18
17
150
175
200
225
250
275
Plate Voltage

Figure 11

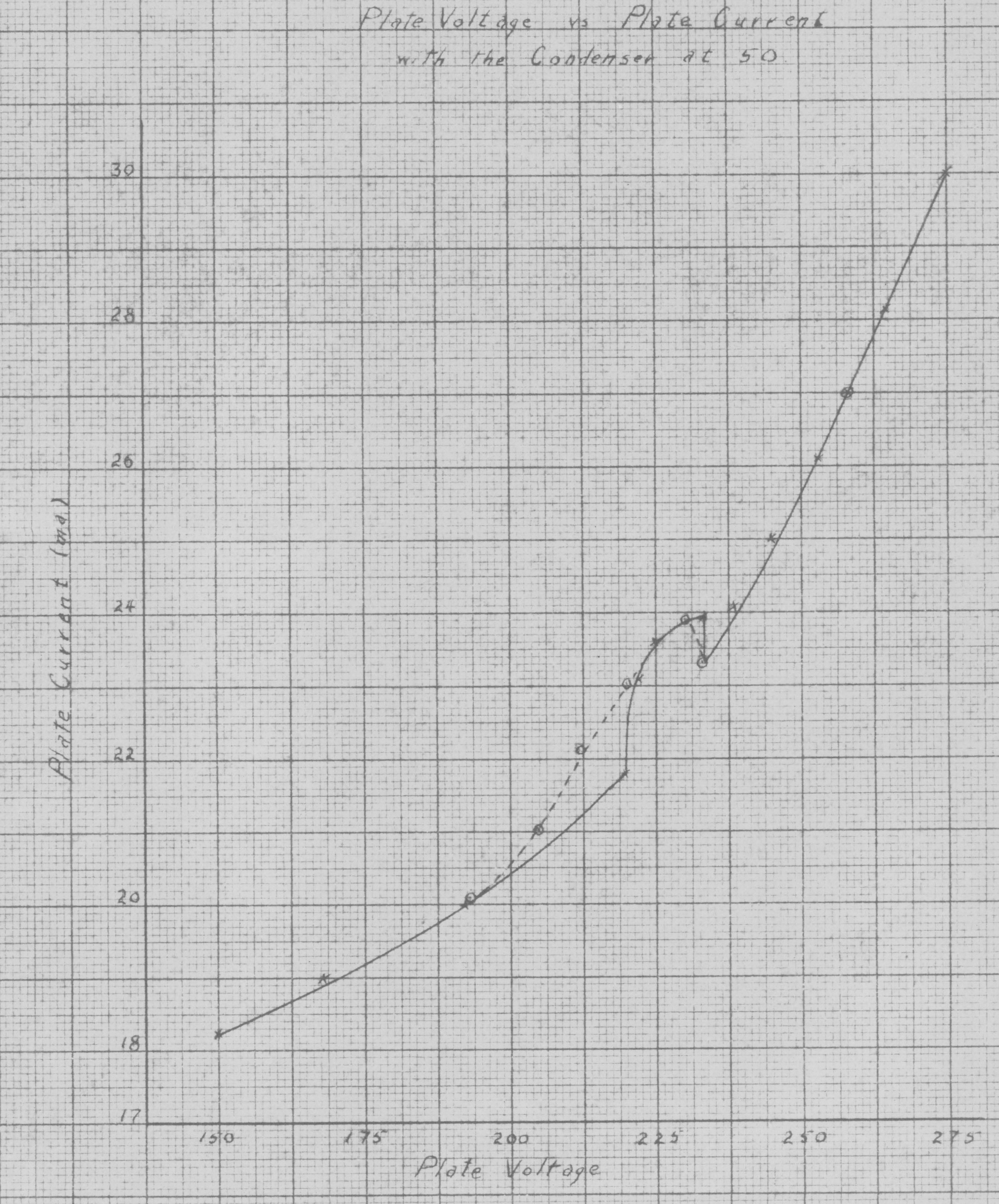
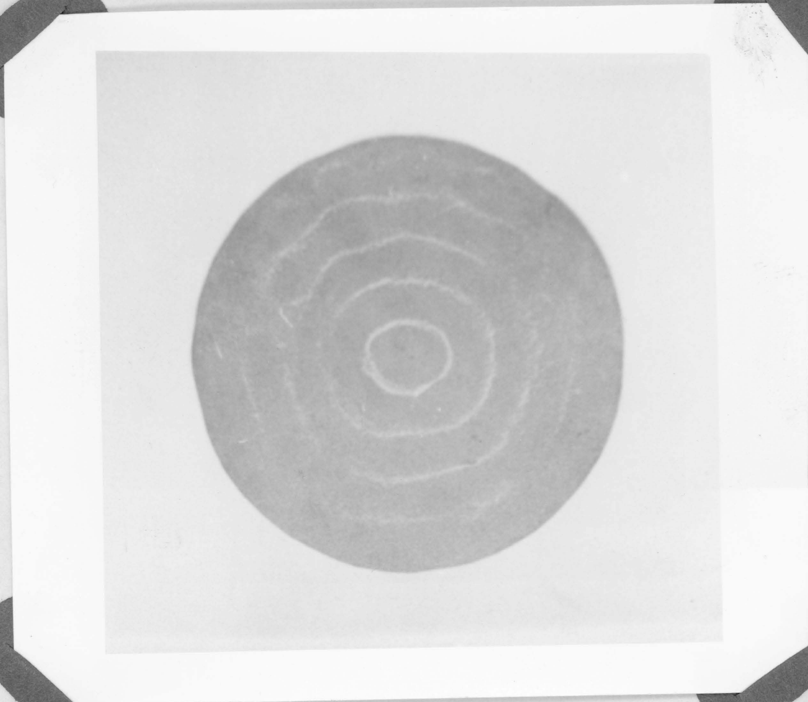
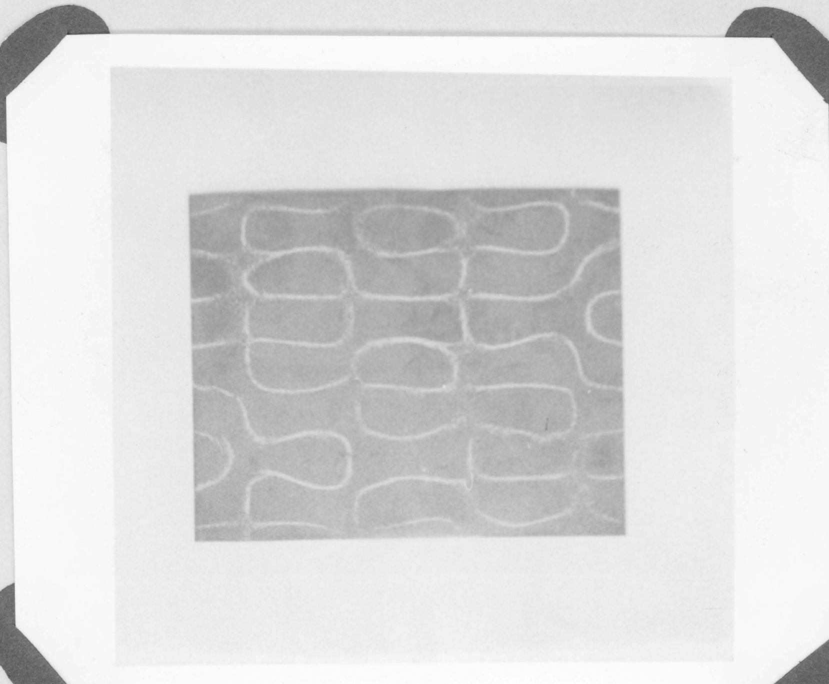


Plate Voltage vs Plate Current
with the Condenser at 50
Plate Current (ma)
30
28
26
24
22
20
18
17
150
175
200
225
250
275
Plate Voltage

Figure 12



A 5" circle of stove iron 0.014" thick
With the rod in the center.



A 4"X5"X0.014" plate of stove iron
with the rod in the center.

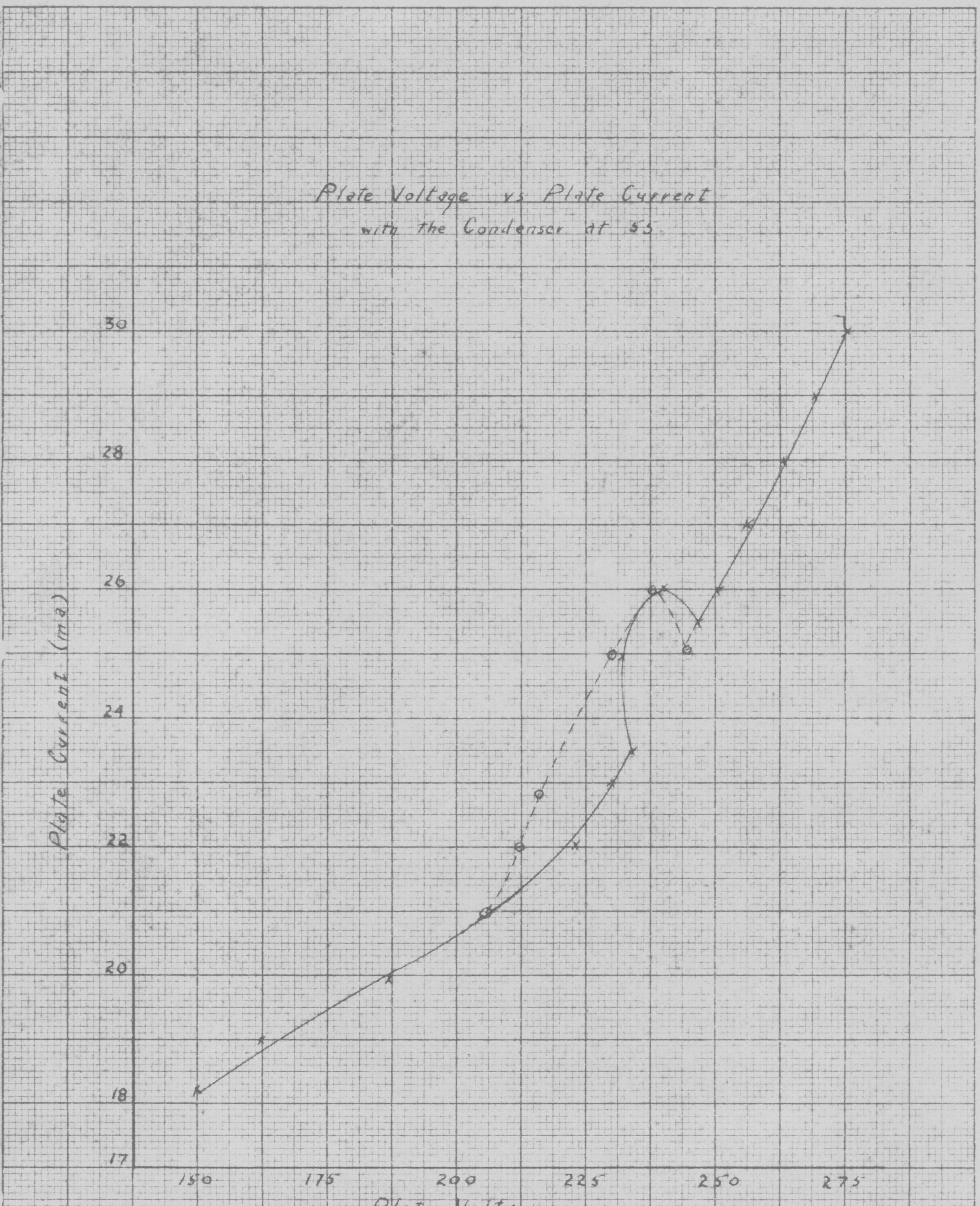


Plate Voltage vs Plate Current
with the Condenser at 55
Plate Current (ma)
30
28
26
24
22
20
18
17
150
175
200
225
250
275
Plate Voltage

Figure 13.

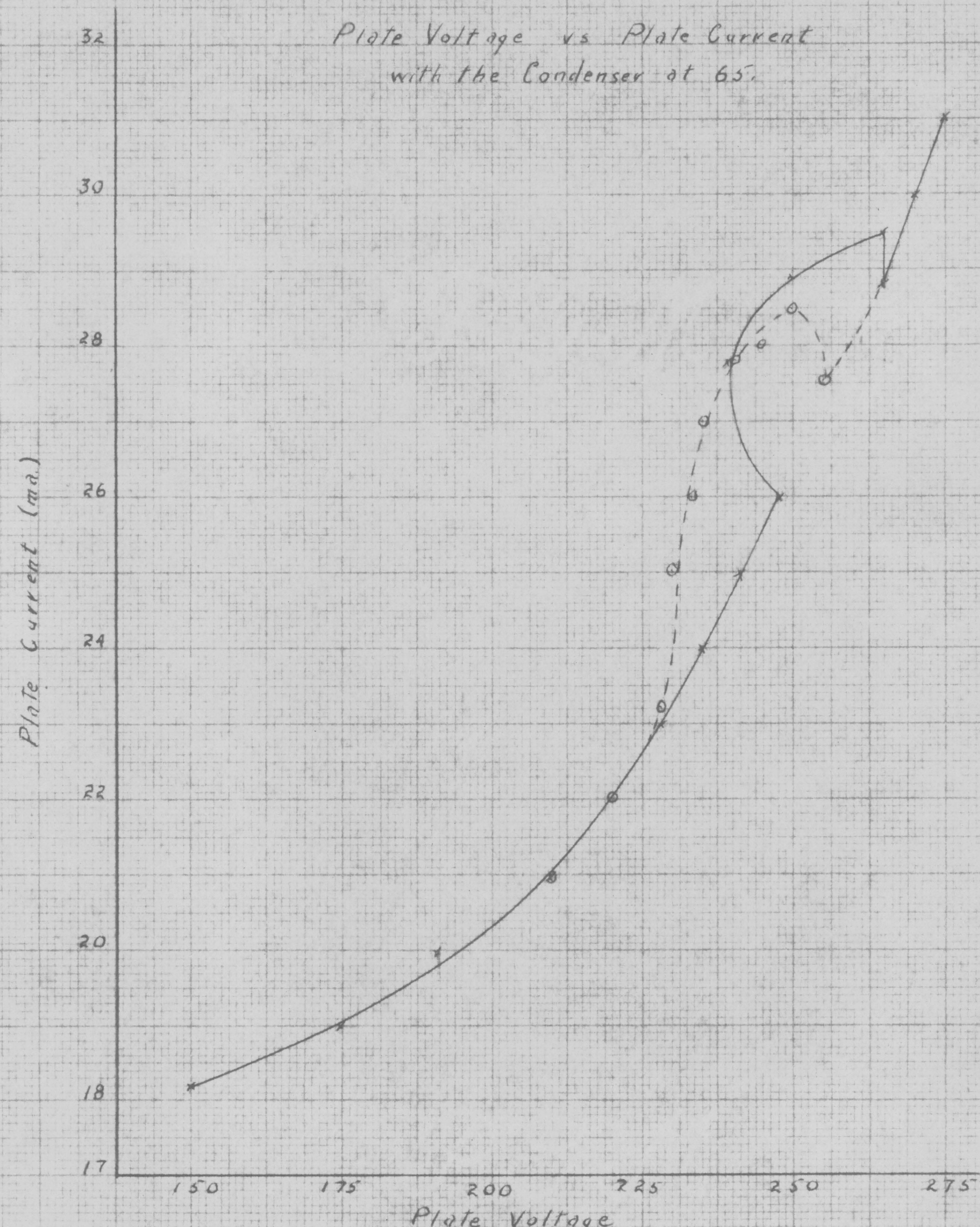


Plate Voltage vs Plate Current
with the Condenser at 65°
Plate Current (ma.)
32
30
28
26
24
22
20
18
17
150
175
200
225
250
275
Plate Voltage

Figure 14

The coil (L_1) in the plate circuit was reversed so the current in the coil (L_1) flowed in an opposite direction from the current in coil (L_2). This condition also caused the rod to vibrate but not as strong as before. A similar set of readings were taken of the condenser settings and the plate current at plate voltages of 150, 175, 200, 225, and 250 volts. The result is shown in figures 15 and 16. For values of 150, 175, and 200 volts, the curves were fairly smooth with the current increasing and decreasing along the same curve. For values of 225 and 250 volts, the plate current increased along a smooth curve, but as the condenser dial was decreased the current first dropped below the smooth curve, as the rod vibrated; and then suddenly, as the rod stopped vibrating, the current jumped to a value above the smooth curve. The current then decreased along a smooth curve higher than the curve for increasing the condenser, as shown by the dotted lines of figures 15 and 16.

From the curves of figures 15 and 16, values of the plate current and plate voltage were taken for condenser settings of 0, 20, 40, 60, 80, and 100. These curves were plotted and are shown in figure 17.

TABLE IV

Data for Figures 15 and 16

Ep Volt	Ip Ma.	Condenser Setting
150	17.3	0
↓	17.5	10
	18.0	42
	18.1	71
	18.1	72
	18.2	75.5
	18.2	79
	18.2	81
	18.2	100
	18.2	79
	18.2	77
	18.2	71.5
	18.0	50
	17.5	10
	17.3	0
175	18.9	0
↓	19.0	12
	19.5	53
	19.8	66.5
	19.8	69
	19.8	71
	19.8	75

Ep Volt	Ip Ma.	Condenser Setting
175	19.9	80
↓	19.9	81
	20.0	100
	19.9	74.5
	19.9	72
	19.8	67.5
	19.8	66.5
	19.5	53
	19.0	12
	18.9	0
200	19.9	0
↓	20.0	13
	20.5	35
	21.1	61
	21.1	65
	21.1	69
	21.1	74
	21.1	75
	21.2	77.5
	21.2	82.5
	21.2	84

TABLE IV CON'T

Ep Volt	Ip Ma.	Condenser Setting
200	21.6	100
↓	21.2	82
	21.2	75.2
	21.2	68
	21.1	67.5
	21.1	66
	20.5	30
	20.0	10
	19.9	0
225	21.0	0
↓	21.5	16
	22.0	24
	22.5	34
	23.0	44
	23.5	63
	23.8	72
	23.9	75
	23.9	76
	24.0	88
	24.0	89
	24.0	95
	24.1	100

Ep Volt	Ip Ma.	Condenser Setting
225	24.0	92
↓	23.1	84
	23.8	63
	23.5	57
	23.0	40
	22.5	30
	22.0	20
	21.5	12
	21.0	0
250	22.0	0
↓	22.5	8
	23.0	13
	23.5	17
	24.0	22
	24.5	31
	25.0	40
	25.5	52
	26.0	65
	26.3	82
	26.5	85
	26.5	90
	26.8	93

TABLE IV CON'T

Ep Volt	Ip Ma.	Condenser Setting
250	26.9	100
	26.8	93
	26.5	85
	26.2	80
	26.0	76
	25.4	70
	26.3	70
	26.0	60
	25.5	45
	25.0	36
	24.5	28
	24.0	20
	23.5	15
	23.0	11
	22.5	7
	22.0	0

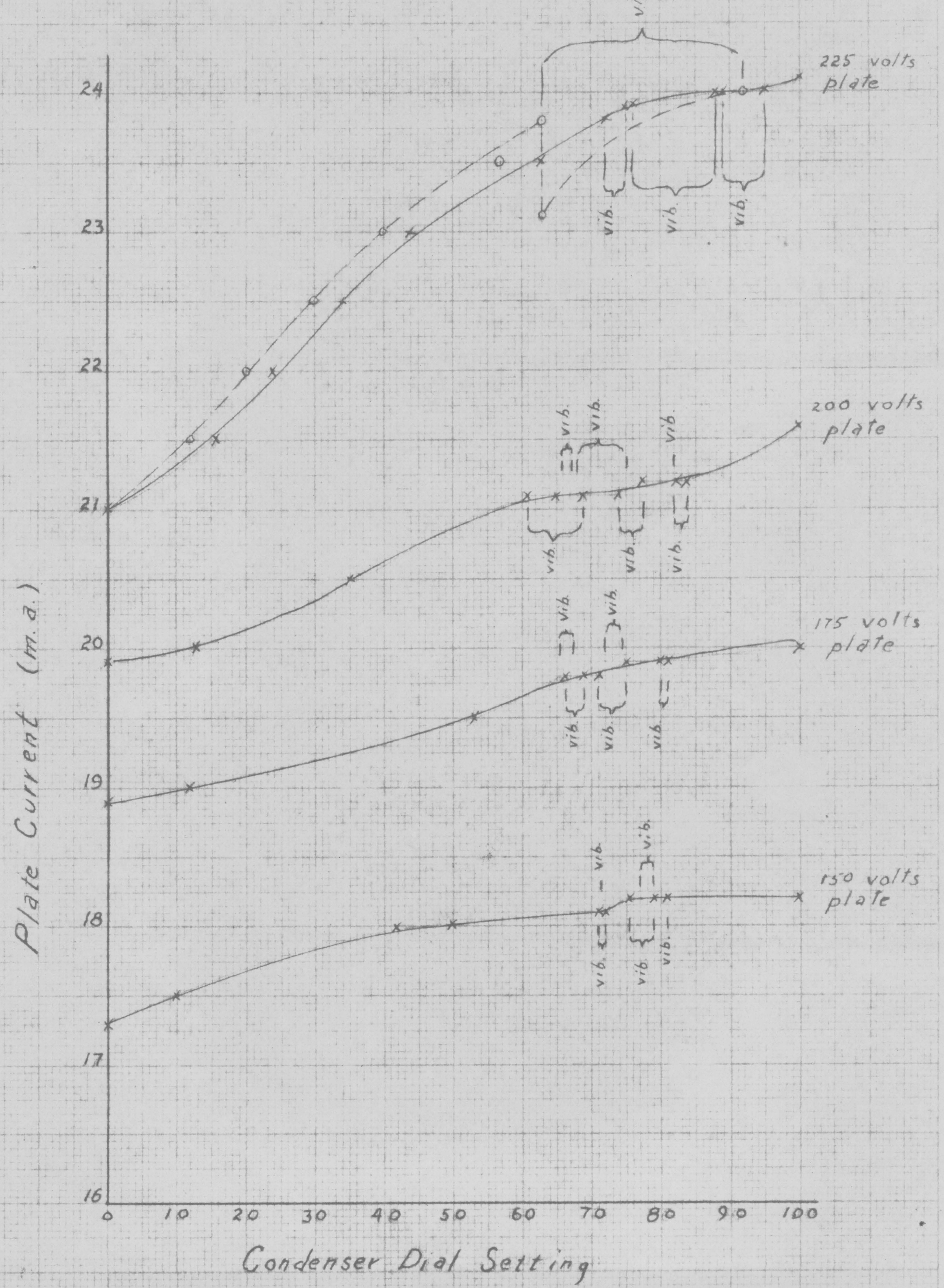
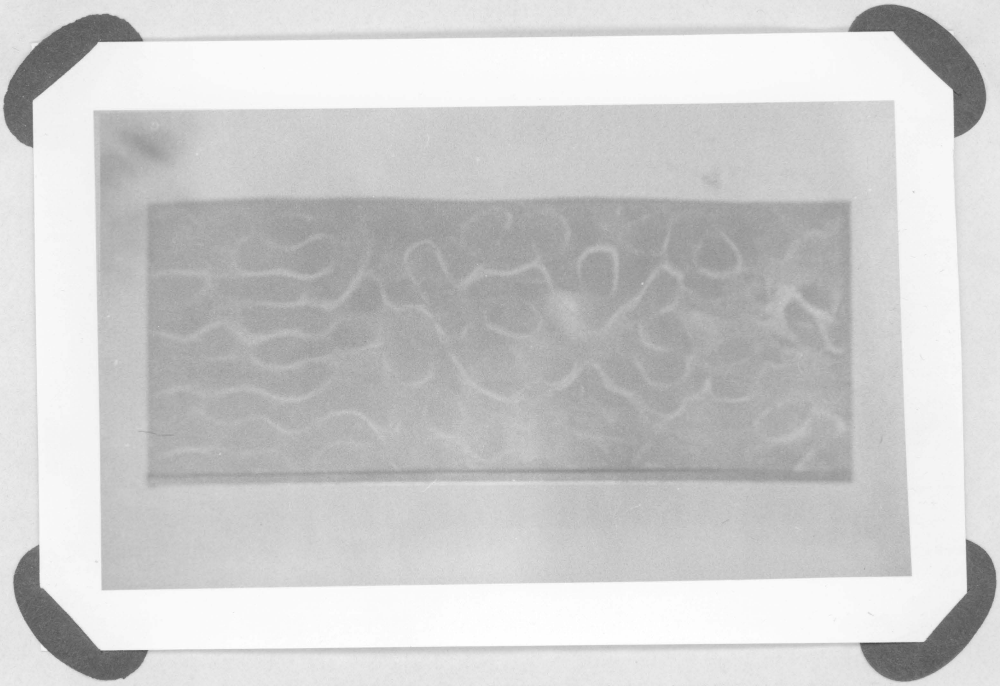
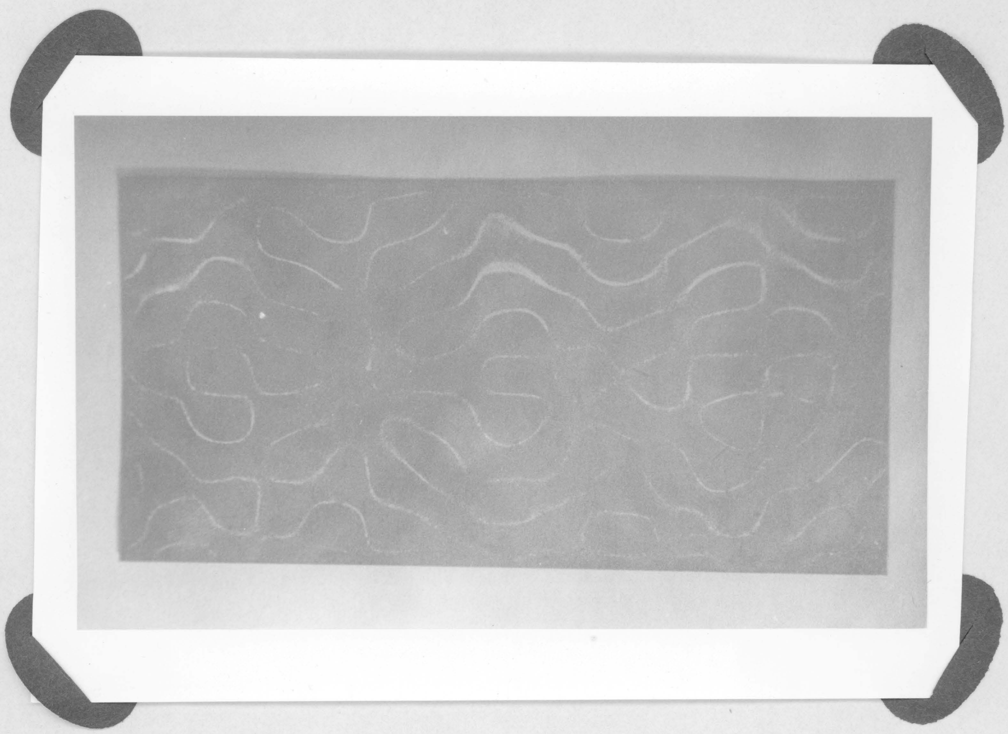

225 volts plate
200 volts plate
175 volts plate
150 volts plate
vib.
Plate Current (m.a.)
Condenser Dial Setting
16
17
18
19
20
21
22
23
24
0
10
20
30
40
50
60
70
80
90
100

Figure 15.



A $4\frac{1}{4}$"X11"X0.0116" plate of aluminium with the rod in the center.

A 5"X9"X0.014" plate of stove iron with the rod in the center.



A 5"X10"X0.014" plate of stove iron with the rod in the center.

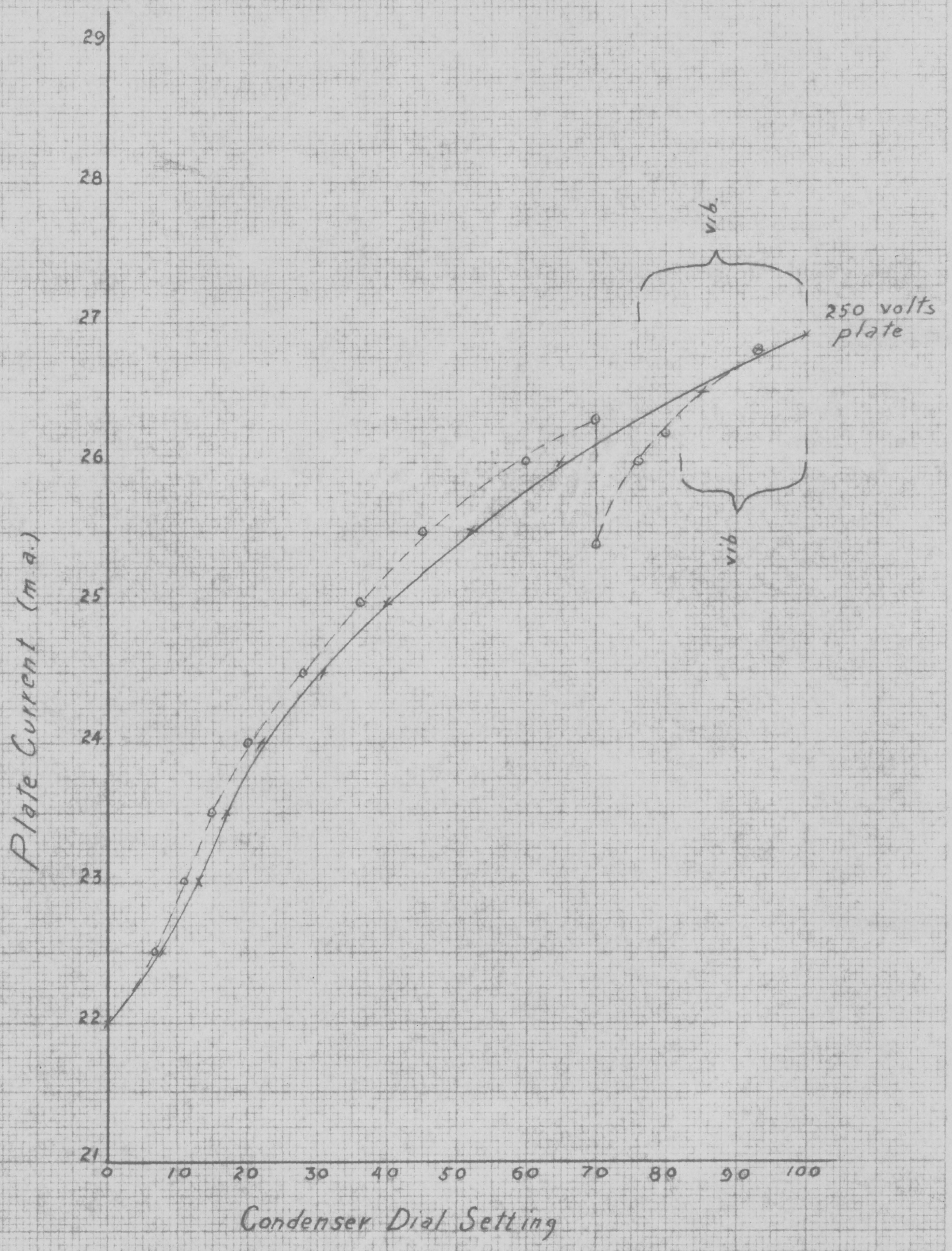


Plate Current (m a.)
21
22
23
24
25
26
27
28
29
0
10
20
30
40
50
60
70
80
90
100
Condenser Dial Setting
vib.
vib
250 volts
plate

Figure 16

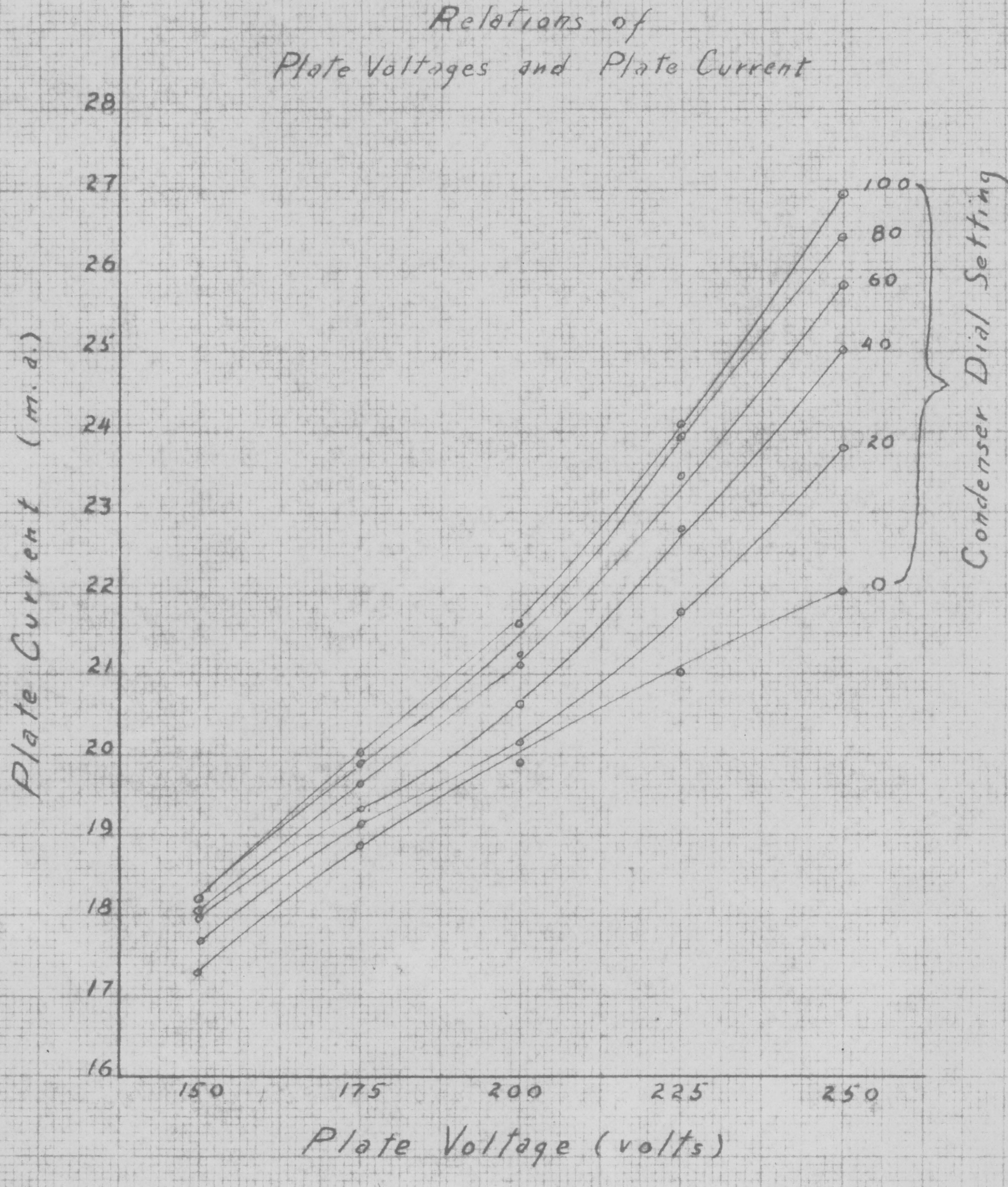
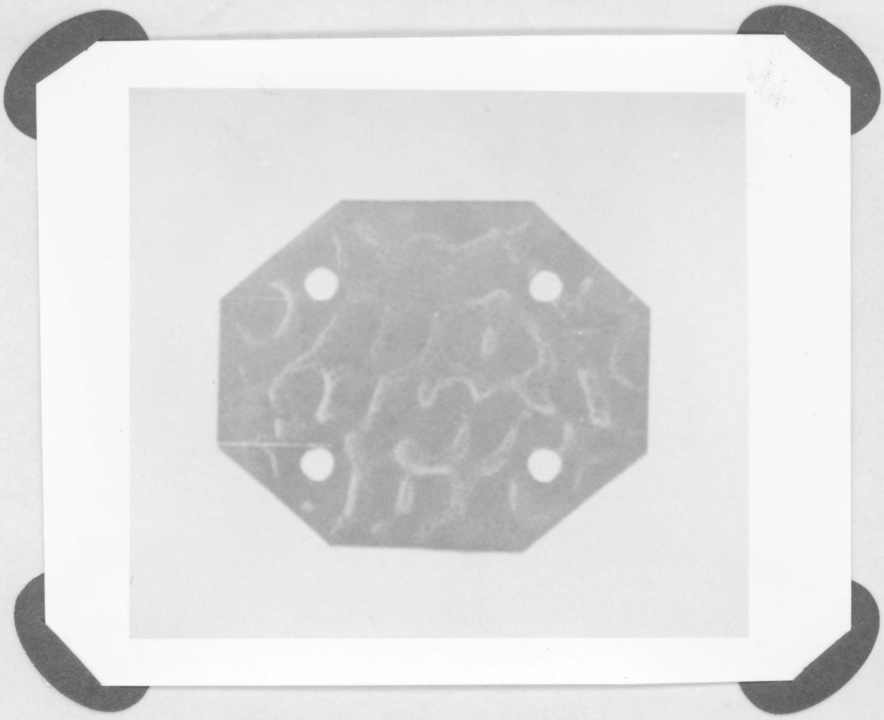

Relations of
Plate Voltages and Plate Current
Plate Current (m. a.)
28
27
26
25
24
23
22
21
20
19
18
17
16
150
175
200
225
250
Plate Voltage (volts)
100
80
60
40
20
0
Condenser Dial Setting

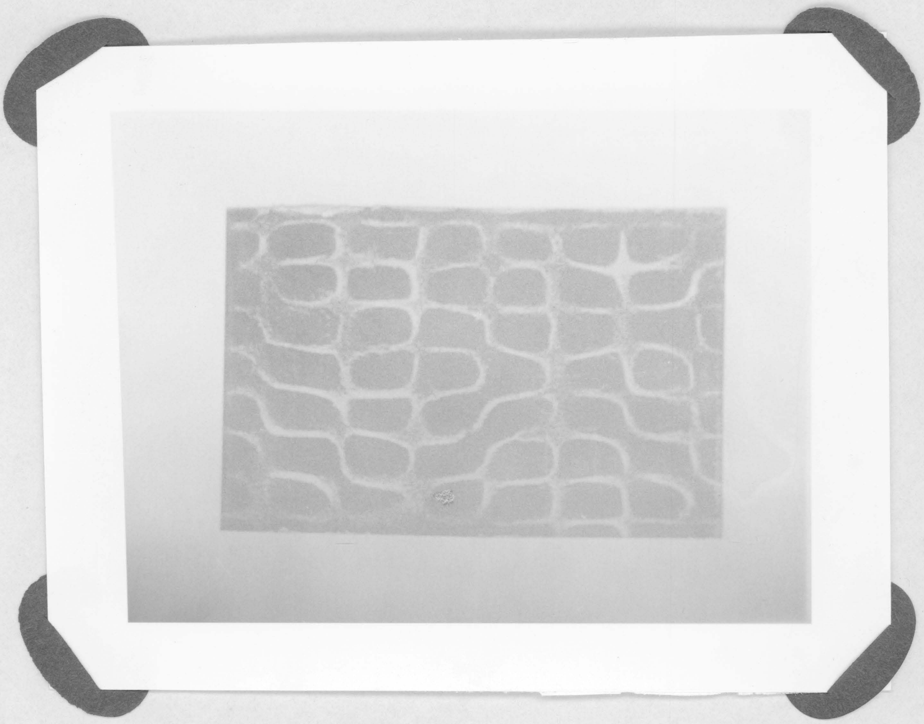
Figure 17.

Another interesting fact is that the oscillator can be tuned by means of a horseshoe magnet. That is, as a horseshoe magnet is moved toward the rod, the rod will start to vibrate when a certain position is reached. Then as the rod is moved in farther, a point is reached where the rod will stop vibrating. Also, when the horseshoe magnet is moved away from the rod, the rod will again start to vibrate but not at the same point, and as the magnet is moved farther away the rod stops vibrating. There seems to be a band encircling the rod. A piece of cardboard was placed under one half of the rod, and radial lines were drawn from the center of the rod 30 degrees apart. Next, a horseshoe magnet, whose upper leg was in a plane parallel to the rod, was moved along these lines. The points at which the rod started to vibrate and stopped vibrating were recorded both when the magnet was moved toward and away from the rod. These results are shown in figure 18, where the full line is the starting of the vibrations and the dashed line is the stopping of the vibration as the magnet is moved toward the rod; and the dashed - dotted line indicates the starting and the small dotted line indicates the stopping of the vibrations as the magnet is moved away from the rod. This gives a band in which the rod will vibrate if the horseshoe magnet is held in it. Readings in this experiment were taken only for a quarter of the horizonal plane, but it is expected by the author that the same effect occurs on the other side of the rod. Also, the author thinks that if the poles of the horseshoe magnet are reversed and observations are made of the other end of the rod, a similar band will be obtained in which the rod will vibrate when the magnet is moved across it.

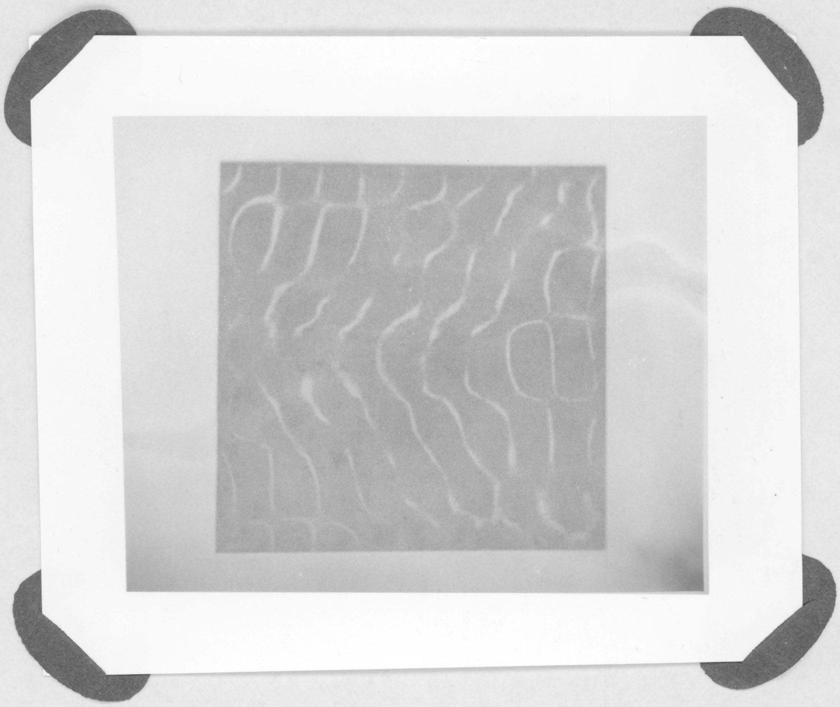


The same plate with all four holes and the corners removed with the rod in the center.

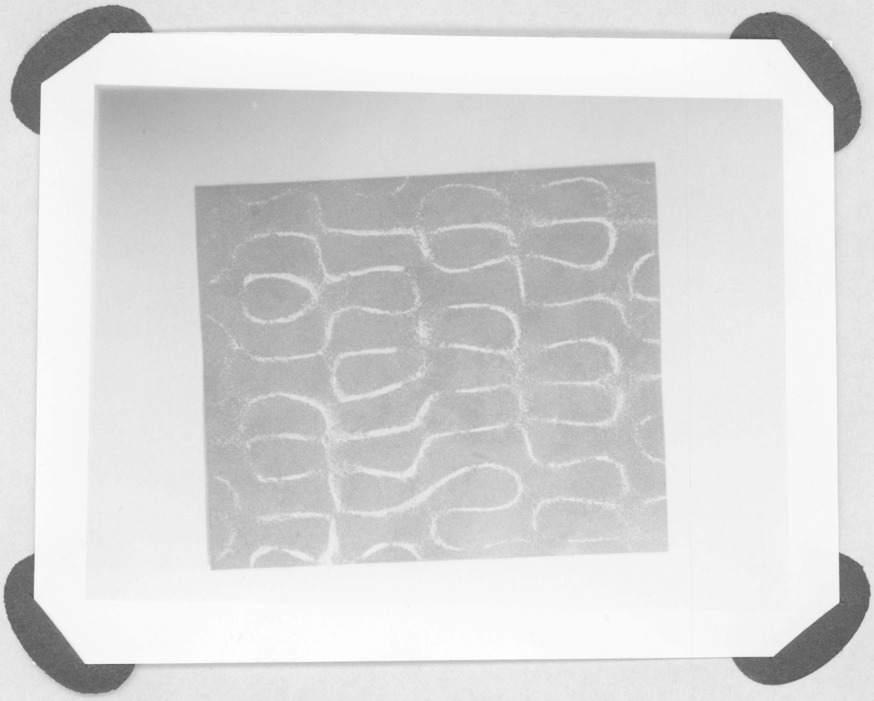
The same 4"X5"X0;014" plate with the corners cut to remove the holes and thus leaving the plate in the form of a cross. The rod was still placed in the center.



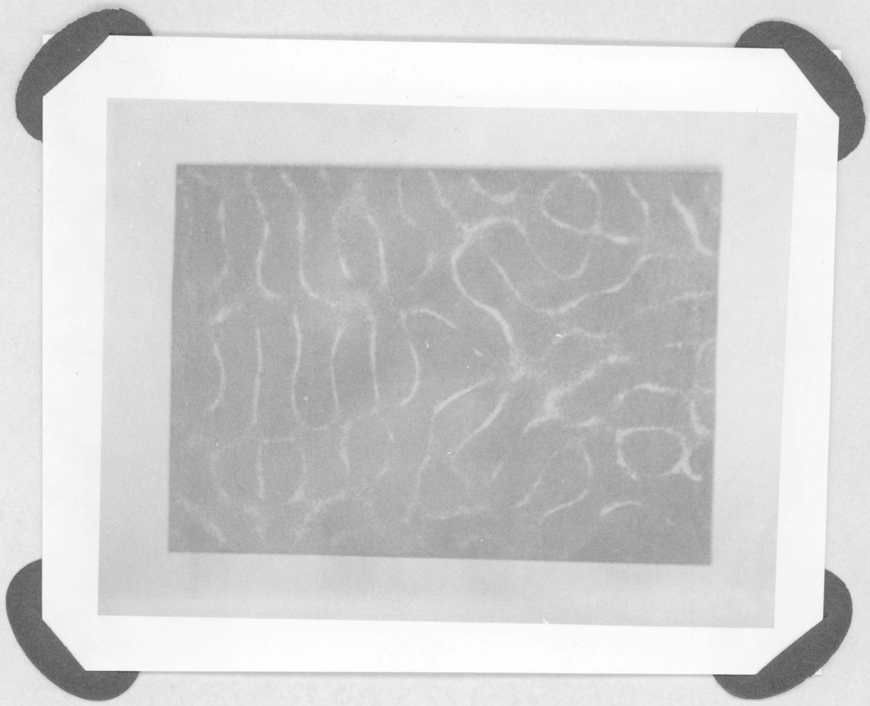
A $4\frac{1}{4}$"X$6\frac{1}{2}$"X0;014" plate of transformer iron coated with a varnish with the rod in the center.



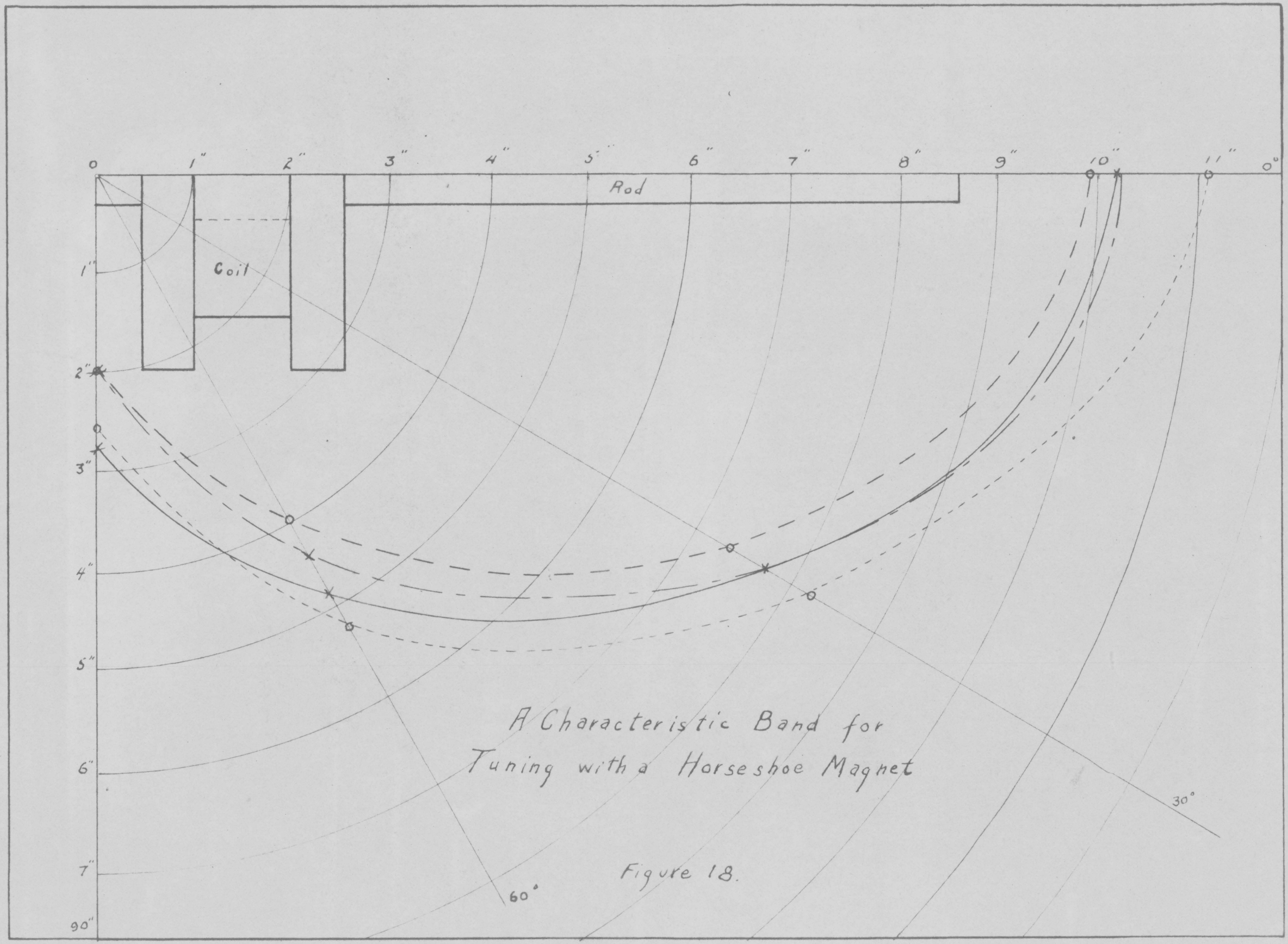
A 5"X5"X0;014" plate of stove iron with the rod in the center.



A 5"X6"X0.014" plate of stove iron with the rod in the center.



A 5"X7"X0.014" plate of stove iron with the rod in the center.



A Characteristic Band for Tuning with a Horseshoe Magnet

Figure 18.

The author found that by placing the magnetostrictive rod in a vertical position and balancing a metal plate on the rod that the rod would cause the plate to vibrate. The plate, of course, vibrates in sections, and the nodal lines were found by sprinkling a fine sand, 100 mesh, over the plate. The nodal lines do not vibrate but remain stationary, and thus the sand runs to these lines. The frequency of the rod and the size and shape of the plates determine the patterns of the nodal lines. Stove iron was used mostly in obtaining the vibrations patterns. The frequency of the magnetostrictive rod was about 6,400 cycles per second. Many different sizes and kinds of plates were tried. The effect on the nodal lines was observed when holes were bored and slots and pieces were cut from the plates. Plates of copper, brass, and aluminium also gave fairly good patterns. Some of the plates used were warped and had stresses set up in them, so the nodal lines were not quite symmetrical in shape in all cases.

DISCUSSION OF RESULTS

From the curves of figure 10, it can be seen that the magnetostrictive rod causes the frequency of the oscillator to remain constant over a considerable range of condenser dial settings. The magnetostrictive rod, of course, vibrates over different ranges for different values of plate voltage. Also, from figures 11, 12, 13, and 14, it can be seen that the set will remain constant, and the rod will vibrate over a large change in voltage.

One disadvantage is that the magnetostriction oscillator requires at least three hours for it to heat up and to reach a constant value of plate current and plate voltage. The changes of plate current and plate voltage with the time it takes the set to heat up are shown in figures 7, 8, and 9.

It was found that for best results of the oscillator that the two coils (L_1) and (L_2) should be so wound and oriented in such a manner that a steady current flowing from the filament to the plate and a steady current, if there were one, flowing from the filament to the grid produces a magnetic field in the same direction along the axis of the coils. This was the case in the first experiment. When the plate coil (L_1) is reversed, the currents flow in a direction as to set up opposing magnetic fields. The rod vibrated but not as strong as before the coil was reversed. The curves of the plate current against dial settings of the condenser are shown in figures 15 and 16, for different values of plate voltage and showing the bands of vibrations. In most cases the rod would vibrate for three different settings on the condenser dial.

It was found that the oscillator could be tuned by changing the number of magnetic lines through the coils. This could be done by means of a horseshoe magnet. When the condenser dial was set near the vibrating value of the rod and a horseshoe magnet brought near the rod, the rod would start vibrating. There was a band around the rod, which, when the horseshoe magnet was placed in it, would cause the rod to vibrate. A characteristic band around the rod is shown in figure 18.

Nodal lines in a vibrating plate can be studied by using the magnetostrictive rod as a means of setting the plate in vibration. The plate can be kept at a constant frequency depending on the length of the rod. Fairly large plates can be made to vibrate when a nichrome steel rod, which has strong magnetostrictive properties, is used as the vibrator. Much work could be done in studying the vibrations of plates and flat bodies by this means. Nodal lines for all shapes and sizes of different materials can be obtained in this way. Initial stresses in the plates may have some effect on the nodal lines, but this is not known to be a fact. First a picture could be taken of the plate with the stresses in it and then compare it with a second picture taken after the plate had been annealed. In one 12 by 12 copper plate there was a peculiar group of very fine lines of sand running across the plate. They didn't seem to have any relation to the nodal lines as they ran right through them without diverting in any way. These small lines didn't follow any scratches on the plate that could be seen. What caused these fine lines is not known. A study could be made on this copper plate to determine the cause of these fine lines. It may be that they were caused by the arrangement of the molecules in the metal.

The magnetostrictive oscillator can be used in various ways such as a frequency standard, provided the temperature coefficient of the magnetostrictive rod is taken into account. The magnetostriction oscillator can be used to calibrate a wavemeter, if a series of beat notes having definite harmonic relationships to the fixed fundamental frequency of the rod is made available. Audio frequency meters can also be calibrated by means of the magnetostrictive oscillator. The sound velocity and the elastic properties of solid non-magnetic and non-magnetostrictive materials can be determined by placing the end of the magnetostrictive driving rod against them and measuring the frequency. A method of measuring the depth of the seabed has been devised by producing and receiving echoes by means of a high frequency magnetostriction oscillator.

These are just a few of the uses that can be made of the magnetostriction oscillator. Not much work has been done with these oscillators since they were used to stabilize low frequencies.

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