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PRELIMINARY REPORT

on

Effects of High Frequency Electric Fields of High
Field Intensities Upon Radio Frequency
Insulating Materials.

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AUTHORIZATION

1. Reference (a) assigned to the Laboratory the problem of finding the effects of high frequency electric fields of high field intensity upon various types of radio frequency insulating materials. Suitable samples of all the various types of insulating materials are not yet available at the Laboratory; however, manufacturers have been requested to submit samples of their products for test. This preliminary report is compiled with the object of showing the results obtained from materials already tested in order to inform the Bureau regarding progress made on this problem. A final report will be submitted when all tests on all types of materials have been completed. !

PURPOSES OF TESTS

2. The purpose of these tests is to make comparisons both on a relative and on an absolute basis of the losses in various types of radio frequency insulating materials when they are subjected to a high frequency electric field of high field intensity.

(a) The relationship between dielectric losses, field intensity, current through dielectric, volume of dielectric, etc., are well known when the applied frequency and field intensity are low. However, it does not necessarily follow that the same relationship exists when the same dielectric is subjected to a high frequency field of high field intensity. One of the purposes of these tests is to find whether or not this relationship remains the same, and if not, what new relationship exists. In order to investigate this matter, the following tests are necessary:

- (1) Determination of dielectric constant of the insulating material at the frequency of test.
- (2) Determination of the relationship of losses and current through the dielectric, all other factors remaining unchanged.
- (3) Determination of the relationship between losses and field intensity, all other factors remaining unchanged.
- (4) Determination of the relationship between loss per unit volume and the volume of the dielectric in the field, all other factors remaining unchanged.
- (5) Determination of the relationship between temperature rise and time of exposure to the field, all other factors remaining unchanged.

(b) Another purpose of these tests is to form an empirical equation to approximately express the relationship existing between the losses in the dielectric, field intensity, time of exposure, and possibly other factors, the information found in the five preceding sub-paragraphs serving as a basis for formulating this equation.

- (c) Still another purpose of these tests is to determine if the equation formed empirically in the preceding sub-paragraph can also be derived theoretically using the laws of electricity and thermodynamics.
- (d) Another purpose of these tests is to take the results found in sub-paragraphs (a), (b) and (c) and to calculate the following properties of a unit cube of the dielectric:
- (1) Equivalent series radio frequency resistance.
 - (2) Power factor.
 - (3) Phase difference.
 - (4) Loss factor.
 - (5) Power loss in the unit cube at a field intensity of 1 kilovolt per centimeter.

REFERENCES

3. (a) Bu.Eng.let.S67/61/L5(1-11-W8) of 1 Feb. 1934.
- (b) Textbook entitled "Electricity and Magnetism" by S. G. Starling.
- (c) Textbook entitled "Dielectric Phenomena in High Voltage Engineering" by F.W. Peek.
- (d) Textbook entitled "Principles of Radio Communication", Third Edition, by J.H. Morecroft.

MATERIALS UNDER TEST

4. The various types of insulating materials tested are listed below:

<u>Material</u>	<u>Manufacturer</u>	<u>Manufacturers Grade</u>
Fused Quartz	General Electric Company	Transparent
Victron	Dielectric Products Corp.	AA
Steatite	" " "	334
Steatite	" " "	306
Steatite	" " "	352-B
Plate Glass	- -	- -
Porcelain	Westinghouse	- -
Bakelite	- -	E

The sample of Plate Glass is not of a type manufactured for radio frequency insulation purposes, but is an ordinary type of commercial plate glass. The sample of porcelain was one of four sent to the Laboratory as enclosure (A) of ref.(a).

METHODS OF TESTS

5. Plate 1 shows the circuit used for testing all types of dielectrics. Radio frequency power is furnished by a 500 watt self-oscillating driver, a Hartley circuit with a type 831 tube being used for this purpose. A circuit composed of a coil and condenser connected in parallel is coupled to the driver through a transmission line, this circuit serving as a means of applying a high frequency field to the dielectric. The condenser used in this circuit consists of two parallel disc-shaped plates 6.5 cm. in diameter, which serve as the electrodes. Plate 2 shows the means of applying the field to the specimen. The specimens of dielectric used are in the form of flat plates having an area of from 150 to 200 square centimeters and a thickness of from 0.4 to 0.7 centimeters. The spacing of the electrodes is adjustable, and thereby the capacity between the electrodes is made variable. In this manner the coupled circuit may be resonated to the frequency of the driver either with or without a dielectric specimen between the electrodes. A radio frequency ammeter is connected in the circuit, its function being to measure the current through the electrodes and also to indicate resonance. The capacity of the condenser at various spacings with no dielectric within the field was measured by means of a capacity bridge at a frequency of 1,000 cycles. The curve shown on Plate 3 shows the relationship between capacity and spacing. It is believed that this value of capacity will also be approximately correct at radio frequencies, since all high grade condensers show very small changes in capacity with change in frequency. All tests were conducted at a frequency of 30 megacycles; however, additional tests at other frequencies will be made in the future. In this report, all values of potential, current, capacity, resistance, power, etc., are expressed in practical units. The c.g.s. system of units is employed for all other purposes.

(a) The method of investigating the effects of high frequency fields of high field intensity upon dielectrics is discussed below:

- (1) A specimen of dielectric of thickness x is placed between the electrodes in the manner stated previously, and the spacing between the electrodes is adjusted until the circuit is resonant with that of the driver. The spacing at resonance with the specimen in the field is noted, this spacing being designated as x' . A value of tuning inductance is chosen so that the spacing between the dielectric and the electrodes is small; however, the electrodes are not allowed to touch the dielectric. The spacing between the electrodes is kept small in order to make the electric field near the edge of the electrodes as uniform as possible. When the edge effect is made small, the action of the field upon the dielectric (although both are of finite area) is approximately the same as if

both had an infinite area. Now if the specimen of dielectric is removed from the field, the spacing of the electrodes must be decreased to bring the circuit into resonance, since the value of tuning inductance is unchanged. The spacing between the electrodes at resonance with the dielectric removed is designated as x'' . Now the dielectric constant of the specimen may be calculated by means of the following formula:

$$K = \frac{x}{x - (x' - x'')} \quad (1)$$

where K = dielectric constant.

x = thickness of dielectric in cm.

x' = distance in cm. between electrodes at resonance with specimen of dielectric between electrodes.

x'' = distance in cm. between electrodes at resonance with specimen removed, the value of inductance being the same as for distance x' .

The proof of this formula may be found in ref.(b), pages 165 and 166. In this manner the values of dielectric constant may be calculated at the frequency of test.

- (2) When radio frequency current of relatively low frequency (below 1000 Kcs.) is passed through a dielectric, the losses are proportional to the square of the current. However, it is necessary to determine if this relationship still exists at high frequencies. It is difficult to accurately measure the losses in a dielectric at high frequencies by bridge or substitution methods, and consequently, a different method of studying such relationships must be used. When a dielectric is subjected to an alternating electric field, the power loss raises the temperature of the dielectric. Since the relationship between electrical energy and heat is fixed, and the temperature rise of any substance is proportional to the heat added, an investigation as to whether the square law remains unchanged at high frequencies can be made by measuring the temperature rise of the dielectric when various values of current are passed through the electrodes. Now if the values of temperature rise are plotted against the square of the current and all points may be connected by a straight line, then the square law relationship holds true at the frequency of test. If all specimens are subjected to the same values of current and exposed to the field equal times, the temperature rise of each specimen is proportional to its losses. These tests may be made most accurately if precautions

are taken to prevent loss of heat during the actual test, and between the completion of the test and the measurement of temperature rise. Now heat may be lost by conduction from the center to the edges of the specimen, and by radiation. These effects may be reduced to a minimum by keeping the temperature rise small and the time of exposure short, and by measuring the temperature rise as soon after exposure as possible. The thermal conduction coefficient of all dielectric materials is small, thereby making the conduction losses small for short periods of time and small temperature rises. The temperature rise of the specimens is measured with a contact thermocouple which is applied to the center of the specimen. This point of application is chosen for two reasons: first, the applied electric field is most uniform at that point, and second, less heat loss will occur at this point than at any other, since the surrounding material is approximately at the same temperature. Since the temperature rise of different dielectric materials is very different for the same current and time of exposure, in order to keep the temperature rise of all the materials small, different times of exposure must be used and all results reduced to the same basis. Subsequent tests will show that all data may be reduced to the same time basis without serious error, provided the temperature rise is small, and the time of exposure not too great. However, the temperature rise must be great enough to measure with a sufficient degree of accuracy, and with the thermocouple used, the temperature rise should not be less than 0.3°C .

- (3) In order to determine the effects of field intensity upon dielectric materials, a means of calculation of the field intensity must be devised. It has been shown that the capacity between the electrodes at a spacing x'' (no dielectric within the field) and that at a spacing x' (the dielectric within the field) are equal, since in each case the dielectric testing circuit is in resonance with the driver frequency. The current through the electrodes is measured with the radio frequency ammeter. The voltage across the electrodes may then be determined as follows:

$$e' = \frac{i}{2\pi f c'} \quad (2)$$

where e' = R.M.S. value of voltage across the electrodes.

i = R.M.S. value of current through electrodes.

f = frequency expressed in cycles per sec.

c' = capacity in farads, this being the capacity of the condenser at resonance with no dielectric between electrodes.

It has been shown that lines of flux near the center of the electrode are approximately normal to the plane of the dielectric; consequently, no refraction of flux takes place at the surface of the dielectric. Since this is true, the value of the potential actually across the dielectric may be calculated from the following formula:

$$e = \frac{e^1}{1 + \frac{(x^1 - x) K}{x}} \quad (3)$$

where e = R.M.S. voltage across the dielectric. The proof of this relationship may be found in ref.(c), pages 31 and 32. From the value of voltage across the dielectric, the field intensity may be calculated in the following manner:

$$E = \frac{e}{x} \quad (4)$$

where E = field intensity in R.M.S. volts per centimeter. At low frequencies the power loss in a dielectric is proportional to the square of the field intensity. If values of temperature rise are plotted against the square of the field intensity, and a straight line can be drawn through all points, the relationships existing at low frequencies also are true at high frequencies. In order to obtain accurate measurements of losses as indicated by temperature rise, the methods of preventing loss of heat discussed in the preceding sub-paragraph must be again used. Also the time of exposure to the field for each of the various materials tested must be reduced to the same basis in order to obtain comparisons of temperature rise.

- (4) When a specimen of insulating material is subjected to a low frequency field, the power loss is distributed throughout its volume. Also the power loss per unit volume is independent of volume if the field intensity is the same. However, when a high frequency field is applied to the same material, it is possible that more of the power loss occurs on the surface at the point where the flux passes from air into the material than occurs within the material. If the high frequency losses occur mainly at the surface, they are in the nature of a "skin effect". Now if the losses are in the nature of a "skin effect", the temperature of the surface of the material will be higher than that of the interior but if they are distributed throughout the volume, the temperature of the surface will be approximately equal to that of the interior. Now if the temperature rise of samples of the same material of various thicknesses at equal field intensities and times of exposure is found to be independent of thickness, then it may be assumed that the losses are distributed throughout the volume. But if the

temperature rise is found to decrease with increase in thickness, it may be assumed that the losses are in the nature of a "skin effect", this decreasing temperature rise (with increase in thickness) being caused by the conduction of heat at the surface to the interior (the thermal capacity of which increases with thickness) which is at a lower temperature. Four pieces of bakelite taken from one piece of material were obtained, and the temperature rise measured, placing successively, one, two, three, and four, pieces of the material between the electrodes. Where more than one piece was tested, the pieces were placed in such a manner as to reduce the effect of the air gap between the pieces of material. Similar tests were also made upon pyrex glass obtained from one piece of material. However, this pyrex glass was not manufactured for radio frequency insulation purposes, but for use in a chemical laboratory. Since it may not always be practicable to apply the same field intensity to the samples of various thicknesses, the various values found must be reduced to the average value, the formula used for this reduction being in accordance with the relationship between field intensity and temperature rise found as the result of the tests made in the preceding subparagraph. Now if it is found that the loss per unit volume is independent of volume in both of these types of materials (which are very different from one another) at a frequency of 30 megacycles, then it may be assumed that the effects will be similar in all the types of material tested.

- (5) The various types of dielectric were placed in the electric field, and the temperature rise determined with the contact thermocouple for various times of exposure, allowing all specimens to return to room temperature between tests. The field intensity of each specimen was kept constant, although the field intensity of different types of materials varied to a certain extent. From this information, a curve may be drawn for each material showing the temperature rise for various times of exposure at a fixed value of field intensity.
- (b) From the information obtained in the preceding five sub-paragraphs it should be possible to form an equation empirically which will show the relationship between losses (temperature rise), field intensity, time of exposure, and possibly other factors at a frequency of 30 megacycles. It is possible that the equation determined empirically may apply only under certain conditions (such as short time of exposure, small temperature rise, etc) and any limitation of conditions for the application of the equation should be stated.
- (c) In order to theoretically analyze this action of an electric field on a dielectric, a unit cube each dimension being 1 centimeter in length, is chosen at or near the center of the piece of material as shown in Plate 4. The capacity of this cube may be calculated from its dimensions and dielectric

constant, for it is unnecessary to include edge effects since the cube is surrounded by similar material. An equivalent electrical circuit of this cube is shown in Plate 5, C being the capacity of the cube and r the equivalent parallel radio frequency resistance. However, r may not be entirely independent of the voltage across the cube, and certainly will not be independent of the frequency. The relationship between r and the field intensity can be found by the methods described previously in this paragraph, and if the losses (temperature rise) are found to be proportional to the square of the field intensity, then r may be assumed to be of fixed value (for a particular frequency) and may be expressed in ohms. However, if the losses (temperature rise) are found not to be proportional to the square of the field intensity, then r is not a fixed value, but is a function of the field intensity, and an equation must be formed to show the relationships existing. Although the capacity of this unit cube may be easily calculated, more information is required to evaluate its equivalent parallel radio frequency resistance. Since the relationship between electrical energy and energy in the form of heat has been determined, a method of calculating the equivalent parallel resistance can be formulated.

- (d) From the values of the capacity and equivalent parallel radio frequency resistance of the unit cube, several other constants of importance may be calculated as indicated below:

- (1) The method of calculating the equivalent series radio frequency resistance is as follows:

$$R = \frac{1}{r(2\pi fC)^2} \quad (5)$$

where R = equivalent series radio frequency resistance
in ohms of unit cube at the frequency of test

f = frequency in cycles per second

C = Capacity of unit cube in farads.

r = equivalent parallel radio frequency resistance
in ohms of the unit cube at the frequency of
test.

This formula is approximately correct when the value of the equivalent parallel resistance is much greater than the reactance. Proof of this formula may be found in reference (d), pages 254-255.

- (2) The power factor may be found in the following manner:

$$P.F. = R \omega C \cdot 100 \quad (6)$$

where P.F. = power factor expressed in per cent

R = Equivalent series radio frequency resistance in ohms.

ω = angular velocity of impressed voltage in radians per second.

C = capacity of unit cube in farads.

- (3) The phase difference angle of the dielectric material is the angle whose sine is equal to the power factor. This phase difference angle may be expressed in minutes.
- (4) The loss factor is defined as the product of the dielectric constant and the power factor in percent. Sufficient information is available for this calculation.
- (5) Since the equivalent parallel radio frequency resistance of a unit cube may be calculated, the power loss within the cube at the frequency of test may also be calculated for any selected value of field intensity by means of the following formula:

$$P = \frac{E^2}{r} \quad (7)$$

where P = power loss in watts in the unit cube.
The selected value of field intensity for computing the power loss was 1 kilovolt per centimeter, this value being comparable with that actually applied to dielectric material when used in a high frequency transmitter.

RESULTS OF TESTS

6. The results of the tests discussed in the preceding paragraph are shown below:

- (a) The result of the tests to determine if the action of an electric field of high frequency is similar to that of a field of low frequency is shown in the following subparagraphs:
 - (1) The values of dielectric constant at a frequency of 30 megacycles and the observed data from which they are computed ~~are~~ shown in Table 1. The values of dielectric constant of the same materials measured at low frequencies ~~are~~ also furnished, this value being recorded under the column headed K'.
 - (2) The results of the tests to determine the effect of passing various values of current through each of the several types of dielectric material tested are shown in Plates 6, 7, 8 and 9. The length of time for the passage of current through each of the specimens is shown in Table 2, this time being chosen

as discussed previously. The values of temperature rise for each value of current and time of exposure were reduced to temperature rise per second for each value of current, in order that all materials may be compared on the same basis. It is noted that a straight line passes approximately through all points, when the temperature rise is plotted against the square of the current on linear cross-section paper. In comparing results, it should be noted that the scales of temperature rise per second are different on each of Plates 6 to 9 inclusive. All information shown on Plates 6 to 9 inclusive is repeated on Plates 10 in order that the results may be more readily compared. From these plates it is shown that the heat produced in all specimens tested is proportional to the square of the current, and likewise, ~~that~~ the losses are proportional to the square of the current.

- (3) The results found in the preceding subparagraph may be expressed in terms of field intensity and temperature rise instead of current and temperature rise, the methods discussed previously being used for this conversion. Since insulators are used mainly for mechanical purposes (all dielectric material being placed out of the electric field wherever possible) an insulator will more likely be subjected to a fixed value of field intensity than to a fixed value of current. Consequently, it is more desirable from a comparative viewpoint to furnish information in terms of the losses (temperature rise) at various values of field intensity. This information for the same types of materials is shown in Plates 11, 12, 13, 14 and 15. It is noted that when the temperature rise for any specimen of the material is plotted against the square of the field intensity on linear cross-section paper that a straight line passes approximately through all points. This was to be expected, since from equations (2), (3) and (4) it is shown that the field intensity applied to any specimen is proportional to the current through it. From these curves, it is shown that the losses of each of the materials tested are proportional to the square of the field intensity. All information shown on Plates 11 to 15, inclusive, is shown again on Plate 16 in order that the results may be more readily compared.
- (4) The results of the tests to determine if radio frequency dielectric losses are distributed throughout the volume are shown in Plate 17. The value of field intensity for each thickness could not always be kept the same, consequently, in order to compare all results on a specimen at the same field intensity, the values of temperature rise were converted to what their value would be if subjected to the average value of field intensity. Now since the temperature rise is proportional to the square of the field intensity, from this relationship all temperature

rises may be converted to the average value of field intensity without error. From the results obtained from pyrex glass, it is noted the temperature rise is very nearly independent of thickness. Bakelite deviates somewhat from the independent relationship found for pyrex glass. However, this deviation is not very great. If all points on Plate 17 for bakelite fell on the dotted line, the temperature rise would be entirely independent of the thickness, and it may be noted that a straight line passing through the observed points deviates not greatly from the dotted line. Consequently, it is shown that losses (temperature rise) in these dielectric materials at equal field intensities are nearly independent of thickness, and since the volume is proportional to the thickness, the loss per unit volume is independent of the volume.

- (5) The result of the tests to determine the effect of the length of time of exposure to the field upon the temperature rise of the dielectric materials is shown by the curves in Plates 18, 19, 20, 21, 22 and 23. It may be noted that for short times of exposure and small temperature rises, that the temperature rise is proportional to the time of exposure. However, for greater times of exposure and larger temperature rises, this linear relationship does not continue, because some of the heat produced at the center of the sample has been lost by conduction to the edges and by radiation. It should be noted that the temperature rise scales of the various plates are different, and that the values of field intensity to which the samples were subjected varied to some extent. It is noted that all curves tend to reach a final temperature, above which no temperature rise is shown regardless of the time of exposure. This final value of temperature is the point at which all heat produced within the specimen is lost by conduction and radiation. All of the curves are of the exponential type which are normally found in all types of similar measurements. All curves shown in Plates 18 to 23 inclusive are reproduced on Plate 24 in order that the results may be compared more readily. None of the materials gave any indication of deterioration as a result of these tests.
- (b) It has been shown in the preceding paragraph that the temperature rise of all of the dielectric materials is proportional to the square of the field intensity and is a function of the time of exposure. Now, if the temperature rise is small and the time of exposure short, then the temperature rise is proportional to the square of the field intensity and to the time of exposure. The following equation expresses this relationship:

$$\underline{dT} = N E^2 \cdot \underline{dt} \quad (8)$$

where $\underline{dT}$ = Temperature rise

E = Field intensity (volts/cm)

$\underline{dt}$ = Time of exposure in seconds

N = A constant depending upon the dielectric material.

It is obvious that for materials having similar thermal properties (radiation and conduction factors, thermal capacity, etc.,) that the value of N will be lower in higher grades of insulating material. The value of N for each of the materials has been computed from the actual values of $\underline{dT}$ and $\underline{dt}$ as shown in Plates 18 to 23, inclusive, and may be found in Table 3. These values must be taken from the lower part of the curve, because the equation (8) applies only where $\underline{dT}$ is proportional to $\underline{dt}$. The values of $\underline{dT}$ and $\underline{dt}$ used for calculating the values of N are also shown in Table 3.

- (c) Now it has been shown that high frequency dielectric losses per unit volume are independent of volume at equal field intensities. It has also been shown that the power loss therein is proportional to the square of the field intensity. Therefore, it has been proved that the equivalent electrical circuit of the unit cube shown in Plate 5 is a correct analogy at high frequencies, and that the value r is a fixed value of resistance which is not at all dependent on field intensity. Now the power loss in the unit cube may be expressed by the following equation

$$P = \frac{E^2}{r} \quad (9)$$

where P = Power loss in watts

E = Field intensity in volts/cm

r = equivalent parallel radio frequency resistance in ohms of the unit cube at the frequency of test.

Now if the dielectric specimen is exposed to the field for a certain time, the energy dissipated within the unit cube may be expressed by the following equation:

$$W = P \underline{dt} = \frac{E^2 \underline{dt}}{r} \quad (10)$$

where W = energy in joules dissipated in unit cube

$\underline{dt}$ = time of exposure of dielectric to field in seconds.

This energy dissipation (which is in the form of heat) may also be expressed in calories. It has been found that one calorie is equal to 0.24 joules, and therefore the following formula also expresses the energy loss:

$$H = 0.24 W = \frac{0.24 E^2}{r} \cdot dt \quad (11)$$

where H = heat in calories produced in the unit cube.
From the principles of physics the following equation is also true:

$$H = D \cdot S \cdot dT \quad (12)$$

where D = density of unit cube in grams per cubic centimeter.

S = specific heat in calories per gram per degree Centigrade

dT = Temperature rise in degrees Centigrade during the time of exposure.

Now if the values found in equations (11) and (12) for H are written equal to each other, the following equation results:

$$\frac{0.24 E^2}{r} \cdot dt = D \cdot S \cdot dT \quad (13)$$

Rearranging equation (13):

$$dT = \frac{0.24 E^2}{D r S} \cdot dt \quad (14)$$

Thus it may be readily seen that equation (8) developed empirically is very similar to equation (14) developed theoretically, since the terms N, D, S, and r are all constants. By means of this analysis, the equation found empirically has also been proved theoretically. From equations (8) and (14) it is obvious that

$$N = \frac{0.24}{DrS} \quad (15)$$

If equation (15) is rearranged, then:

$$r = \frac{0.24}{DSN} \quad (16)$$

Now the value of N has already been calculated, and when the values of density and specific heat are determined, the value of r may be computed. The density of the material may be obtained from the mass and volume of the material. The specific heat may be determined by calorimetric methods.

The value of r is of great importance, since from it, many properties of the dielectric may be computed. Table 4 shows the value of r for each of the materials tested, together with other data used in this calculation. Since it is desirable for dielectric losses to be as low as possible, it is obvious that the values of r will be greater in the higher grades of dielectrics. The value of r is a true comparison factor for dielectric materials, since the effects of all thermal properties of the material have been considered in its computation.

- (d) The results of the calculations to determine the various radio frequency characteristics of a unit cube of each of the materials tested are furnished:
- (1) Table 5 shows the computed values of the equivalent series radio frequency resistance at 30 megacycles and the data used for this calculation.
 - (2) Table 6 shows the computed values of power factor at 30 megacycles, and similar information at lower frequencies for comparison purposes.
 - (3) Table 7 shows the computed values of the phase difference angle in minutes at 30 megacycles, and similar information measured at low frequencies.
 - (4) Table 8 shows the loss factor at 30 megacycles, and also similar information at low frequencies.
 - (5) Table 9 shows the power dissipation in a unit cube of the material at a field intensity of 1 kilovolt per centimeter.

DISCUSSION

7. An additional discussion of the results obtained is furnished below:

(a) In regard to the action of a high frequency electric field upon a dielectric material, it may be stated:

- (1) The dielectric constants of all materials measured at 30 megacycles agree to within 10% of their low frequency values with the exception of Steatite 306 and Victron AA, whose differences are found to be 48% and 20% respectively. These percentages are based on the assumption that the low frequency values are correct. From Table 1 it may be noted the high frequency values are either equal to or greater than the low frequency values. In the equipment used, the electrodes were not entirely parallel and the average spacings were used to obtain information to calculate the dielectric constants. These imperfectly aligned electrodes may be the cause of some of the disagreement between the low and high frequency values.

Improved equipment for testing dielectric materials at high frequencies is now being constructed and it is believed that more accurate results will be obtained.

- (2) and (3). Three sources of error are introduced in the calculation of field intensity from the electrode current, dielectric constant, and electrode spacing. There is reasonable doubt as to the accuracy of thermal ammeters at frequencies as great as 30 megacycles. Errors in the values of dielectric constants will produce inaccuracies nearly as great in the calculations of field intensities. The imperfectly aligned electrodes will also introduce errors in the calculations of field intensities. The total effect of these three factors may produce considerable inaccuracies in the calculations of field intensities. The effect of the latter two sources of error will be reduced by use of the new equipment discussed in the preceding subparagraph. An effort will be made to calibrate at a frequency of 30 megacycles the thermal instruments used for the measurement of electrode current in order to reduce the effect of this source of error.
- (4) and (5). The three sources of error discussed in the three preceding subparagraphs also are introduced into the results of the tests to determine if the losses are distributed throughout the volume and the effect of time of exposure on temperature rise. From a relative standpoint these results are probably correct, although some errors are introduced in the absolute magnitude of the results.

(b) and (c). An equation developed theoretically expressing the relationship between losses and field intensity has been proved correct by experiment. The value of r (the equivalent parallel radio frequency resistance of a unit cube) or any data computed from it, is more satisfactory as a comparison factor than the value of N (a factor expressing the relative temperature rise.) It may be noted that the tests made on each type of material require considerable time. However, the amount of work involved in testing a sample of material may be reduced. If the value of N found in equation (15) be substituted in equation (8), and the new equation is rearranged the following equation results:

$$r = \frac{0.24}{D S} \frac{E^2}{dT} \cdot \frac{dt}{dT} \quad (17)$$

From this equation the value of r may be computed, as well as many other properties of the dielectric material. It has been shown that losses in a dielectric are proportional to the square of field intensity. However, this square law may not apply on all materials at very high values of field intensity, and to apply equation (17) correctly it must be shown that this square law is true at the field intensity applied during the

test. Also the temperature rise and time of exposure must be chosen so that they are proportional to one another. Consequently several trial runs are necessary to be sure that the values of E , dt , and dT are chosen properly for substitution in equation (17).

(d) In regard to the radio frequency properties of a unit cube of the material, it may be stated that although the values of power factor, phase difference angle, and loss factor of the materials determined at high frequencies differ considerably in some cases from their low frequency values, they are still of the same order of magnitude. A complete explanation of these discrepancies cannot be furnished at the present time. However, considering that the methods of measurement at low and high frequencies were entirely different, and that the high frequency measurements were made at frequencies approximately 70 times as great, the error is not considered serious. In Table 10, Column 1, the various materials are listed in the order of their power factor measured at 30 megacycles, and in Column 2, these same materials have been arranged according to their measurement at low frequencies. It may be noted, with the exception of Steatites 334 and 306, that their relative standing is the same. This would seem to indicate in most cases, that low frequency measurements furnish a good indication of what their operating characteristics will be at high frequencies. It may be seen from Table 6 that power factors measured at 30 megacycles are either approximately equal to or less than those measured at a much lower frequency. It may then appear from these results that if the power factor is not greatly changed with change in frequency, a dielectric material would be as satisfactory at high frequency as at low frequency. But it is well known that some materials are satisfactory at low frequencies and are entirely unsatisfactory at high frequencies, which appears to disagree with the previous statement. This apparent discrepancy can be explained satisfactorily, however. If an insulator be subjected to an electric field at a low frequency, a certain quantity of radio frequency current passes through the insulator. The power loss is equal to the product of voltage and current and power factor. If this same insulator is subjected to the same voltage at a frequency one hundred times as great, the current will also increase by a factor of one hundred. If the power factor is unchanged with frequency, it is obvious that the power loss at the high frequency is one hundred times as great as that at the low frequency. It is thereby shown that even though a material may be such that its power factor is independent of frequency, the power dissipation within the material increases directly with frequency. Also as the applied frequency to a dielectric is increased, in order to keep the power dissipation at a fixed value, the allowable power factor must be decreased in like proportion. By this analysis the apparent discrepancy discussed previously in this paragraph is found not to be an actual discrepancy. From the results shown in Table 6, the power factors of some of the materials are nearly independent of frequency, but those of the rest of the materials decrease as the frequency is increased. Theoretically, power factors should be independent of frequency. However, there are indications that the

An equation developed theoretically expressing the relationship between losses and field intensity has been proven correct by experiment.

Regarding the properties of a unit cube of the material it may be stated that a method of making quantitative measurements of power factor, phase difference, loss factor, and power loss, at a frequency of 30 megacycles has been developed.

TABLE 1

Dielectric Constants

Material	Grade	x	x'	K	K'
Fused quartz	Trans.	0.7	1.70	3.5	3.4 (477 kcs)
Victron	AA	0.495	1.53	3.0	2.5 (484 kcs)
Steatite	334	0.565	1.67	6.0	5.7 (492 kcs)
Steatite	306	0.455	1.60	8.3	5.6 (467 kcs)
Steatite	352-B	0.560	1.67	6.2	5.7 (482 kcs)
Plate Glass	—	0.595	1.70	6.3	6.3 (390 kcs)
Porcelain	—	0.715	1.80	6.2	5.9 (500 kcs)
Bakelite	E	0.463	1.58	5.6	5.0 (485 kcs)

See Equation (1)

All distances expressed in cm.

$$x'' = 1.2 \text{ cm}$$

K = Dielectric Constant at 30 mcs.

K' = Dielectric Constant measured substitution method at low frequencies by Naval Research Laboratory.

TABLE NO. 2

Time of Exposure of various materials to electric field to
obtain results shown in Plates 6 - 16 incl.

<u>Material</u>	<u>Grade</u>	<u>Time of Exposure</u>
Fused Quartz	Transparent	120 sec.
Victron	AA	120 sec.
Steatite	334	120 sec.
Steatite	306	120 sec.
Steatite	352-B	120 sec.
Plate Glass	-	120 sec.
Porcelain	-	60 sec.
Bakelite	E	15 sec.

TABLE NO. 3

Values of N computed from Plates 18 to 23 inclusive

Frequency - 30 mcs.

Material:Grade:	Date	from:	$\frac{dt}{sec.}$	$\frac{dT}{^{\circ}C}$	E : volts :	E^2	:	N
Fused								
Quartz Trans.:	Plate 23	:	960	:4.1	: 1350	: 1.81 .10 ⁶	:0.00236	.10 ⁻⁶
Victron: AA	:	"	19	: 120	:5.75 : 1580	: 2.505 .16 ⁶	:0.0191	.10 ⁻⁶
Steatite 334	:	"	22	: 120	: 1.3 : 767	: 0.588 .10 ⁶	:0.0185	.10 ⁻⁶
Steatite 306	:	"	21	: 120	: 1.75: 525	: 0.275 .10 ⁶	:0.0529	.10 ⁻⁶
Steatite 352-B	:	"	20	: 120	: 3.7 : 615	: 0.378 .10 ⁶	:0.0815	.10 ⁻⁶
Plate Glass -	:	"	19	: 120	: 6.0 : 718	: 0.515 .10 ⁶	:0.0971	.10 ⁻⁶
Porcelain -	:	"	18	: 120	:11.0 : 552	: 0.3030 .10 ⁶	:0.313	.10 ⁻⁶
Bakelite E	:	"	18	: 60	: 9.0 : 349	: 0.1210 .10 ⁶	:1.23	.10 ⁻⁶

See Equation (8).

TABLE NO.4

Values of equivalent parallel radio frequency resistance
of a unit cube.

Frequency - 30 Mcs.

Material	Grade	N	:	D	:	S	:	r in ohms
Fused								
Quartz	: Trans.:	0.00236	$\cdot 10^{-6}$:	2.20	:	0.19	:	243.0 $\cdot 10^6$
Victron	: AA	: 0.0191	$\cdot 10^{-6}$:	1.07	:	0.21	:	55.4 $\cdot 10^6$
Steatite	: 334	: 0.0185	$\cdot 10^{-6}$:	2.66	:	0.23	:	21.75 $\cdot 10^6$
Steatite	: 306	: 0.0529	$\cdot 10^{-6}$:	2.66	:	0.23	:	7.58 $\cdot 10^6$
Steatite	: 352-B	: 0.0815	$\cdot 10^{-6}$:	2.61	:	0.25	:	4.520 $\cdot 10^6$
Plate								
Glass	: -	: 0.0971	$\cdot 10^{-6}$:	2.50	:	0.27	:	3.67 $\cdot 10^6$
Porcelain:	-	: 0.313	$\cdot 10^{-6}$:	2.40	:	0.24	:	1.33 $\cdot 10^6$
Bakelite	: E	: 1.23	$\cdot 10^{-6}$:	1.36	:	0.32	:	0.450 $\cdot 10^6$

See Equation (16).

TABLE NO. 5

Values of equivalent series radio frequency resistance
of a unit cube.

Frequency - 30 mcs.

Material	Grade	r : Ohms	C : Farads	$1/\omega C$: Ohms	$1/(\omega C)^2$: Ohms	R : Ohms
Fused quartz	Trans:	243.0	$.10^6:0.31$	$.10^{-12}:1.713$	$.10^4:2.93$	$.10^8:1.2$
Victron	AA	: 55.4	$.10^6:0.267$	$.10^{-12}:1.962$	$.10^4:3.84$	$.10^8:6.9$
Steatite	334	: 21.75	$.10^6:0.53$	$.10^{-12}:1.002$	$.10^4:1.0$	$.10^8:4.7$
Steatite	306	: 7.58	$.10^6:0.723$	$.10^{-12}:0.723$	$.10^4:0.522$	$.10^8:6.9$
Steatite	352-B:	4.515	" : 0.549	" : 0.978	" : 0.938	" : 21.3
Plate Glass	-	: 3.67	" : 0.557	" : 0.953	" : 0.908	" : 24.8
Porcelain	-	: 1.33	" : 0.549	" : 0.978	" : 0.938	" : 71.
Bakelite	E	: 0.447	" : 0.496	" : 1.067	" : 1.135	" : 254.0

See Equation (5)

r = Equivalent Parallel R.F. Resistance of Unit Cube.

R = " Series " " " " " "

TABLE NO. 6

Power Factors at low and high frequencies

Material	Grade	R		ω C	P.F. %		(P.F.)' %	
		: Ohms	:		: 30 megacycles	:	Low Frequencies	
Fused Quartz	Trans.	:1.205	:	5.84 10^{-5}	:	0.007	:	0.01 (477 kcs)
Victron	AA	:6.93	:	5.1 "	:	0.035	:	0.06 (484 kcs)
Steatite	334	:4.71	:	9.99 "	:	0.047	:	0.31 (492 kcs)
Steatite	306	:6.89	:	13.84 "	:	0.089	:	0.29 (467 kcs)
Steatite	352-B	:21.25	:	10.33 "	:	0.222	:	0.34 (482 kcs)
Plate Glass	-	:24.75	:	10.5 "	:	0.26	:	0.70 (390 kcs)
Porcelain	-	:70.5	:	10.33 "	:	0.729	:	0.63 (500 kcs)
Bakelite	-	:254.0	:	9.35 "	:	2.375	:	2.60 (485 kcs)

See Equation (6)

Low frequency measurement made by Naval Research Laboratory
by substitution method.

TABLE NO. 7

Values of phase difference angle at low and high frequencies.

Material	Grade	P.F. %	(P.F.)' %	Phase Difference	
				30 Megacycles	Low Frequency
Fused Quartz	Trans.	0.007	0.01	0.24'	0.34' (477 kcs)
Victron	AA	0.035	0.06	1.21'	2.06' (484 kcs)
Steatite	334	0.047	0.31	1.66'	10.4' (492 kcs)
Steatite	306	0.089	0.29	3.06'	9.97' (467 kcs)
Steatite	352-B	0.222	0.34	7.37'	11.69' (482 kcs)
Plate Glass	-	0.260	0.70	8.95'	24.07' (390 kcs)
Porcelain	-	0.729	0.63	25.06'	21.66' (500 kcs)
Bakelite	E	2.375	2.60	81.48'	89.39' (485 kcs)

P.F. = Power Factor measured at 30 mcs.

(P.F.)' = Power Factor at low frequencies measured by Naval Research Laboratory, by substitution method.

(See paragraphs 5(d)(3) and 6(d)(3).

TABLE NO. 8

Values of loss factor at low and high frequencies.

Material	Grade	K	K'	P.F. %	(P.F.)' %	Loss Factor %	
						30 megacycles	Low frequency
Fused quartz	Trans.	3.5	3.4	0.007	0.001	0.0245	0.034 (477 kcs)
Victron	AA	3.0	2.5	0.035	0.06	0.105	0.15 (484 kcs)
107 Steatite	334	6.0	5.71	0.046	0.31	0.276	1.80 (492 kcs)
Steatite	306	8.3	5.62	0.089	0.29	0.712	1.61 (467 kcs)
Steatite	352-B	6.2	5.66	0.222	0.34	1.376	1.93 (482 kcs)
Plate Glass	-	6.3	6.3	0.260	0.70	1.638	4.41 (390 kcs)
#98 Porcelain	-	6.2	5.9	0.729	0.63	4.52	3.91 (500 kcs)
Bakelite	E	5.6	5.0	2.375	2.60	13.3	14.56 (485 kcs)

K = dielectric constant 30 megacycles.

K' = dielectric constant low frequencies measured by Naval Research Laboratory by substitution method.

P.F. = power factor 30 mcs.

(P.F.)' = Power factor low frequencies measured by Naval Research Laboratory by substitution method.

(See paragraphs 5(d)(4) and 6(d)(4).

TABLE NO. 9

Power dissipation in a unit cube at a field
intensity of 1 kilovolt/cm.

Frequency 30 mcs. E^2 1,000,000

Material	Grade	r Ohms		Power loss in watts
Fused quartz	trans.	243.0	$\cdot 10^6$	0.00415
Victron	AA	55.4	"	0.018
Steatite	334	21.75	"	0.0460
Steatite	306	7.58	"	0.132
Steatite	352-B	4.515	"	0.222
Plate Glass	-	3.67	"	0.273
Porcelain	-	1.33		0.75
Bakelite	E	0.447	"	2.24

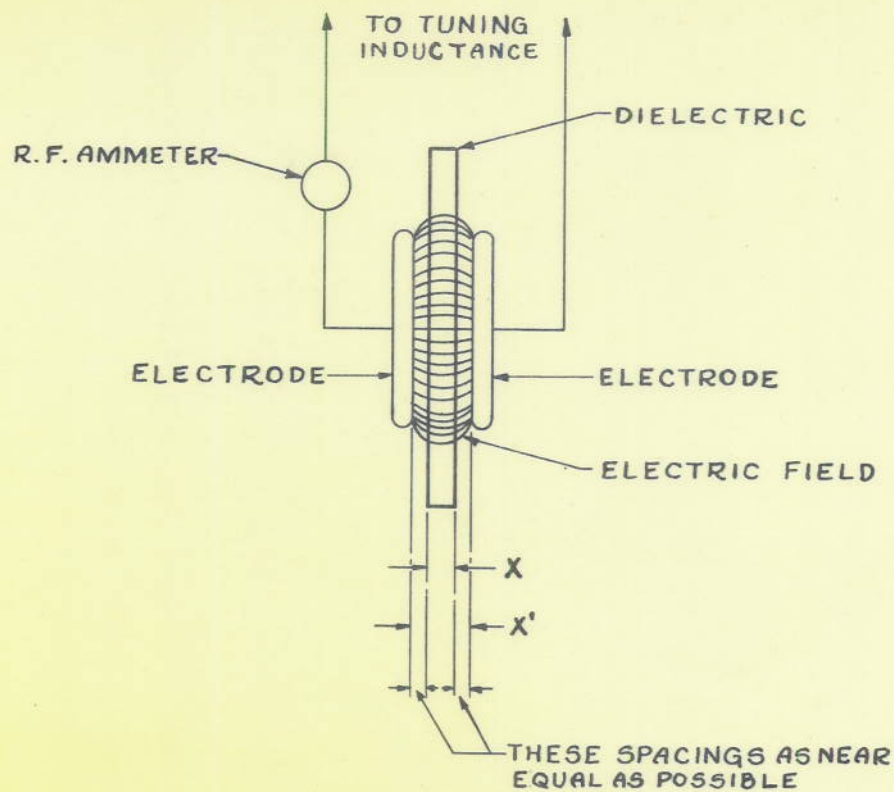
See Equation (7)

TABLE NO. 10

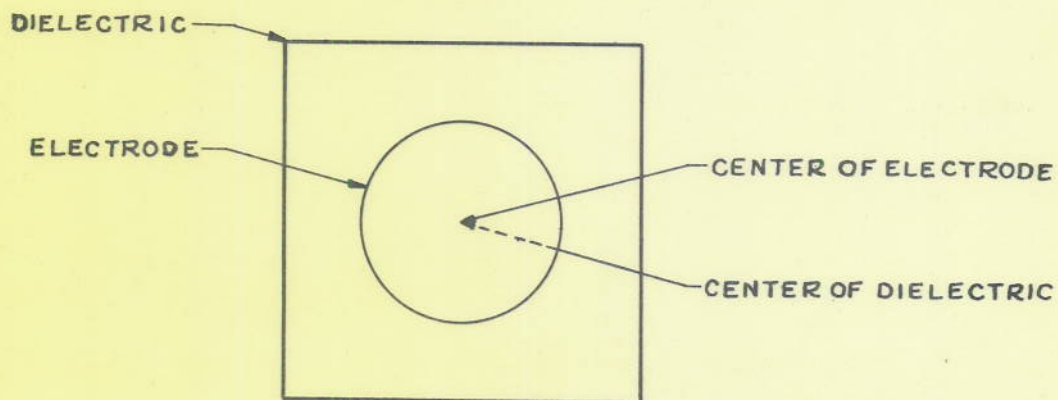
Relative standing of power factors of materials at
low and high frequencies.

<u>Column 1</u>		<u>Column 2</u>		
Frequency 30 mcs		Low frequencies		
<u>Material</u>	<u>Grade</u>	<u>Material</u>	<u>Grade</u>	<u>Freq. Kcs.</u>
Fused Quartz	trans.	Fused Quartz	trans.	477
Victron	AA	Victron	AA	484
Steatite	334	Steatite	306	467
Steatite	306	Steatite	334	492
Steatite	352-B	Steatite	352-B	482
Plate Glass	-	Plate Glass	-	390
Porcelain	-	Porcelain	-	500
Bakelite	E	Bakelite	E	485

See paragraph 7(d)(3).



EDGE VIEW



CENTER OF DIELECTRIC SPECIMEN
COINCIDES WITH CENTER OF ELECTRODE

SIDE VIEW

SHOWING HOW SPECIMEN IS PLACED IN FIELD

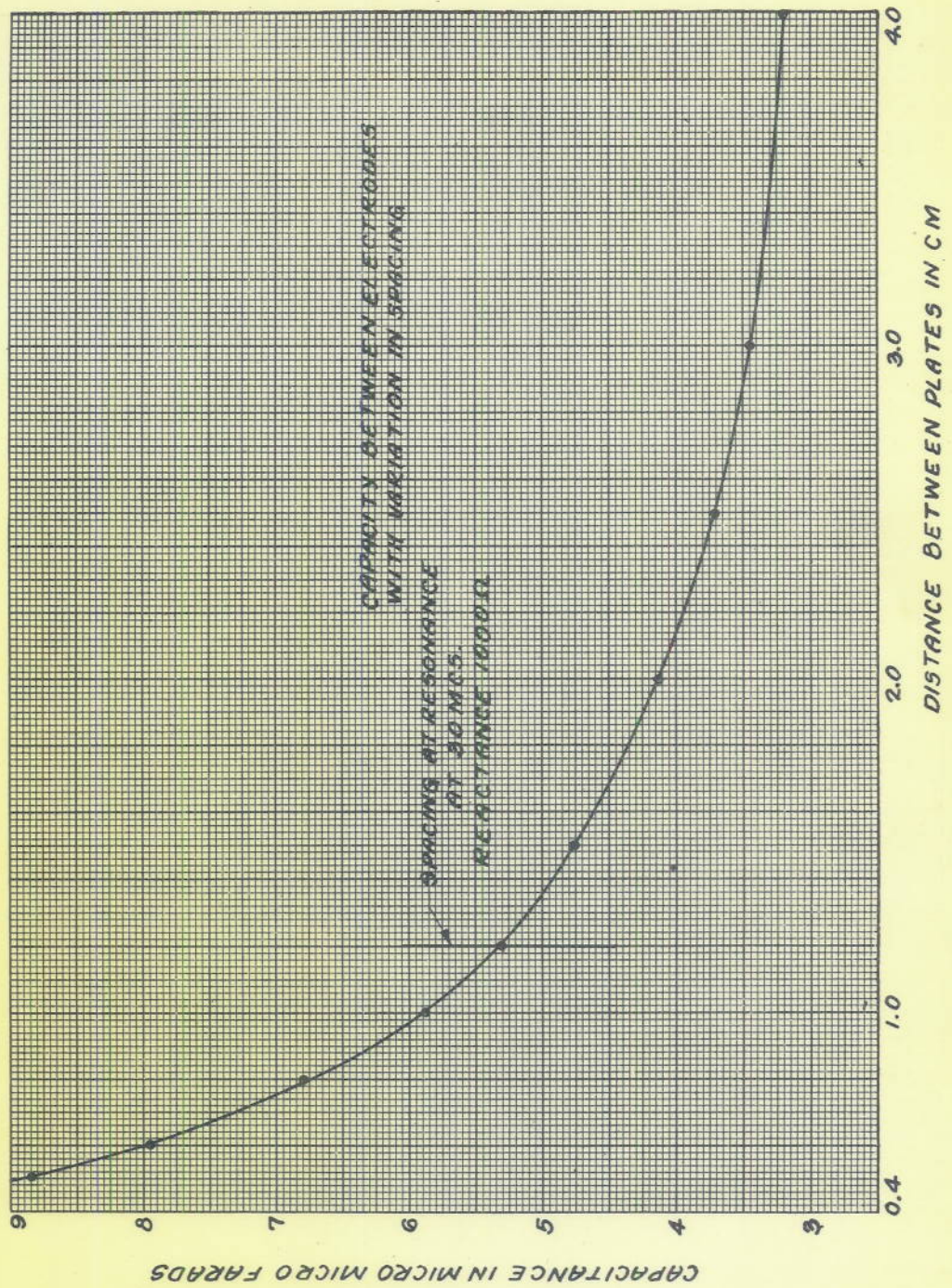


PLATE 3

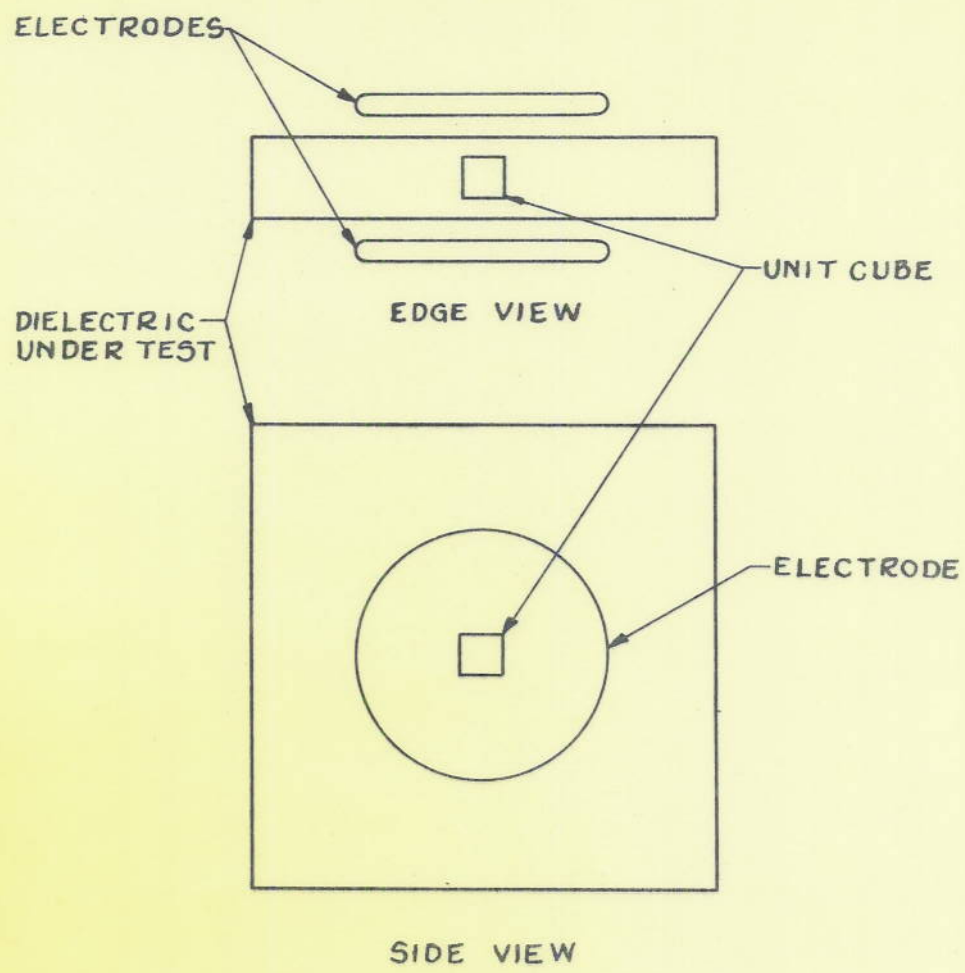
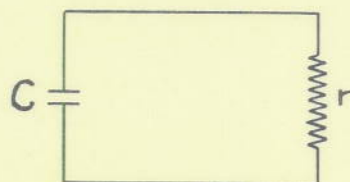


PLATE 4



ELECTRICAL EQUIVALENT OF UNIT CUBE

PLATE 5

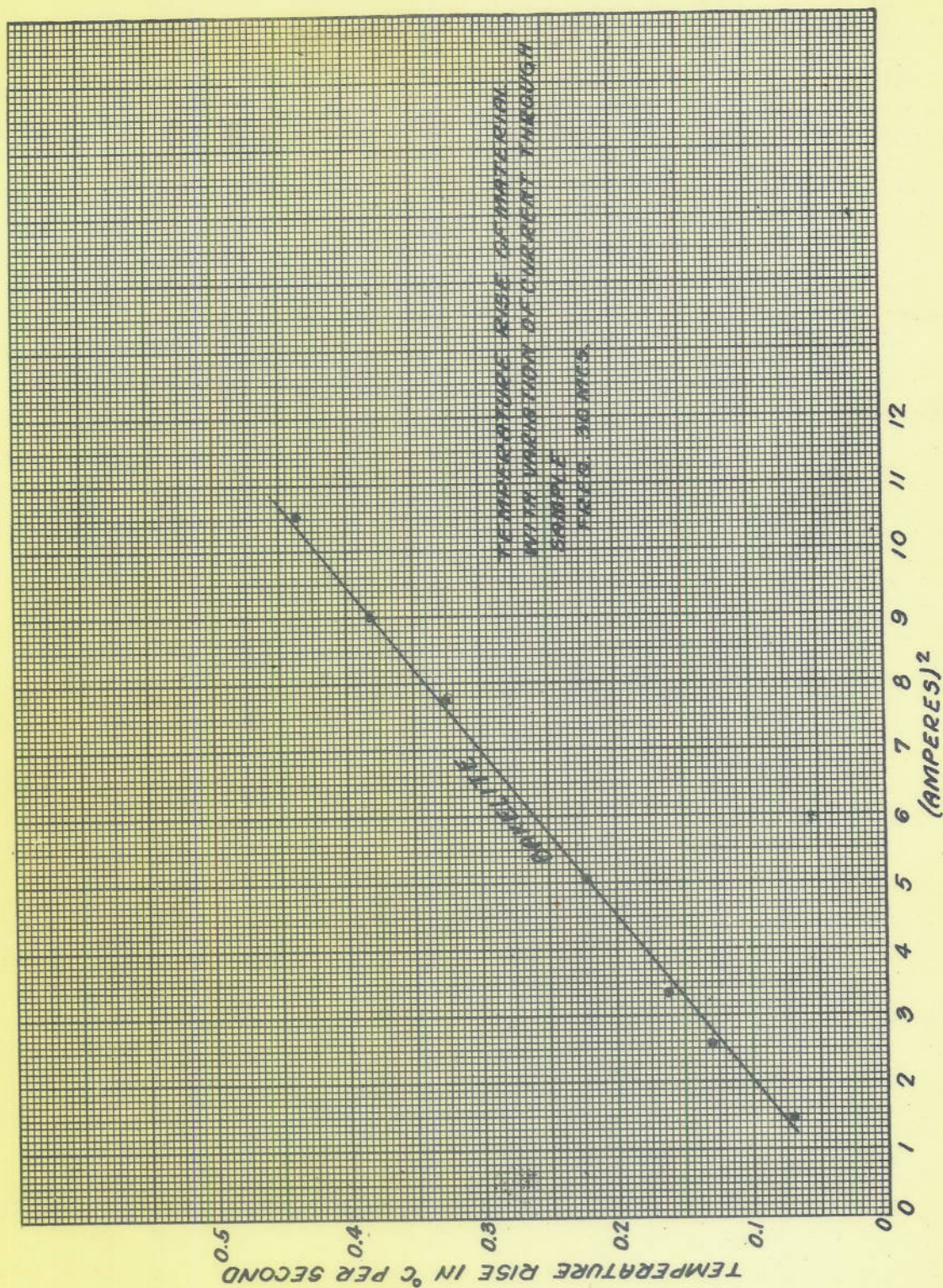


PLATE 6

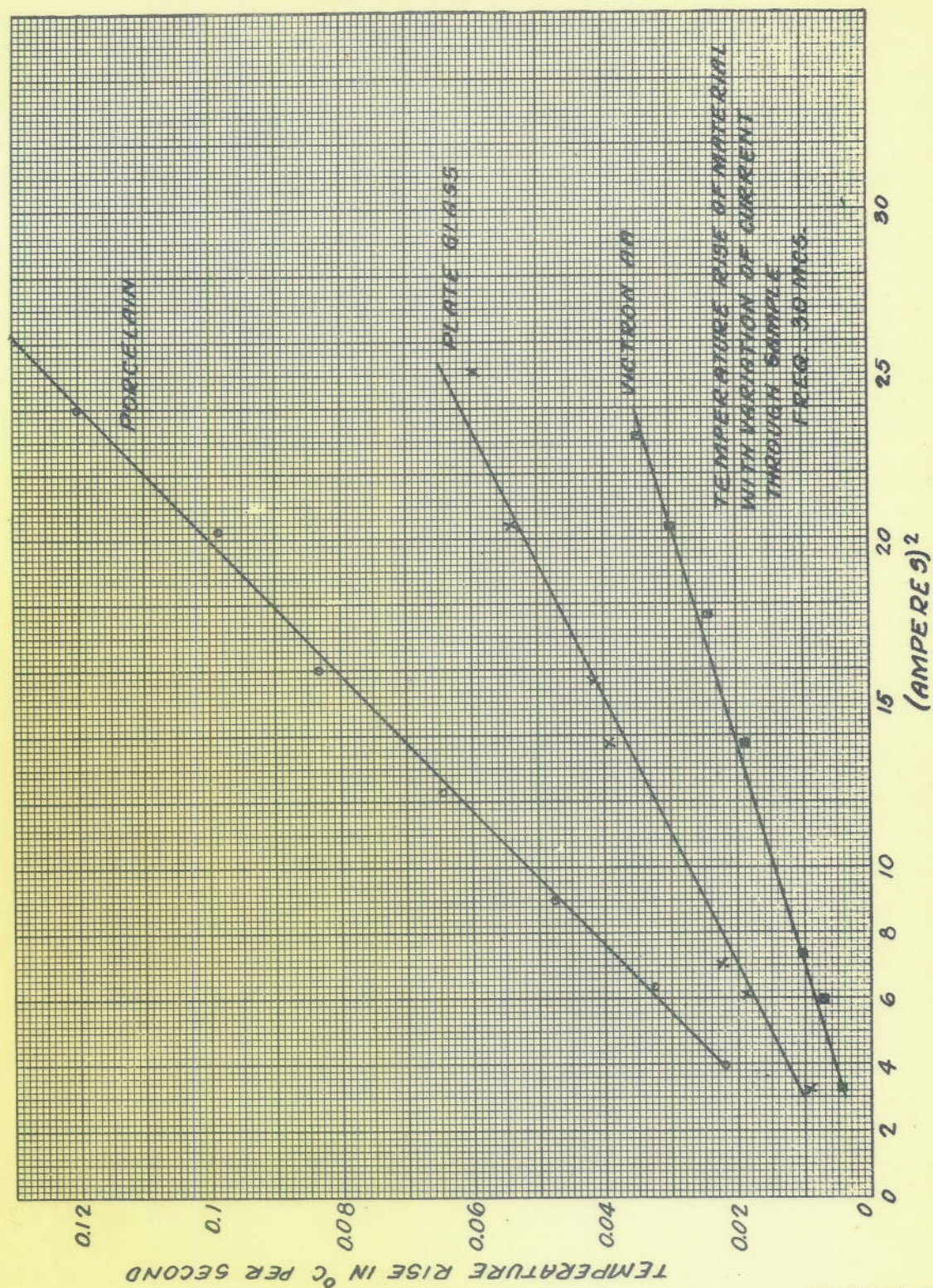
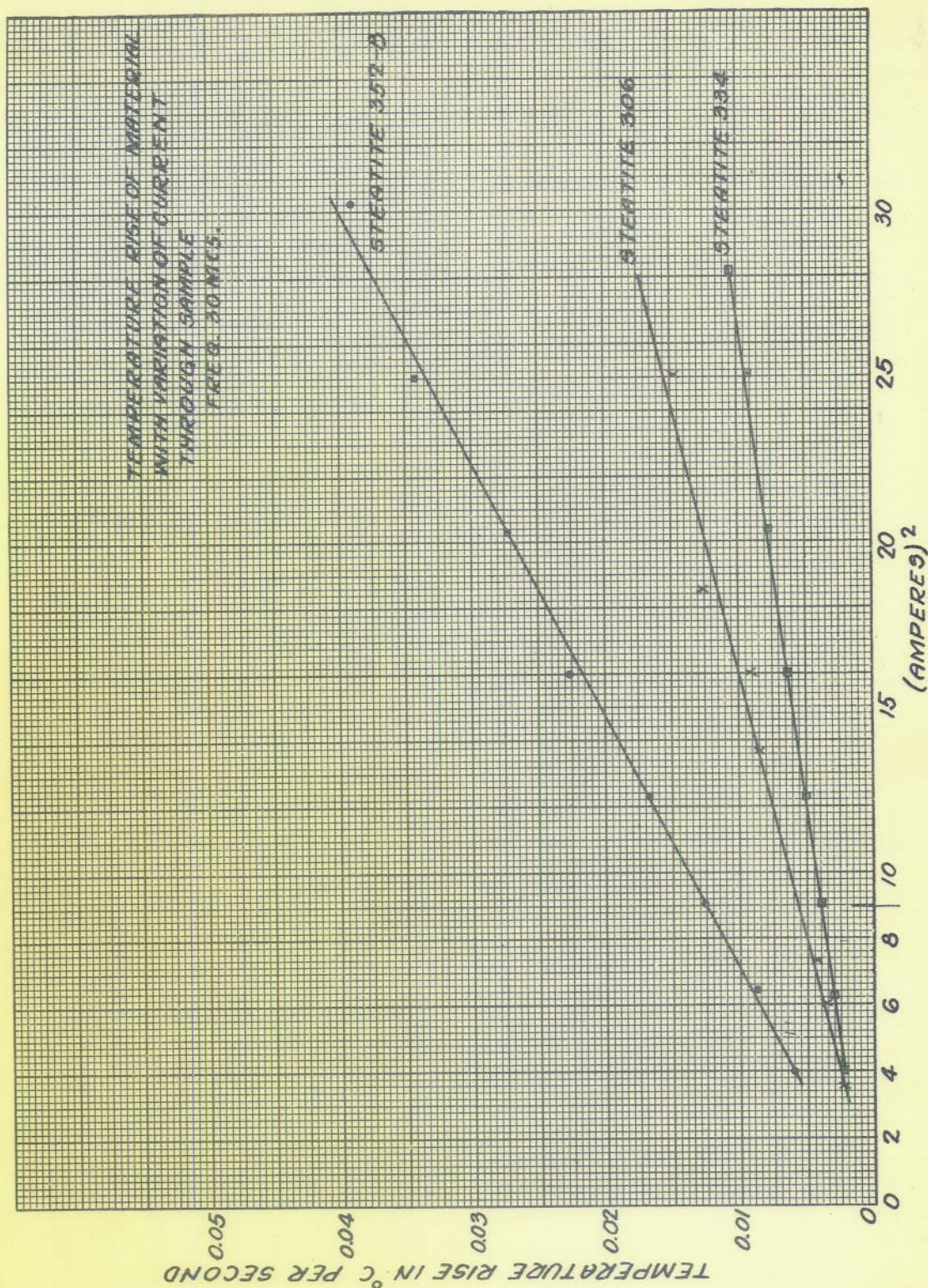


PLATE 7



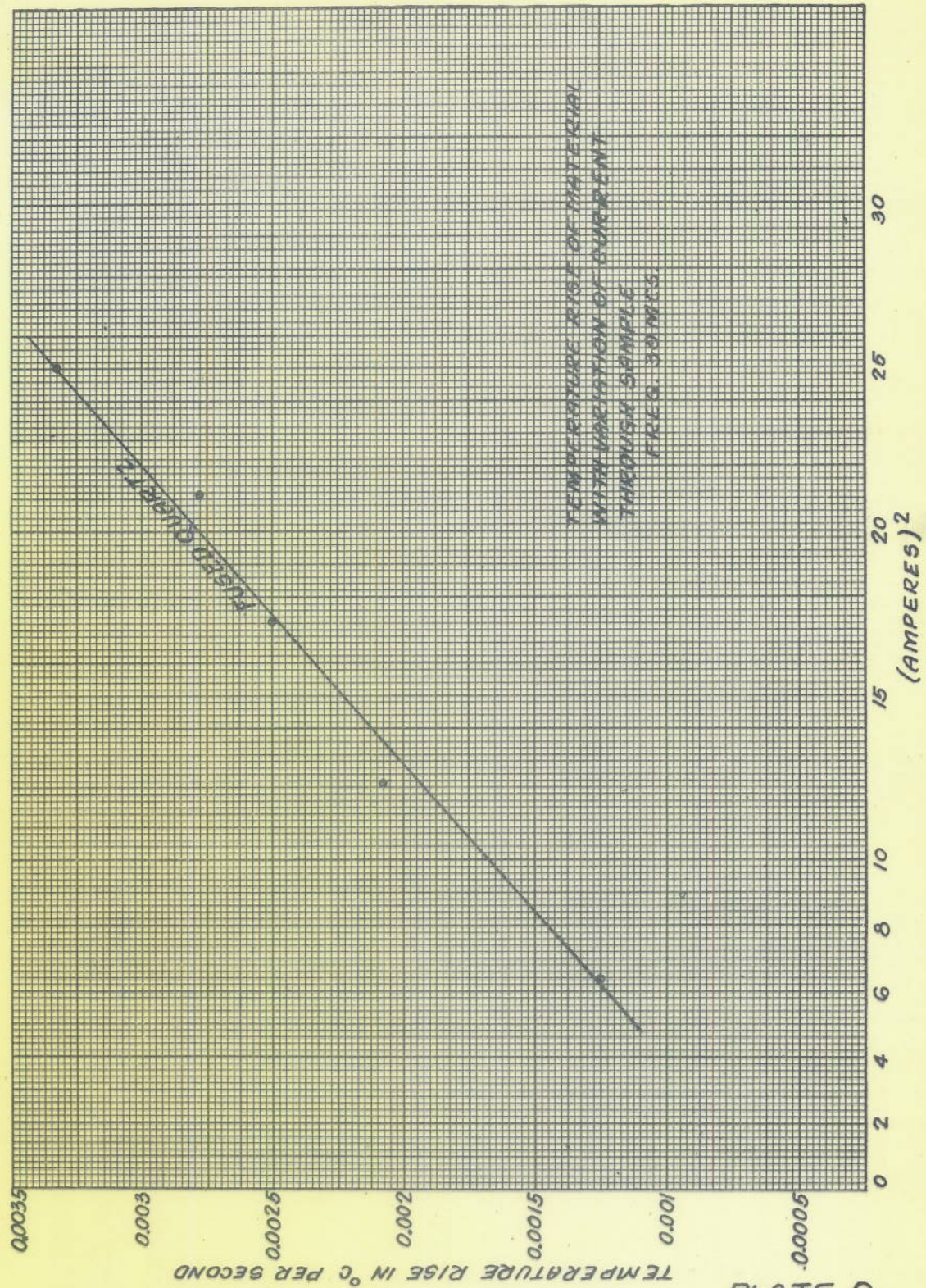
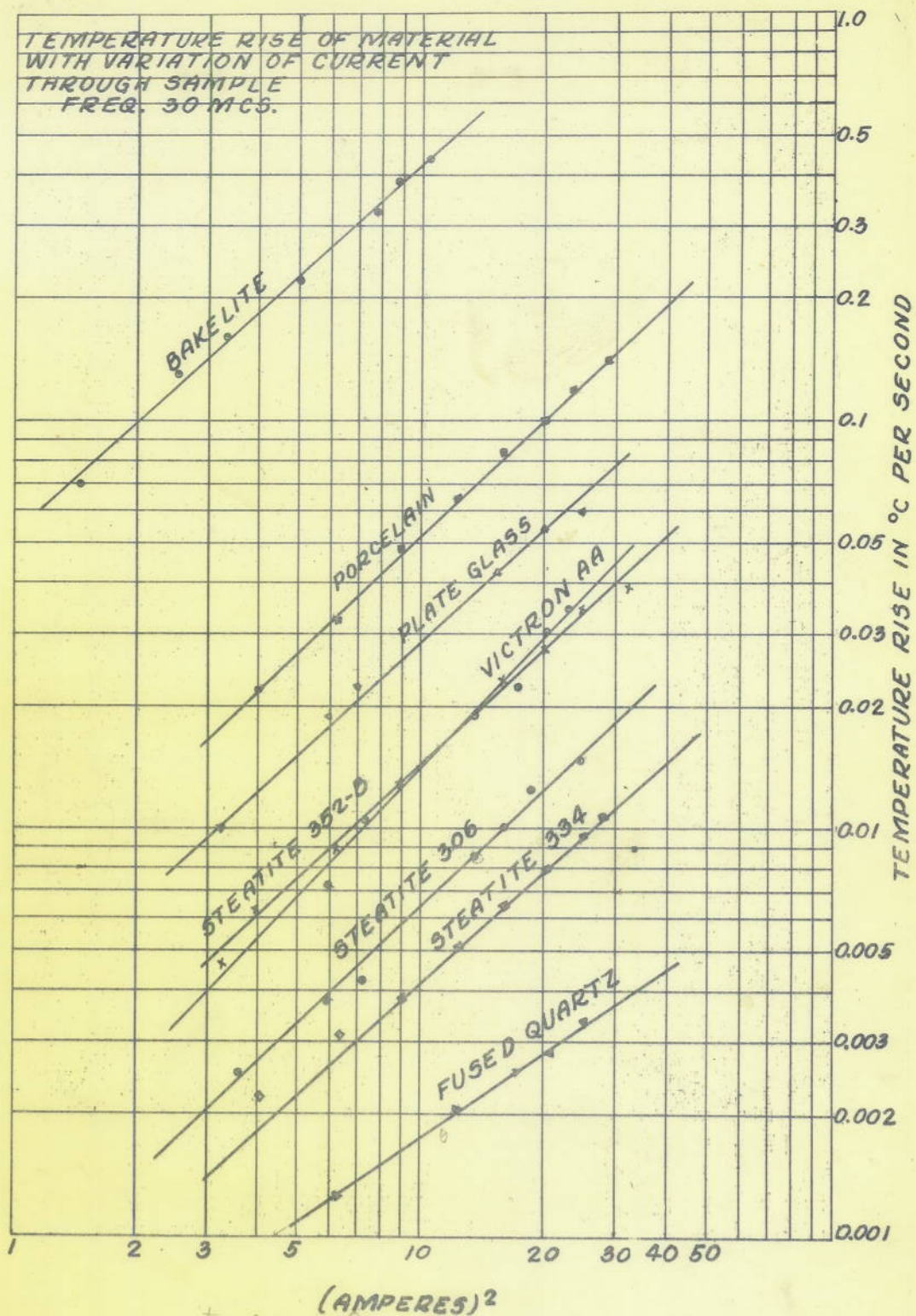


PLATE 9



Fused Quartz	-	$\tan \delta$	0.687	34.5°
Steatite 334	-		0.915	42.5°
" 306	-		0.955	43.7°
" 352	-		0.932	42.0°
Victron AA	-		1.062	46.7°
Plate glass	-			

PLATE 10

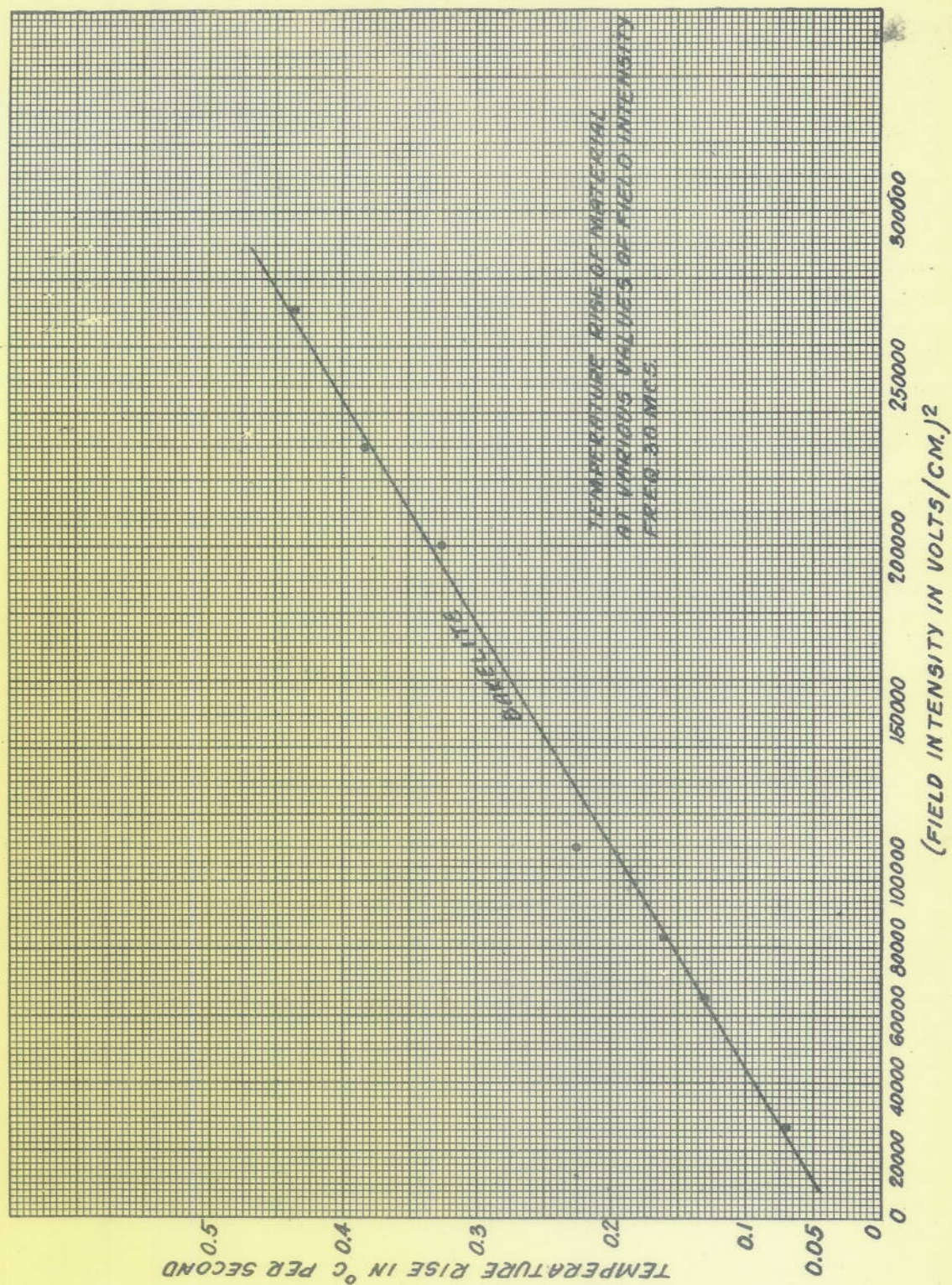


PLATE II

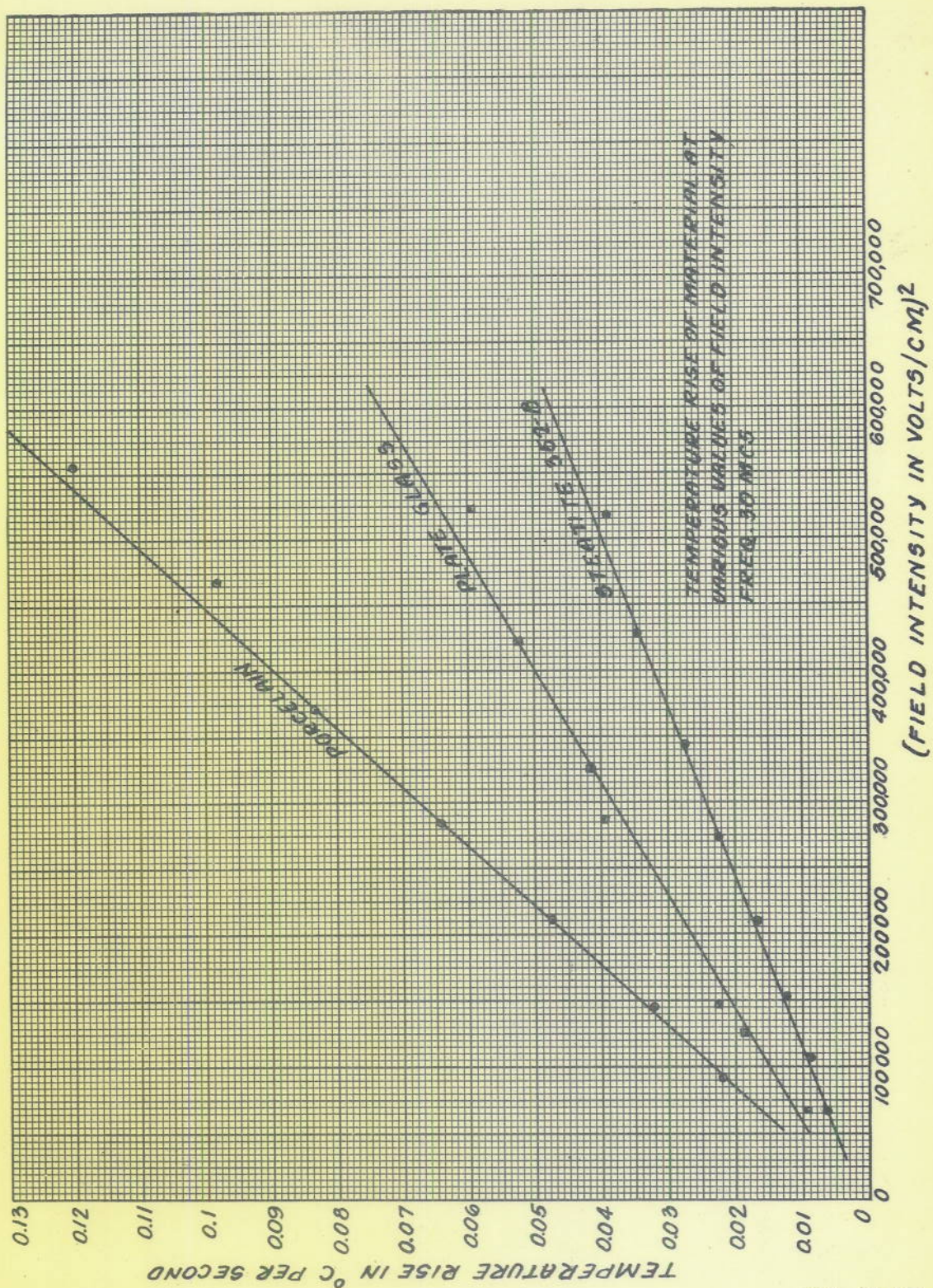


PLATE 12

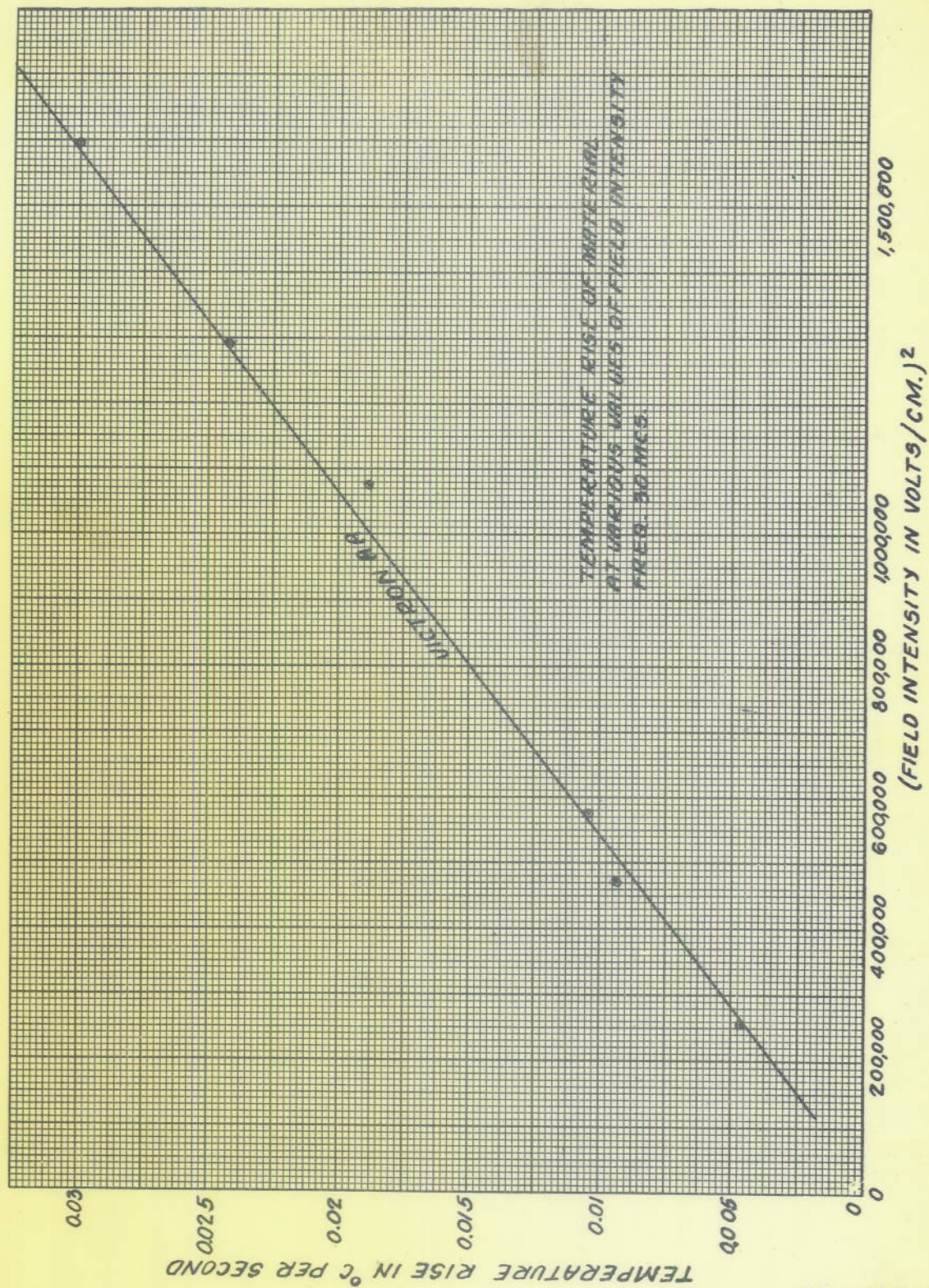


PLATE 13

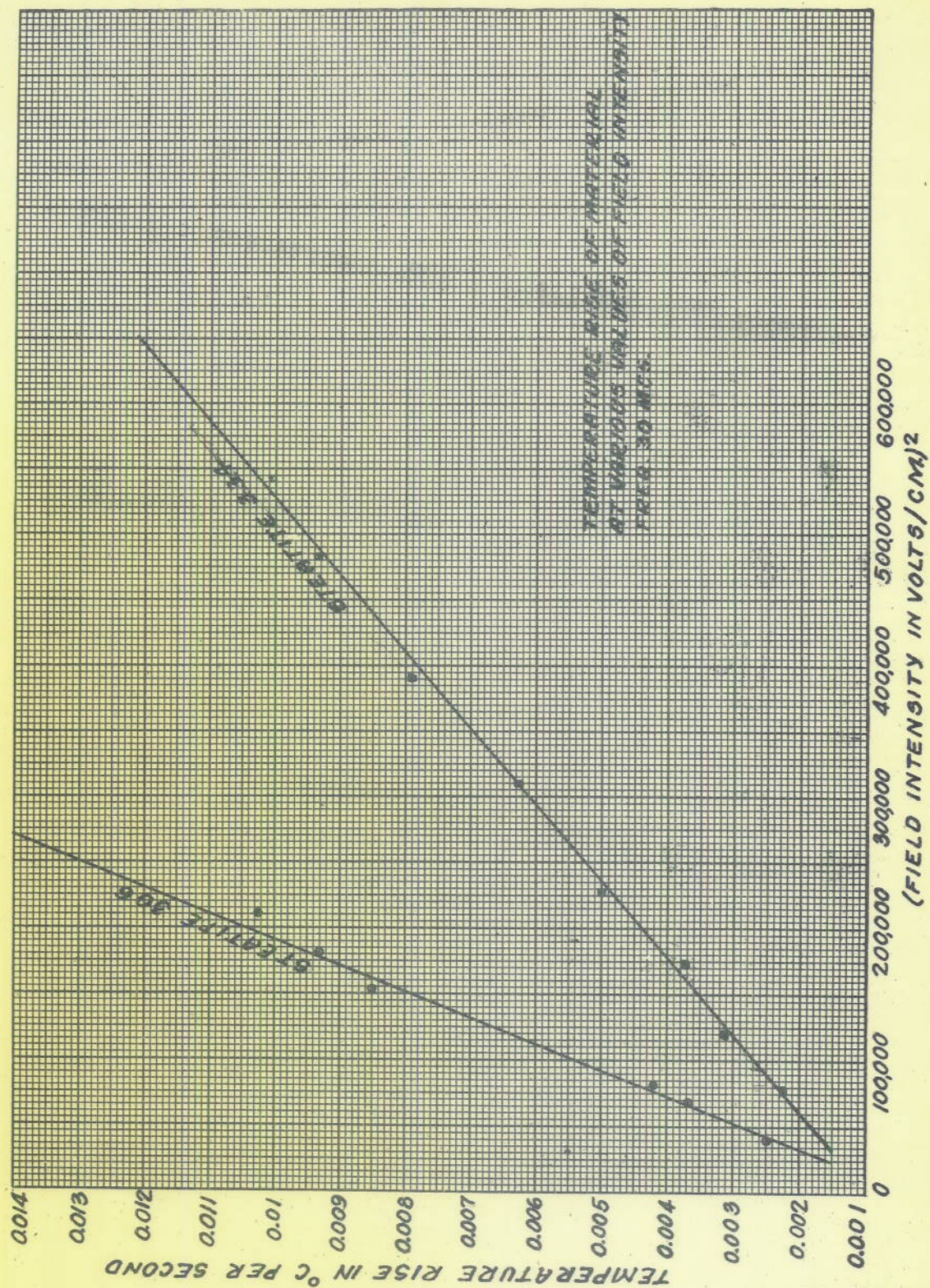
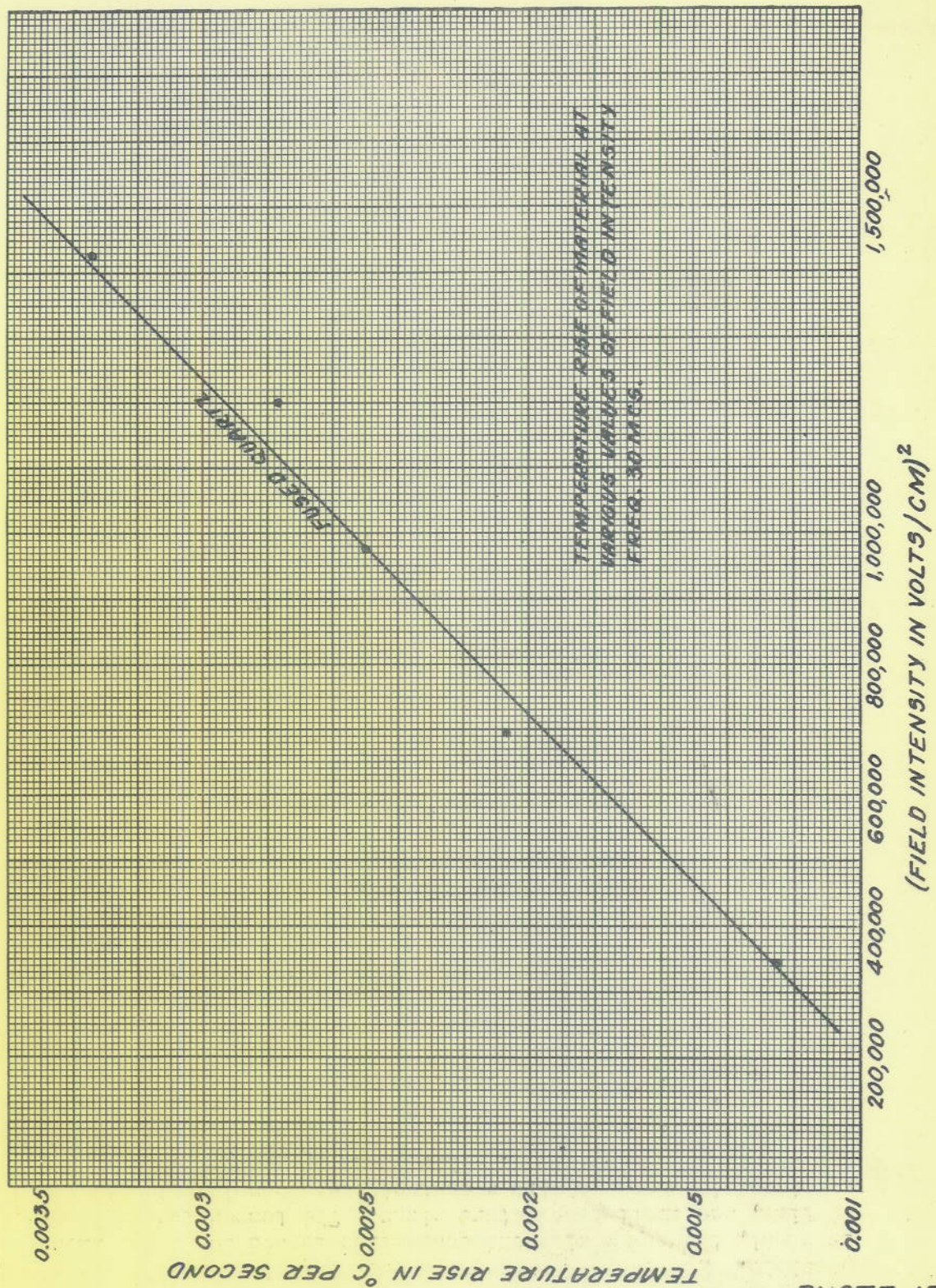


PLATE 14



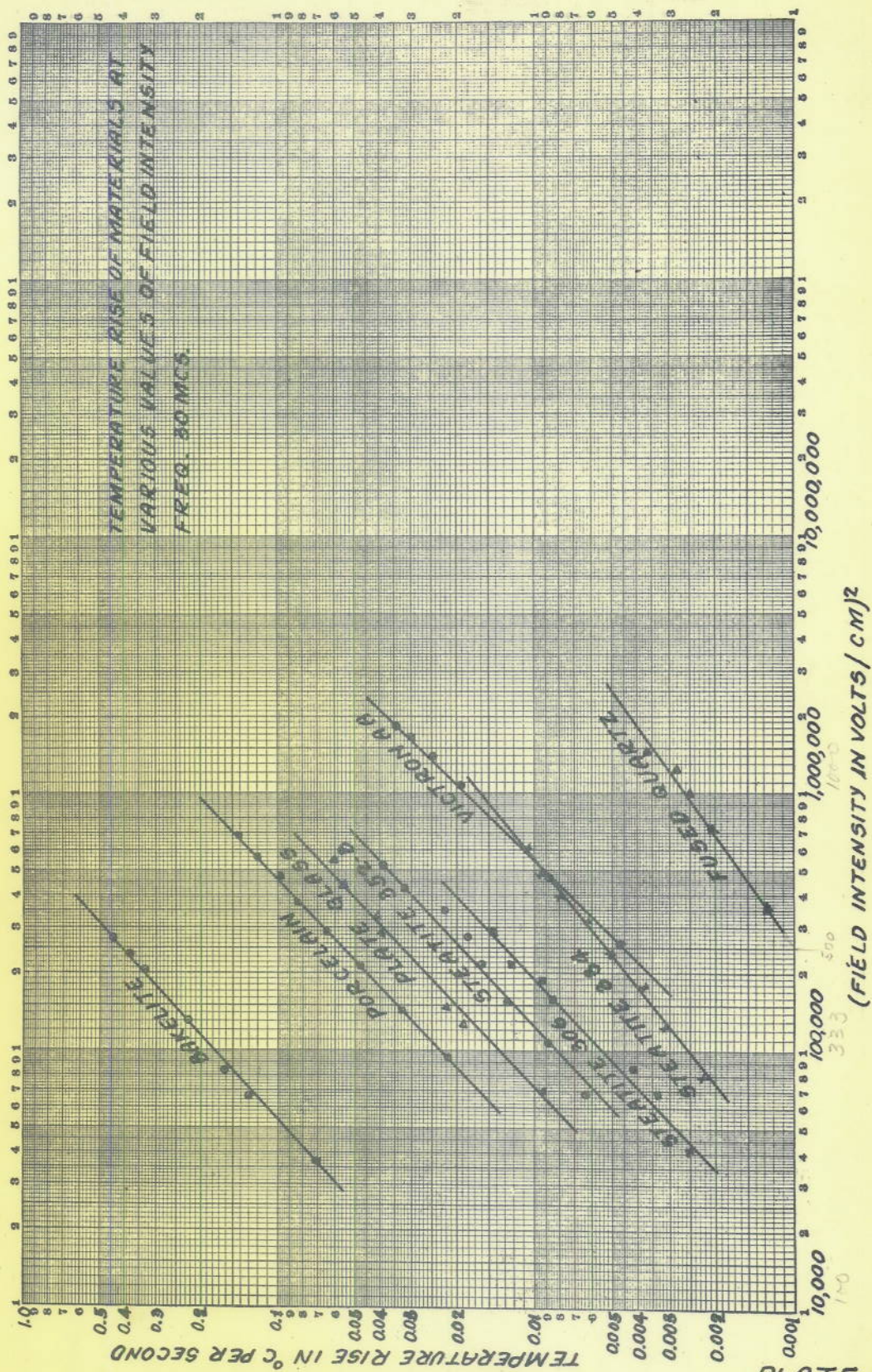


PLATE 16

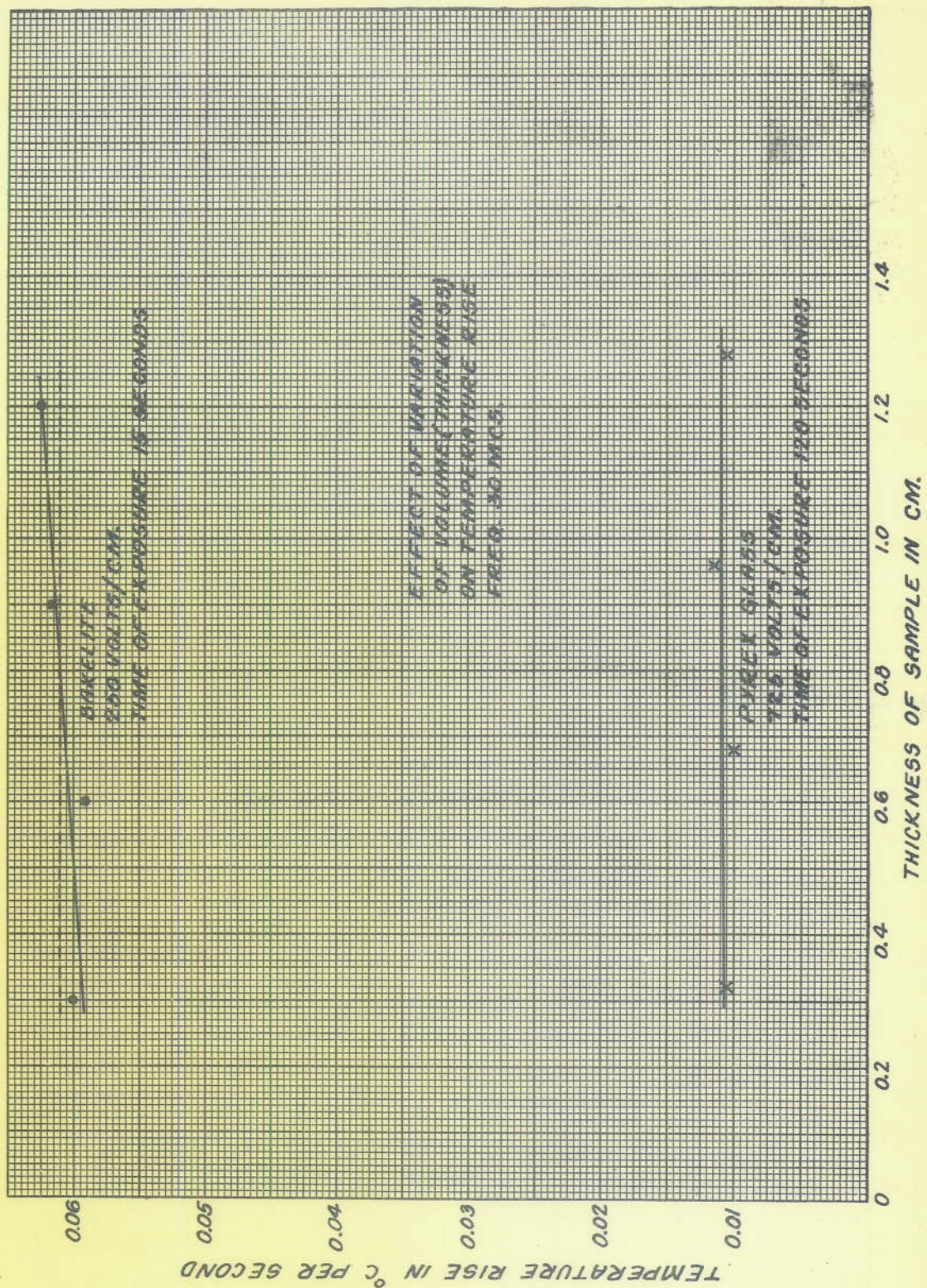


PLATE 17

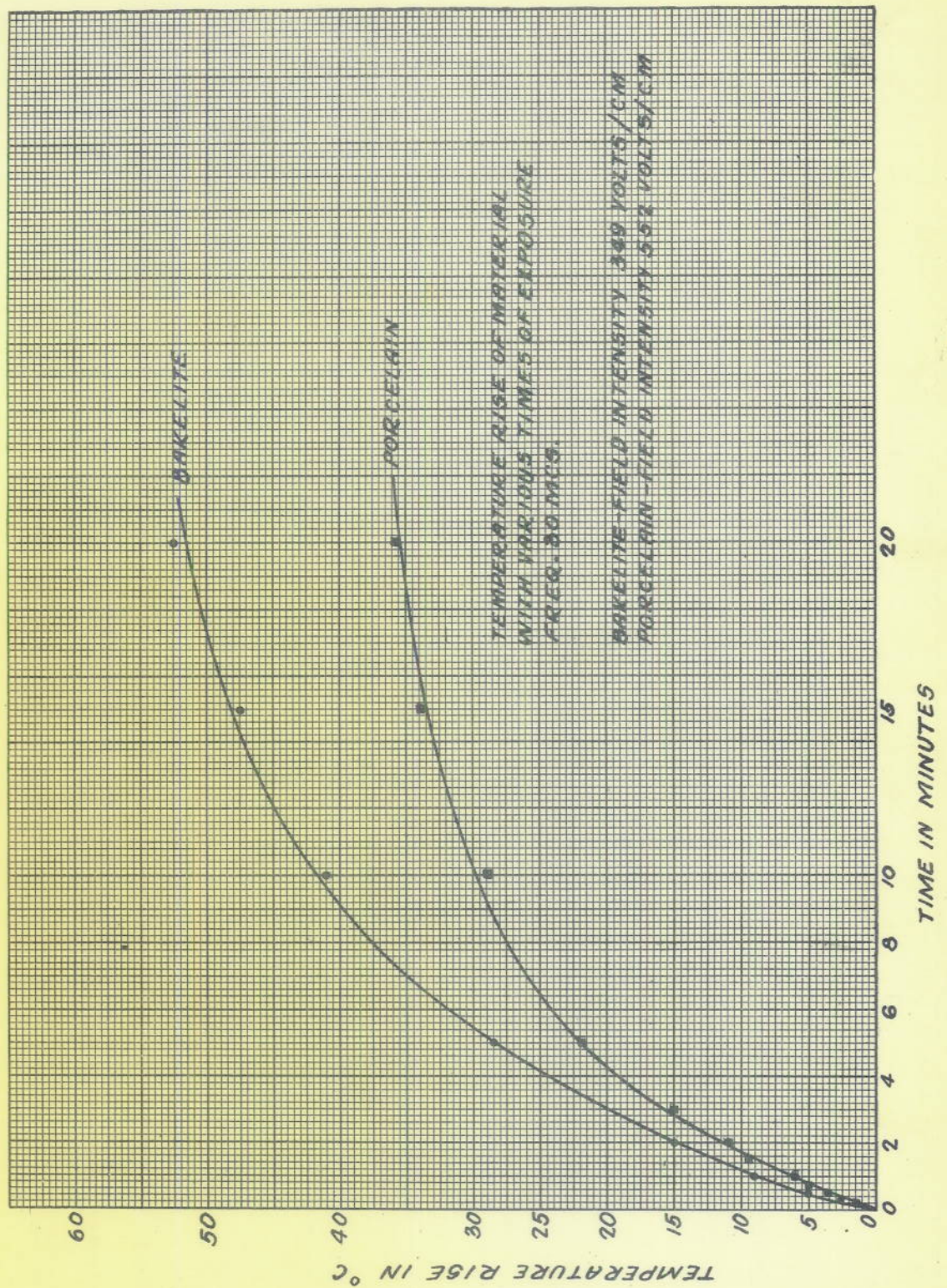
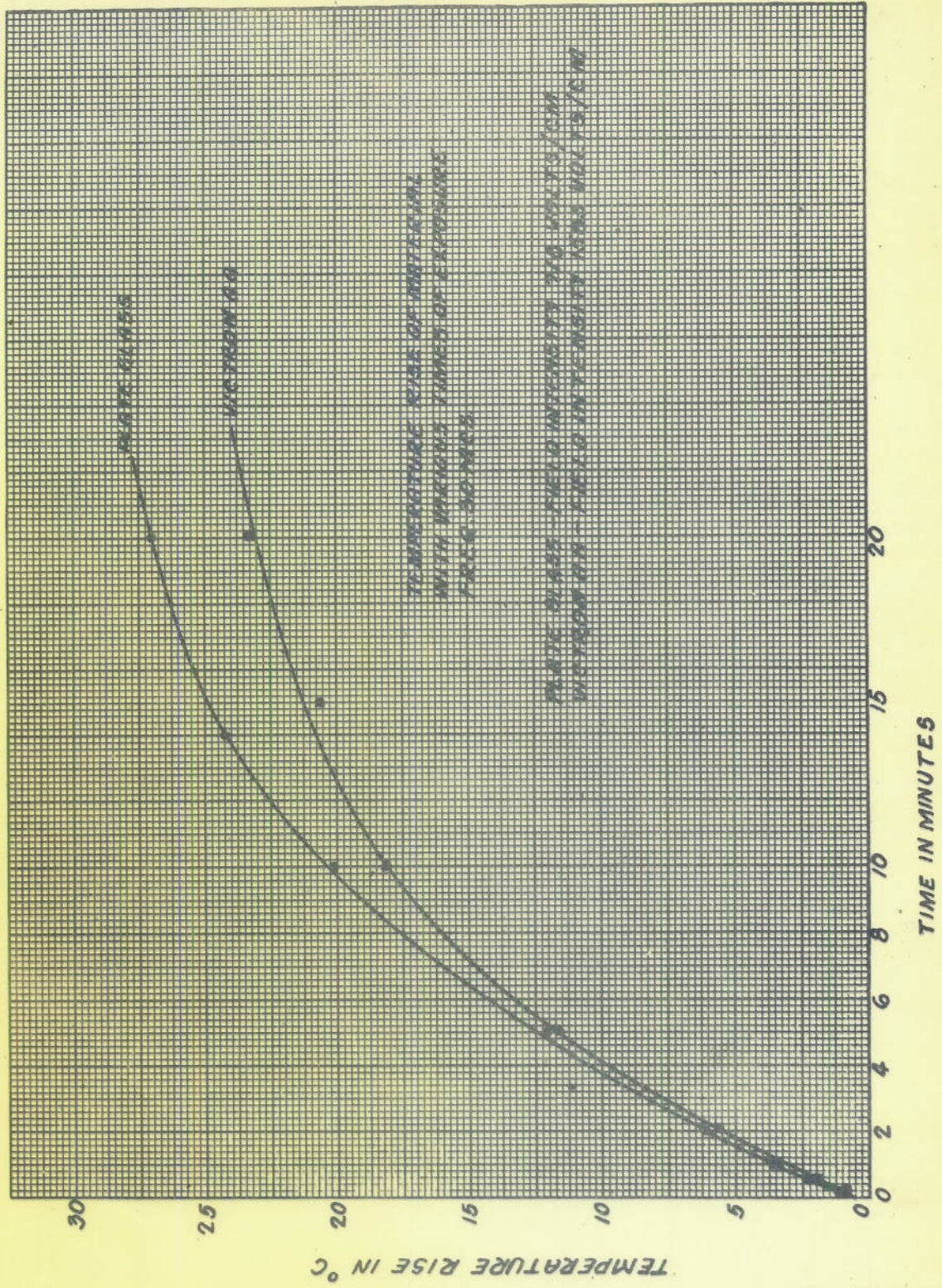


PLATE 18



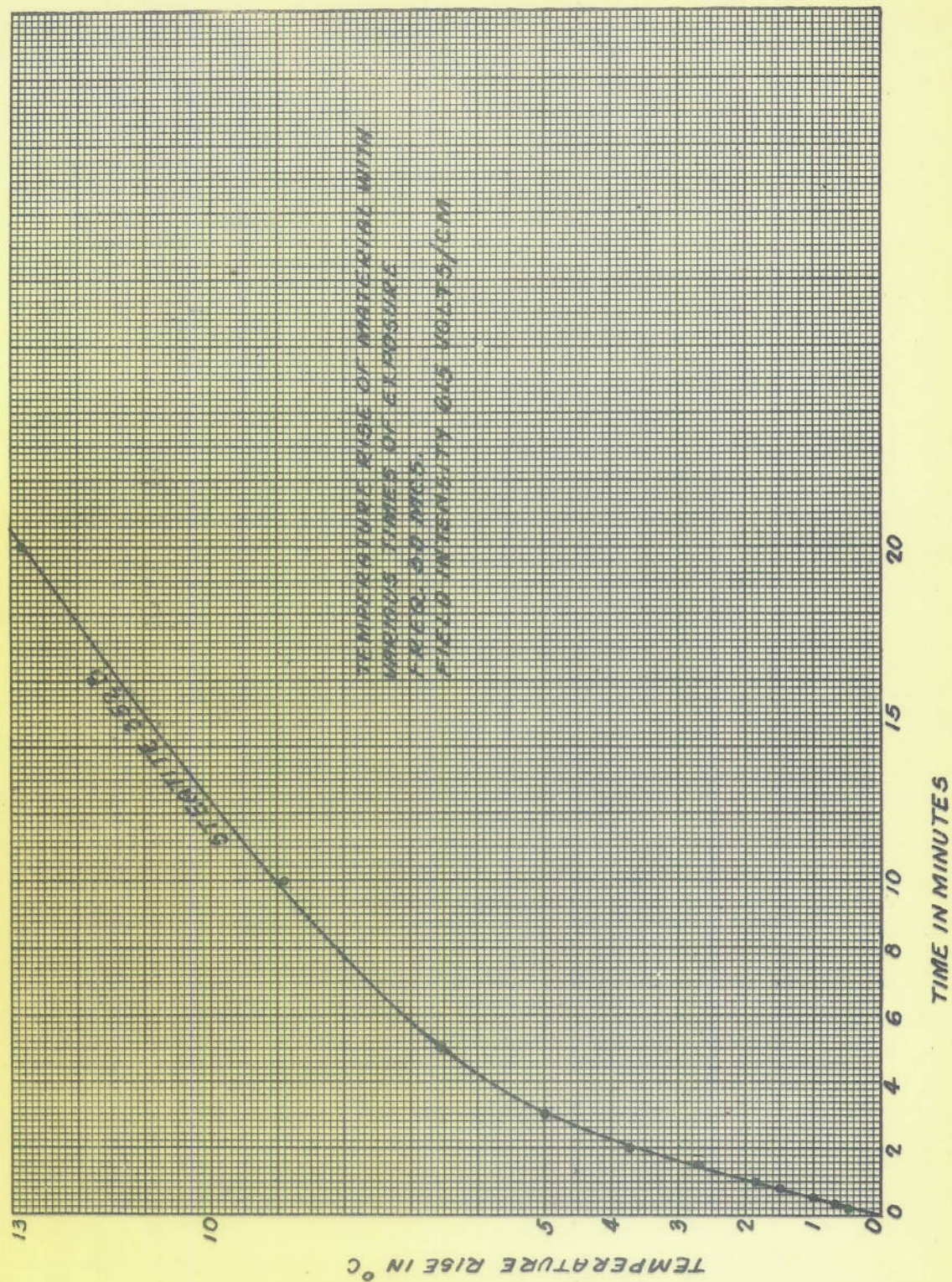
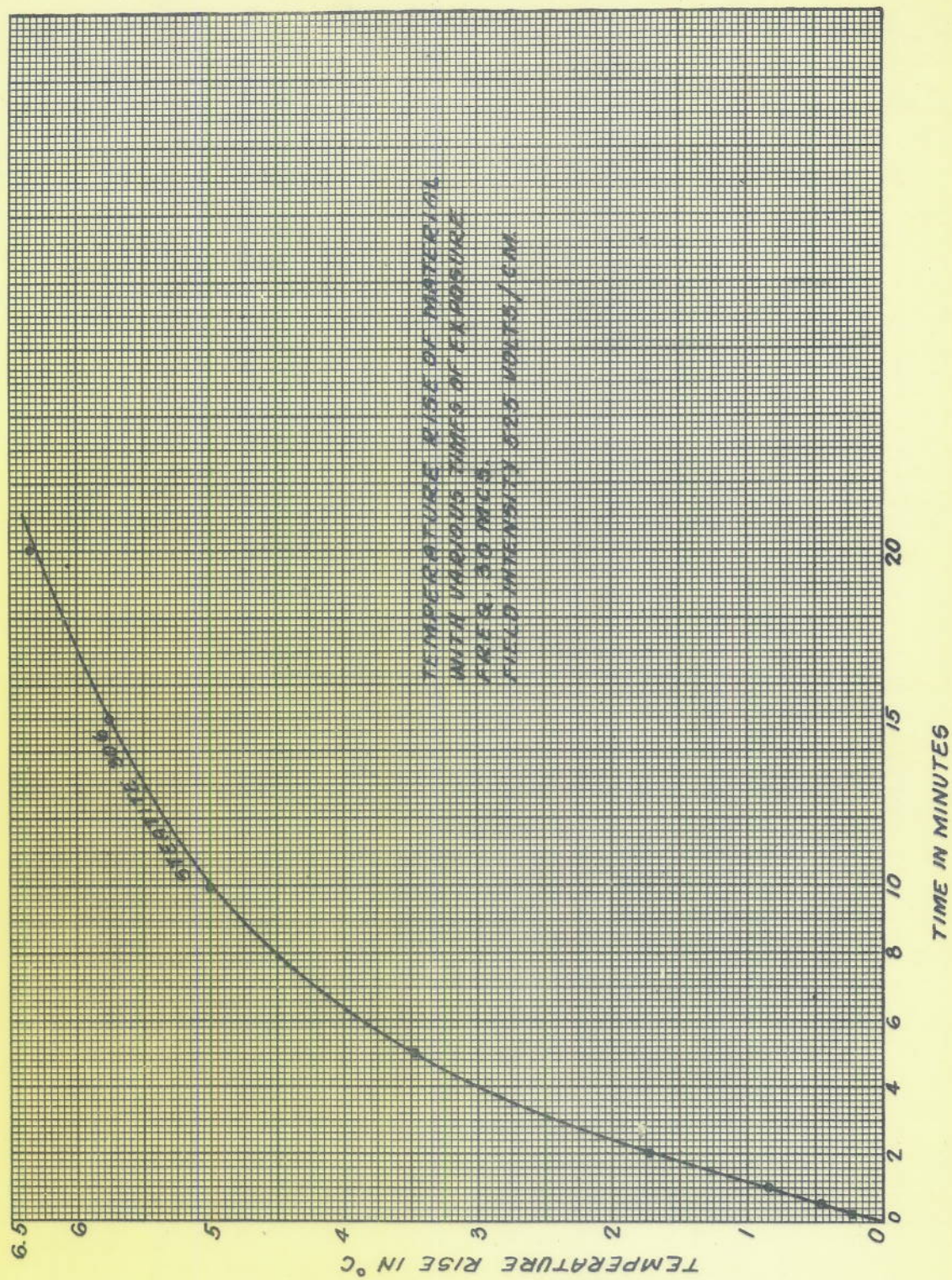
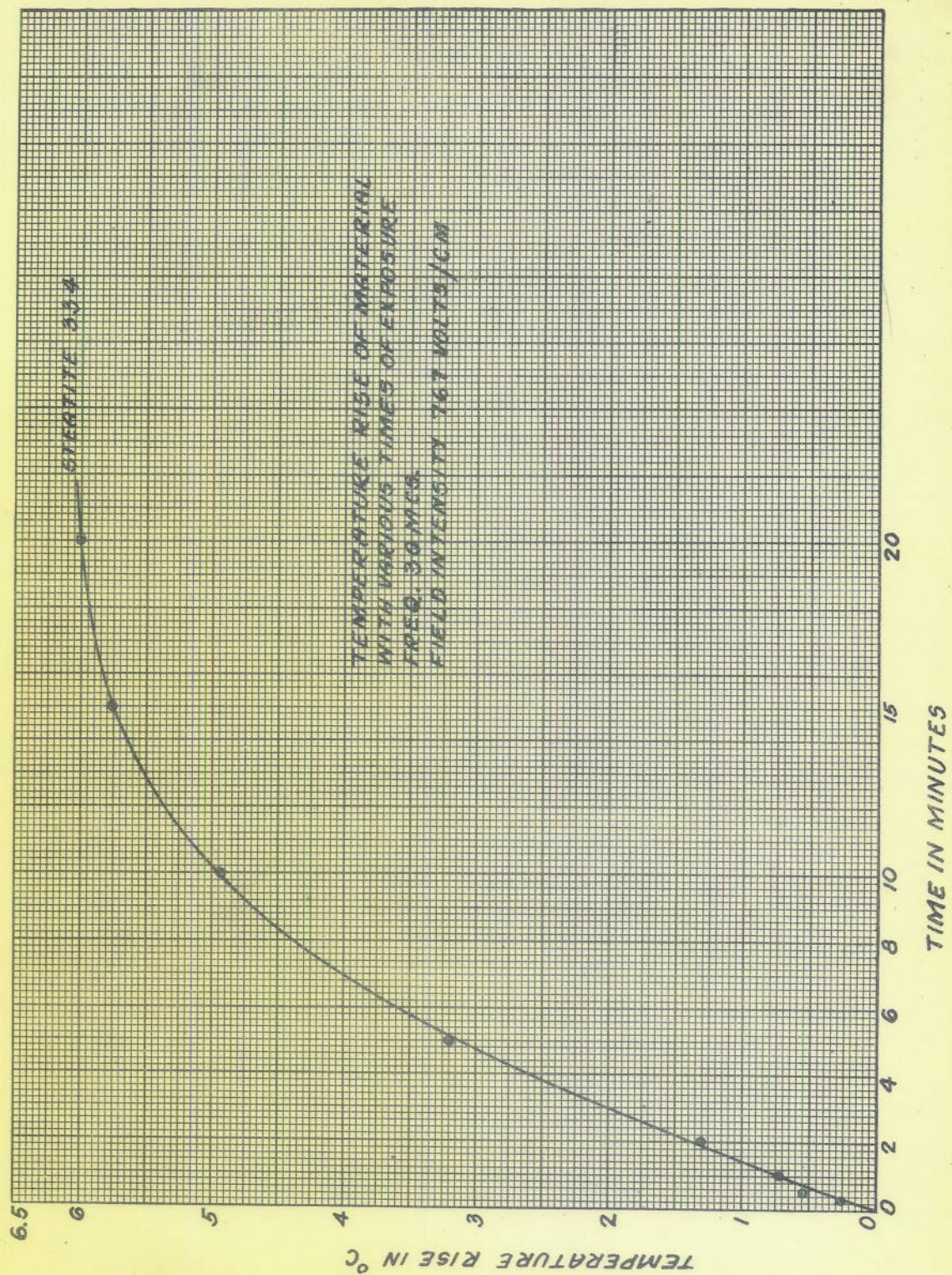


PLATE 20





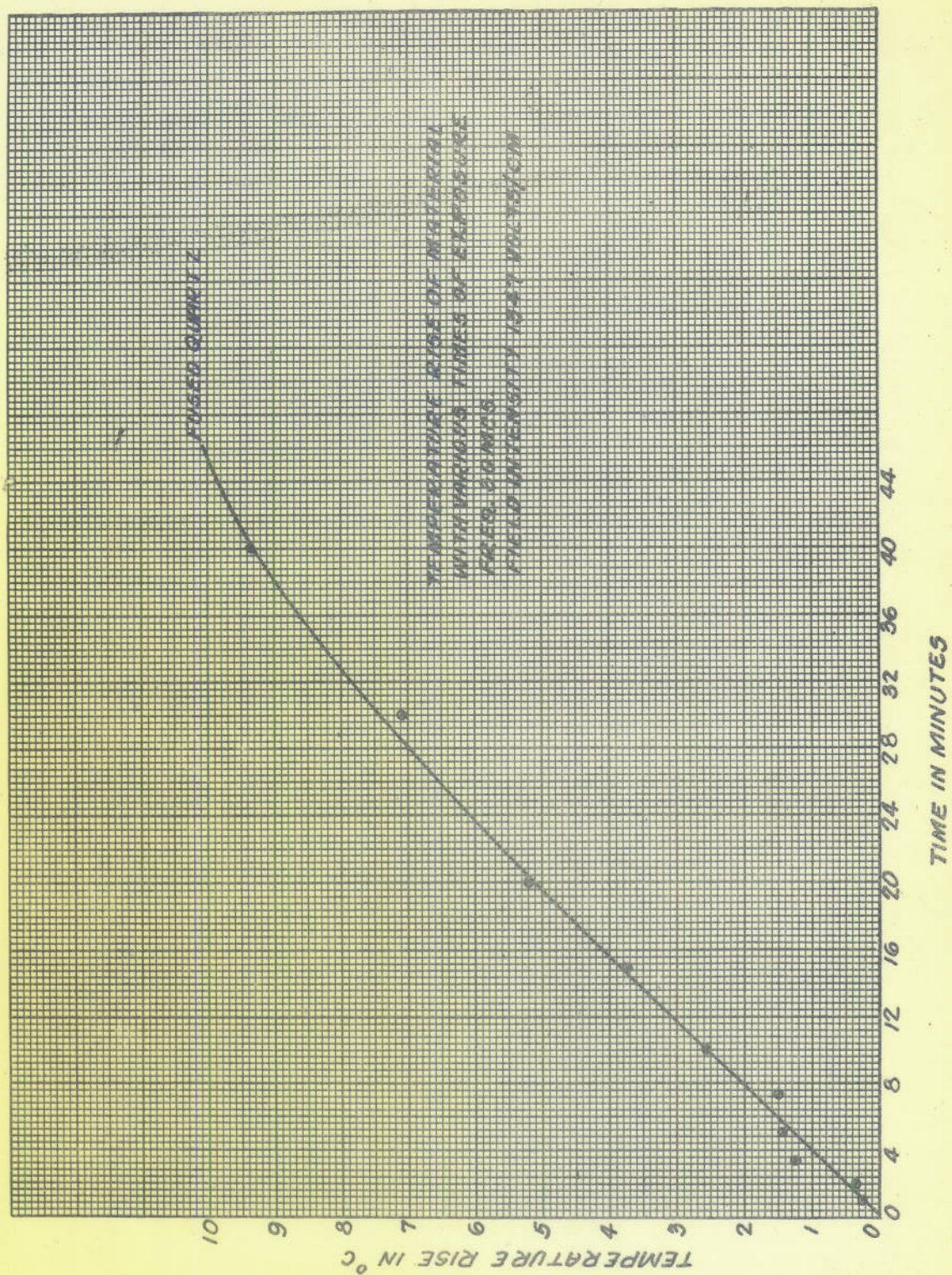
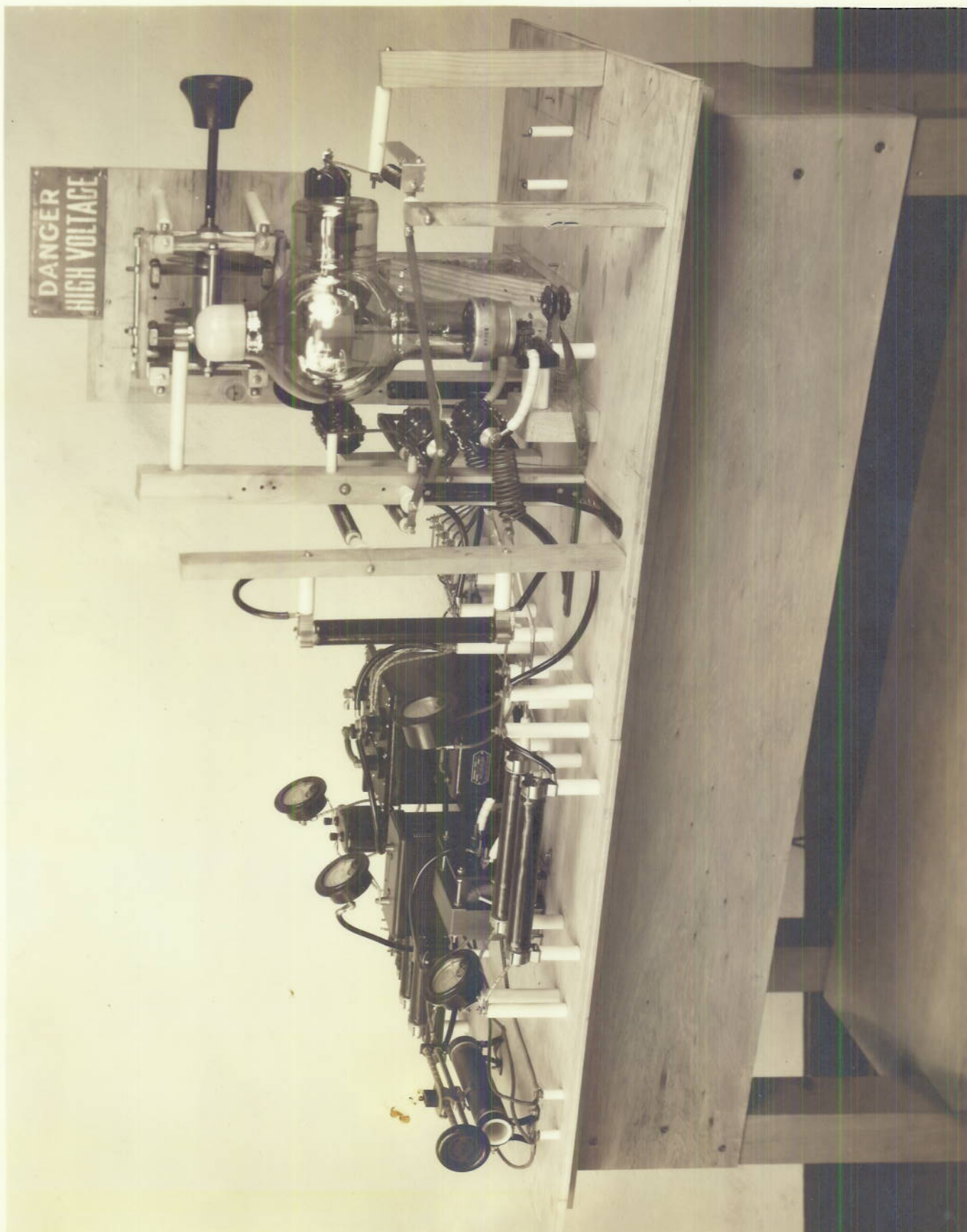
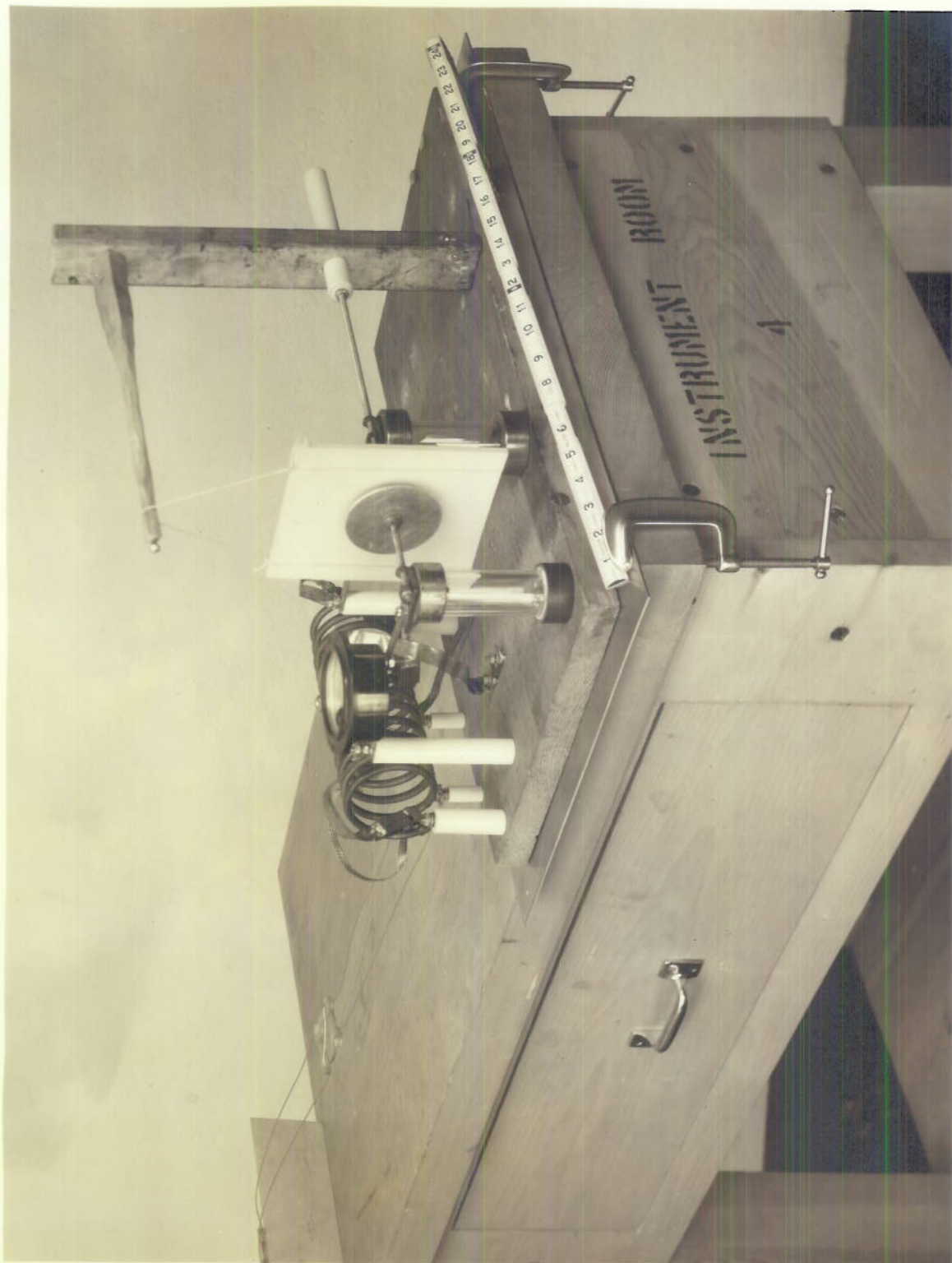


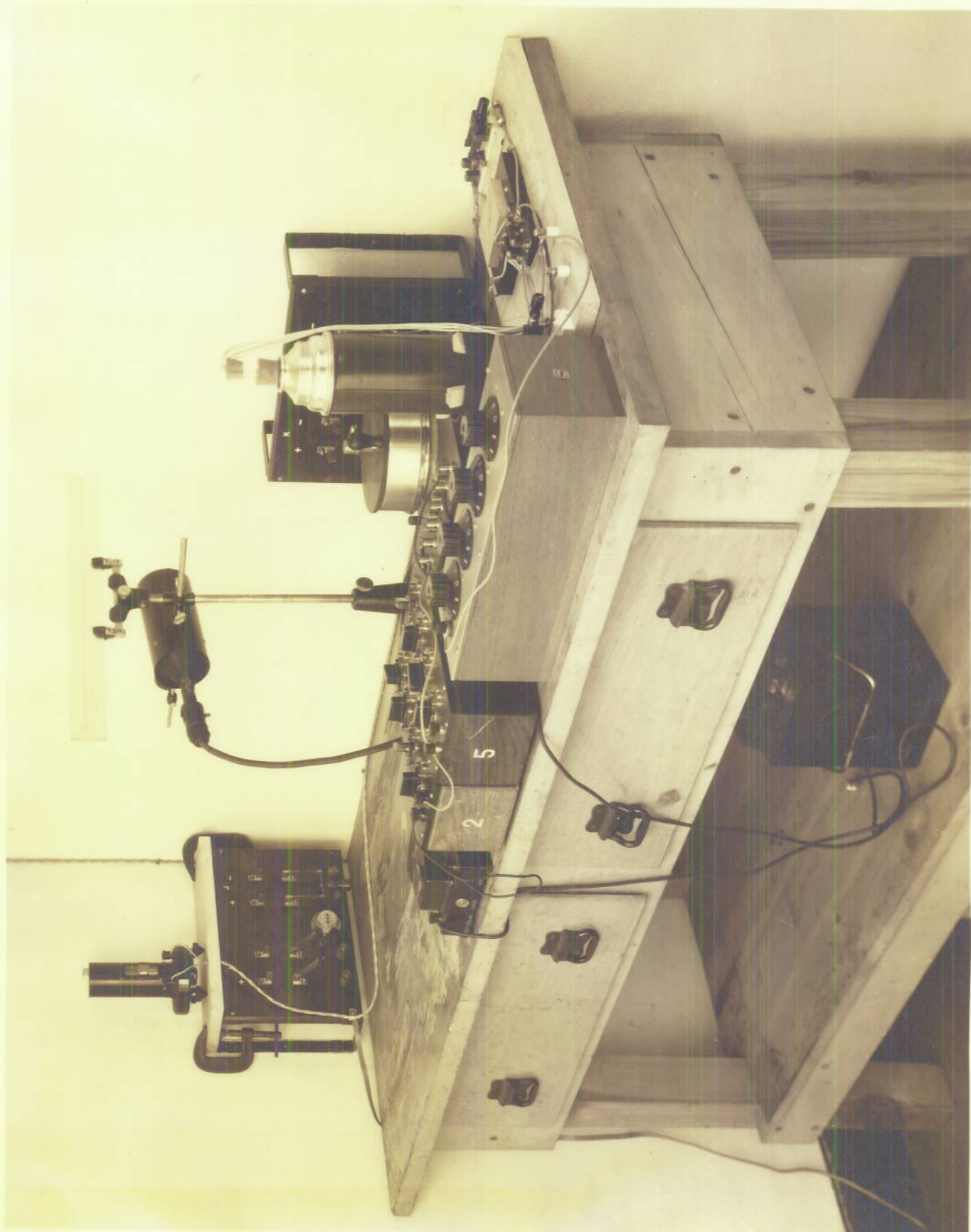
PLATE 23



500 Watt 30 Megacycle Driver



Dielectric Testing Circuit



Equipment for Measuring Temperature Rise