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Report  
on  
Properties of Dielectric Materials  
at High Frequencies.

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## ABSTRACT

A means of quantitatively measuring the dielectric properties of radio frequency insulating materials at high frequencies is described herein. Tests were conducted over a frequency range from 15 to 60 megacycles, with fairly large radio frequency electric fields being applied to the materials. Dielectric power loss is determined by means of the quantity of heat produced within the material when an electric field of known magnitude is applied. This investigation has shown that, in general, the dielectric constant, power factor and loss factor are not functions of frequency, although there are exceptions to this rule. Usually the power loss per unit volume, with a given field intensity, is proportional to the frequency. It has also been shown that the existing Navy specifications for ceramic radio frequency insulation are adequate for the purpose at the present time, if supplemented by a high frequency endurance test. A suitable qualification test in this respect has been recommended.

\* \* \*

This report supersedes NRL Preliminary Report No. R-1065 of 17 July 1934.

## AUTHORIZATION

1. This problem was authorized by Bureau of Engineering letter, reference (a), and additional references pertinent to this problem are listed as references (b) to (g).

- Reference:
- (a) BuEng. ltr. S67/61/L5(1-11-W8) of 1 February 1934.
  - (b) Navy Specifications for Insulator Material (Radio) - Ceramic and Glass, RE 13A 317F.
  - (c) NRL Report No. R-1065 of 17 July 1934 - Effects of High Frequency Electric Fields of High Field Intensities upon Radio Frequency Insulating Materials.
  - (d) L. Boltzmann, Wien Akademie Sitzungsberichte, 67, (2), page 17, 1873.
  - (e) Text Book entitled "Electricity and Magnetism" by S.G. Starling, page 165.
  - (f) NRL Report No. R-1228 of 6 January 1936 - Frequency Errors in Thermal Instruments.
  - (g) NRL Report No. R-1117 of 25 January 1935 - Test of Loss Factor and High Frequency Flash-over of Phenolic Insulating Materials.

## STATEMENT OF PROBLEM

2. The purpose of this investigation was to determine if the existing Navy specifications, reference (b), for low loss ceramic insulating materials are now adequate, considering that many Naval applications require the use of such insulation at very high radio frequencies; and if they are inadequate, to obtain sufficient information on which to base recommendations for a revision of these specifications. The existing requirements for low loss radio frequency insulation are based on tests conducted at a low frequency (300 kilocycles) with a very low impressed radio frequency voltage. These specifications were adequate at the time when the highest frequencies used in Naval communication did not exceed a few hundred kilocycles. However, at the present time there are many Naval applications in which such insulation is used at much higher frequencies (in some cases up to 60 megacycles); and in addition, there are many instances where insulating materials are subjected to an intense radio frequency field. It is not difficult to realize the existing specifications for low loss ceramic insulating materials may now be unsuitable, as the qualification tests are conducted under conditions differing greatly from actual operating conditions. Hence this investigation was undertaken.

## KNOWN FACTS BEARING ON PROBLEM

3. Many investigations have established that the dielectric properties of insulators are unchanged over a frequency range of 100 to 1000 kilocycles, that is, the dielectric constant, power factor, and loss factor are unchanged over this frequency range. It has also been determined that these values are independent of the impressed field intensity, that is, the square law relationship between impressed field intensity and dielectric power loss exists. It has also been established that the dielectric power

loss is distributed throughout the volume of the dielectric material. From a consideration of these facts, it is not difficult to show that the power loss per unit volume in a dielectric material, over this frequency range, is proportional to the frequency, other factors being equal. This fact may be stated otherwise, as follows - that the energy loss per unit volume per cycle is a constant over the above frequency range, if all other factors are equal. If the relationship between losses and frequency continues up to the very high frequencies, obviously, an insulator whose performance is satisfactory at 300 kilocycles may prove unsuitable at 60 megacycles, this frequency now being used for communication in the Naval service.

4. An investigation of the effects of the application of an electric field at a frequency of 30 megacycles upon a few dielectric materials, was conducted by this Laboratory, the results of which have been submitted to the Bureau in a preliminary report, reference (c). The conclusions based upon that investigation (although it was stated therein that they were not final, as only a few materials had been tested at one frequency) were that the action of a high frequency field of high field intensity upon a dielectric material was similar to and obeyed the same laws as one of low frequency and low field intensity.

#### THEORETICAL CONSIDERATIONS

5. In the measurement of dielectric properties at the higher frequencies (15 to 60 megacycles), the methods commonly used for such measurements at the lower frequencies would likely prove unsuitable, as available standards of capacity and resistance would likely be inaccurate over the high frequency range. In addition, if suitable standards were available, such a test may not indicate the performance of an insulator when subjected to a high value of field intensity, which would occur in a high frequency transmitter of considerable power output. Consequently, it is highly desirable to test an insulator with a high frequency field at a value of field intensity as great as would likely be encountered in transmitter use in the Naval service, which in some instances is probably as great as 1000 volts per centimeter.

6. In the investigation of the effects of high frequency fields upon dielectric materials, it is highly desirable that a method of test be used which is capable of yielding quantitative data in regard to the properties of the insulator. It would therefore be necessary to select a means of application of the high frequency field to the insulator so that the magnitude of field intensity may be readily evaluated. It would likewise be necessary to choose a method by which the actual power dissipated in the material may be determined. A means of application of a high frequency field to a specimen of insulating material, in which the magnitude of the impressed electric field may be determined, is shown in Plate 1. Two parallel disc-shaped metallic plates serve as electrodes for the application of the field to a sample of insulating material. The test specimen is in the form of a flat plate of suitable thickness to place between the electrodes, somewhat greater in area than the electrodes. Radio frequency current may be passed through this arrangement by making it the capacitative portion of

a tuned circuit. The spacing between the electrodes may be made adjustable to assist in tuning to any required test frequency. A value of tuning inductance may be associated with the condenser formed by the electrodes so that there is an air gap between the electrodes and the test specimen, as is illustrated in Plate 1. The physical arrangement of the parallel plane electrodes and the slab of insulating material makes it possible easily to compute the value of field intensity applied to the dielectric from the radio frequency current through the test specimen, the dielectric constant of the material, the frequency, and the area of the electrodes, by means of the well known laws of electricity. All of the quantities used in the computation of field intensity, with the exception of the dielectric constant, may be readily determined. A method of determination of dielectric constants at high frequencies will be discussed subsequently in this report. A quantitative method of determining dielectric power loss at high frequencies must also be devised. Dielectric power loss manifests itself in the form of heat, as is illustrated by an appreciable temperature rise of the radio frequency insulating material of a high power, high frequency transmitter. A method of test depending upon the quantity of heat produced in an insulator (or the temperature rise thereof) under known test conditions would be satisfactory, since the relationship between electrical and thermal energy has been determined. The temperature rise of a dielectric material may be determined with a contact thermocouple after the material has been exposed to a known value of electric field for a measured time; and from the temperature rise, specific heat, and density of the material, it is possible to determine the quantity of heat produced, and the power dissipated in the dielectric under the particular condition. In this manner the properties of various insulating materials may be compared. This method of test would also be useful to determine if an insulating material will withstand without deterioration or actual breakdown, the application of an intense radio frequency field, such as would be encountered in a high power, high frequency transmitter. A test specimen may be subjected to an intense field for a considerable period of time, and any defects produced thereby could be readily noted.

7. In order to investigate the effects of high frequency fields upon insulating materials, certain tests must be conducted to establish the relationships existing between the various governing factors and dielectric power loss. Prior to this investigation, it **had** not been definitely established that the square law relationship between field intensity and power loss exists, when an intense high frequency field is applied to a dielectric. If this relationship was found to be governed by some factor other than the square law, it would not be possible to state the power factor of the material as a definite value, rather the power factor could only be correctly expressed as some particular value at a stated field intensity. As radio frequency insulating materials may be used over a wide band of frequencies, it would be desirable to investigate the effect of frequency upon losses, as results may indicate that insulation tests may be more advantageously conducted at some particular frequency. In addition, some information regarding the dielectric constant of materials at high frequencies is also desirable, since the value of the dielectric constant of a material is related to the dielectric power loss therein. It is therefore necessary, in order to completely investigate

dielectric properties at high frequencies, to determine the following properties of, and relationships existing in, insulating materials:

- (a) Dielectric constant of insulating materials, investigating whether or not it is a function of either frequency or field intensity.
- (b) The relationship between dielectric power loss and applied field intensity.
- (c) The relationship between dielectric power loss and frequency.

8. If the results of the investigation of the behavior of dielectric materials, when subjected to an intense high frequency field, should indicate that the dielectric constant is independent of field intensity, and that dielectric power loss is proportional to the square of the field intensity, it would not be difficult to compute the dielectric properties of the material. These properties may be expressed in terms of power factor, loss factor, power loss per unit volume under some standard test condition, etc.; and in this manner the relative merits of various materials may be compared. However, if the aforementioned relationships differ somewhat from these assumptions, it would likely be possible to analyze the test data in such a manner that some relative basis of comparison may be formulated.

9. The value of the dielectric constant of a specimen of insulating material may be determined by an adaption of a method employed by Boltzmann in measuring dielectric constants with a continuous impressed potential, which is described in references (d) and (e). A condenser composed of two parallel plates was used, between which a slab of the material could be placed, and the capacity of the condenser with the specimen between the plates was determined with an electrometer and a suitable source of potential. Then the dielectric material was removed, and the spacing of the plates decreased until their capacity was the same as in the previous condition. It is not difficult to show that the dielectric constant of the material may be computed from the thickness of the test specimen and the change in plate spacing, by means of the following formula:

$$K = \frac{1}{1 - \Delta s/u} \quad (1)$$

where K = Dielectric constant of material.

$\Delta s$  = Change in condenser plate spacing in centimeters.

u = Thickness of test specimen in centimeters.

Proof of this formula is furnished in the text book, reference (e). In the above formula no allowance is made for fringing of the flux at the edges of the plates. However, as the spacings may be made small with respect to the dimensions of the plates, no large error is introduced. A similar arrangement may be used in the determination of

dielectric constant at radio frequencies. The electrode system shown in Plate 1, together with a tuning inductance, and a source of radio frequency power may be employed for this purpose as shown in Plate 2. The design of the electrode system should be such that it is possible to change the electrode spacing. The specimen may be inserted between the electrodes, and their spacing changed until the tuned circuit formed is resonant with the frequency of the power supply, and the spacing at resonance is noted. Then the specimen may be removed, the electrode spacing decreased until resonance is again obtained, and this spacing also noted. During such a test it is necessary that the frequency, tuning inductance, coupling, etc., remain unchanged, and obviously, if these factors are maintained, the electrode capacities at resonance with and without the test specimen are equal. The formula shown in equation (1) may then be used to compute the dielectric constant, as the change in spacing is the difference in the two aforementioned spacings, and the thickness of the specimen may be obtained by actual measurement. In the measurement of dielectric constant of insulators, it is necessary to select a value of tuning inductance to associate with the electrode system such that the electrode spacing is as small as possible, in order to reduce errors introduced by fringing of the flux near the electrode edges. It is obviously necessary to have an inductance large enough to produce resonance with the specimen inserted at a spacing somewhat greater than the specimen thickness in order to make it possible to obtain resonance. A value of inductance may be chosen so that the length of each of the air gaps between the electrodes and specimen does not exceed 0.1 centimeter, thereby reducing the error produced by "edge effect." By the means described in this paragraph, an investigation of the effect of field intensity upon dielectric constant may be conducted by tests at various electrode currents. The effect of frequency on dielectric constant may be readily determined by tests at various frequencies.

10. By means of the apparatus shown in Plates 1 and 2, augmented with a device for measurement of the temperature rise of a test specimen of insulating material, the relationship between applied field intensity and dielectric power loss may be established, as will be explained in the discussion to follow. If a dielectric material be subjected to a high frequency electric field, the dielectric power loss raises the temperature of the material. Since the relationship between electrical and thermal energy is fixed, and the temperature rise of a substance is proportional to the heat added, an investigation concerning the relationship between field intensity and dielectric power loss may be conducted by determination of the temperature rise at various values of applied field intensity, keeping all other factors such as frequency, time of exposure to the field, etc., constant during the test. It is likely that this relationship will be found to be in the nature of a square law, as in most analogous instances, indeed, such is found to be the case. If the square law relationship holds true, it would be found that in plotting along logarithmic coordinates, the temperature rise of the material as the ordinate and the field intensity as the abscissa, a straight line could be drawn through all points whose slope would be 2. If this is experimentally verified, it will thereby be shown that the square law relationship between field intensity and dielectric power loss holds true.

It will hardly be necessary to make an investigation as to whether the square law relationship holds true at every test frequency, for if it is found to be true at some frequency approximately at the mid-point of the test frequency range, it may be safely assumed that such is the case over the test frequency range.

11. In conducting an investigation of the relationship between field intensity and dielectric power loss, and in any other test involving the measurement of temperature rise, precautions must be taken to insure the smallest possible loss of heat from the test specimen, in order to determine accurately the quantity of heat added, or the temperature rise thereof. From a consideration of the manner in which the radio frequency field is applied to the material, as shown in Plate 1, obviously the entire specimen is not subjected to the field, and therefore only the central portion of the material will undergo a rise in temperature. Consequently, loss of heat from the central portion will result by conduction to the edges and by radiation. Loss of heat may be minimized by keeping the temperature rise small, the time of exposure to the field short, and by measuring the temperature rise as soon as possible after exposure to the field. The temperature rise of the materials may be measured immediately after the test with a contact thermocouple, on the surface of the specimen at or near its center, this being the point at which the smallest loss of heat will occur, as this portion of the specimen is surrounded by material at approximately the same temperature. Since the properties of insulating materials vary considerably, the resulting temperature rise of various materials will likely be considerably different when tested at the same field intensity and time of exposure to the field. Therefore, in order to keep the temperature rise of all materials small, it will be necessary to use different times of exposure for the various products, reducing them to the same time basis (temperature rise per second) for comparison. The question may arise as to whether results may be reduced to the same time basis without the introduction of error. However, considering the familiar exponential law of rise in temperature until equilibrium is established, it would be expected that for a small temperature rise during a test of short duration, the temperature rise would be approximately proportional to the time of exposure. Since it is also planned to expose the specimens of insulating material to the radio frequency field for considerable periods of time to investigate any possibility of deterioration, the temperature rise at various times of exposure will be determined, other factors remaining unchanged. From these data it will be possible to choose an optimum time of exposure, which will allow a temperature rise great enough to measure, without allowing the time of exposure to be great enough to cause the relationship between temperature rise and time of exposure to deviate from an appropriate linear relationship.

12. By means of the apparatus used to determine the effect of field intensity upon dielectric power loss, which has been described in paragraph 10, the relationship between frequency and power loss may be established. From the discussion in paragraph 10, it is not difficult to see that the effect of frequency upon power loss may be determined by finding the temperature rise resulting from the exposure of a material

to a radio frequency field at various frequencies, keeping all other factors such as field intensity, time of exposure to the field, etc., unchanged during the tests. The test frequencies and the corresponding temperature changes may be illustrated graphically, and from the curves, the relationship between power loss and frequency may be found. It is entirely possible that this relationship may not be the same in all types of materials, but will depend on its nature.

13. In the preceding paragraphs, the various investigations discussed were based upon radio frequency tests in which the temperature rise of a material was purposely kept small, in order to prevent loss of heat. Such tests may be valuable in finding the relative merits of materials at or near room temperature. Such tests may not be indicative of the performance of materials when they are continuously subjected to an intense radio frequency field. Certain insulating materials may have a considerable positive temperature coefficient of dielectric power loss. If such a material were used in a transmitter, wherein it was subjected to a considerable radio frequency field, a small rise in temperature would increase the power loss, which would thereby increase the rate of change in temperature, this effect continuing until a temperature is reached at which all heat due to power loss is dissipated. It is quite possible that a break-down of the material would occur, or some other form of deterioration would result before temperature equilibrium could be established. A material may be exposed to an intense high frequency field for a considerable period of time, and any resulting defects noted. It would be preferable to expose a material to an intense field for several periods, gradually increasing the time of exposure during each successive period, measuring the temperature rise after each exposure, thereby determining when temperature equilibrium is established. At the end of each exposure, the materials may be examined for any possible deterioration. It will hardly be necessary to make such an investigation at every test frequency, for the effect of prolonged subjection of a material to high frequency field is in the nature of a thermal effect, and may be found from tests conducted at some frequency approximately at the mid-point of the test frequency band.

14. It is desirable that all materials which receive high frequency tests be tested also at a low frequency, in order to determine if there is any correlation between the relative merits of materials at the two frequencies. Information regarding the effect of moisture on the performance of the materials at both frequencies is also desirable. Tests can be conducted both at low and high frequencies after immersion of the test specimens in water for a considerable period of time.

15. A list of the various materials tested, together with the symbol used in this report in referring to these products is shown in Table 1. In some cases more than one sample of a material was tested, and separate samples are distinguished by the appending of a letter to the symbol shown in this table. It may be noted that, included among these materials, nearly all of the various classes of insulating material are represented.

16. It is not necessary to subject every material to all tests outlined in the previous discussion in order to establish the various laws and relationships governing high frequency dielectric power loss; rather, such factors may be determined by tests of a few of the materials, selecting a representative sample from each of the various classes. Any governing factor or relationship found to be common to all of the selected representative materials would most certainly apply to any other of the commonly used radio frequency insulating materials. Products 2, 3, 5, 6, 7, 13, 19 and 20 were selected as representative samples, to be used in establishing the various governing factors. Reference to Table 1 indicates that among these representative samples are included a ceramic type, a glass bound mica material, some silicates, and several types of organic insulation including a phenolic material.

#### NARRATIVE OF ORIGINAL WORK DONE AT THIS LABORATORY ON PROBLEM

17. The development of a method for testing dielectric materials at high frequencies is the original work of this Laboratory. The data concerning high frequency dielectric properties, which will subsequently be furnished, are based on an original investigation by this Laboratory.

#### METHODS

18. A view of the apparatus used in the test of insulating materials at high frequencies is shown in Plate 3. The electrodes are in the form of brass discs, 8.9 centimeters in diameter, the edges of which are rounded in order to prevent corona. Means is provided for variation of the spacing of the electrodes, as is shown by screw drive, gear arrangement, and crank. Both of the electrodes are operated at high radio frequency potential, and the test specimen placed in their neutral plane. Radio frequency ammeters are provided to measure the current in order to evaluate field intensity applied to the material. From a consideration of the physical structure of the apparatus, obviously the electrodes have stray capacities to ground as well as a direct capacity between one another. The electrical circuit formed thereby is shown in Plate 4, Figure A. The direct capacity path (the one in which the test specimen is placed) has in shunt with it another capacity path formed by the two stray capacities in series. It may be noted that the ammeters indicate the total current through the direct path and the stray path as well. Mechanical design difficulties make it impractical to construct the apparatus so that the instruments may be placed in such a manner as to indicate current through the direct path only. In order to evaluate the field applied to the test specimen, the actual current through the specimen, or through the direct capacity path, must be determined. An equivalent circuit of the direct and stray capacity paths is shown in Plate 4, Figure B. The current  $I_t$  represents that flowing into both branches, or the current indicated by one of the instruments in Figure A, and the current  $I_d$  is that through the direct path, or that through the test specimen. The condensers  $C_d$  and  $C_s$  represent the direct and stray capacities, respectively, of the electrode system. Symmetrical design makes it possible to assume that the stray capacities of each of the electrodes are equal, which actual measurement verifies. In a circuit arrangement as

shown in Plate 4, Figure B, it is not difficult to show, by means of alternating current theory, that the following relationship is true:

$$I_d = \frac{I_t \cdot C_d}{C_d + C_s/2} \quad (2)$$

where  $I_d$  = Radio frequency current through test specimen.  
 $I_t$  = Radio frequency current reading of the instruments.  
 $C_d$  = Direct capacity between electrodes.  
 $C_s$  = Electrode stray capacity.

By means of the above formula the actual current through the test specimen may be computed in terms of the reading of the instruments, and the direct and stray capacities. As the spacing of the electrodes is variable, and since the capacities are a function of spacing, the relationship between  $I_d$  and  $I_t$  will also be a function of spacing. The direct and stray capacities of the electrode system were determined at a frequency of 1000 cycles with a capacity bridge, and their values are shown by curves in Plate 5. The total capacity curve represents the sum of direct and half of the stray, which is the total effective capacity of the electrode system, or the term  $C_d + C_s/2$  in equation (2). It has been stated that the relationship between  $I_d$  and  $I_t$  is a function of spacing, this relationship being governed by the ratio of the direct to the total electrode capacity, as is shown by equation (2). The ratio of the direct to total electrode capacity at any electrode spacing may be obtained from the curves in Plate 5. By this means a curve may be plotted showing this ratio as a function of spacing. This curve is shown in Plate 6; however, it is not expressed in the form of a capacity ratio, but as the component of total electrode current which follows the direct capacity path as a function of electrode spacing. The question may arise as to whether or not it is safe to assume that the high frequency current distribution is the same as would be expected from a computation based on measured capacities at 1000 cycles. Tests have been conducted which show that the radio frequency current distribution is actually governed by the capacity ratio. At any particular frequency, if the tuning inductance is changed, the spacing of the electrodes must also be changed to produce resonance. When the electrode spacing is changed, the portion of the current passing through the direct path also changes, as is indicated by the curve in Plate 6. This provides a means of determination if the radio frequency current distribution is actually that indicated by calculations based on capacity ratio. A specimen of material may be tested at a constant frequency with several values of tuning inductance, and the total electrode current and corresponding temperature rise in each instance noted. On the assumption that the curve in Plate 6 may correctly be used to compute the current through the test specimen from the total electrode current, it is found that the temperature rise of the material is independent of the spacing for the same computed value of current. From these tests it may easily be inferred that the curve shown in Plate 6 may be used without serious error in determining the actual current through the test specimen.

19. The apparatus shown in Plate 3 was used in the measurement of dielectric constant, the circuit arrangement shown in Plate 2 being used

for this purpose. A coil was associated with the electrode system, of suitable inductance to produce circuit resonance at an electrode spacing which allowed only a very small air gap between electrodes and test specimen. The length of the air gap, in most instances, did not exceed 0.1 centimeters. The procedure used in the measurement of dielectric constant consisted in observing the electrode spacings at resonance, both with the test specimen between the electrodes and with it removed, and finding the change in spacing from these two spacings; the dielectric constant of the material was then computed from the change in spacing and the thickness of the test specimen by means of equation (1). The stray capacities of the electrode system will not introduce an error into dielectric constant measurements. The stray capacity is in effect approximately a fixed capacity in shunt with the electrode system, as is shown by the stray capacity curve in Plate 5. Obviously, a fixed capacity in parallel with the electrodes will not introduce error into this measurement. Tests were conducted at various values of radio frequency current in order to determine if the dielectric constant of a material depended upon the impressed field intensity. Tests were conducted at various frequencies to determine the effect of frequency on dielectric constant. In conducting dielectric constant measurements, the actual duration of the test was kept short in order to prevent a large temperature rise. It is possible that the dielectric constant of a material may have a considerable temperature coefficient, hence the precaution in regard to allowing too great a temperature rise. Dielectric constant measurements were conducted over a frequency range from 15 to 60 megacycles in steps of 7.5 megacycles. Tests to determine the effect of field intensity upon dielectric constant were conducted at 30 megacycles, the actual field intensity applied depending somewhat on the dielectric constant of the material, but with a field intensity variation ratio of about 3 to 1.

20. It was stated in paragraph 6 of this report that the magnitude of the high frequency field applied to a test specimen could easily be computed in a circuit arrangement similar to that in Plate 1, and the means of determining the intensity of the field will be described. It has been previously stated that temperature rise measurements are taken at or near the center of the test specimen, and this point is also the one at which the value of applied field intensity may be determined most correctly. At the central portion of the electrodes the lines of electric flux are approximately perpendicular to the surfaces of the test specimen and the electrodes, or radio frequency current from a small area at or near the central portion of the electrode passes through the test specimen without appreciable fringing. Because of this effect, it is possible to compute the magnitude of the radio frequency electric field applied to the specimen at its center, as the following discussion will show. The radio frequency current passing from an electrode over a unit area located at or near the electrode center may be found by the following formula:

$$I_e = \frac{I_d}{A} \quad (3)$$

where  $I_a$  = Radio frequency current per unit area expressed in amperes per square centimeter.  
 $I_d$  = Radio frequency current through direct path of electrode system.  
 $A$  = Area of electrode in square centimeters.

The radio frequency current from this unit area passes through a similar area of the test specimen. The capacity of the unit area of the test specimen may be computed with the following formula:

$$C_a = \frac{0.0885 K \cdot 10^{-12}}{u} \quad (4)$$

where  $C_a$  = Capacity per unit area of specimen expressed in farads per square centimeter.  
 $K$  = Dielectric constant of test specimen.  
 $u$  = Thickness of test specimen in centimeters.

The capacitative reactance per unit area of the material may be computed by the following formula:

$$X_a = \frac{1}{\omega C_a} = \frac{u \cdot 10^{12}}{0.0885 K \omega} \quad (5)$$

where  $X_a$  = Capacitative reactance per unit area expressed in ohms per square centimeter.  
 $\omega = 2\pi f$  = Angular velocity of impressed voltage in radians per second.  
 $f$  = Frequency in cycles per second.

The potential across the test specimen in the region around the center may be found from the product of the current per unit area and the reactance per unit area, and is shown in the following formula:

$$E' = I_a X_a = \frac{I_d \cdot u \cdot 10^{12}}{0.0885 K \omega A} \quad (6)$$

where  $E'$  = Potential difference between surfaces of test specimen in volts.

The field intensity may be computed from equation (6) as follows:

$$E' = \frac{E'}{u} = \frac{I_d \cdot 10^{12}}{0.0885 K \omega A} \quad (7)$$

where  $E$  = Field intensity applied to specimen in volts per centimeter.

Equation (7), when rearranged, and when the area of the electrodes (62.2 square centimeters) is substituted, becomes:

$$E = \frac{289 I_d \cdot 10^8}{K f} \quad (8)$$

In the above formula the term  $I_d$  may be obtained from the reading of the radio ammeters in the circuit and the appropriate correction factor for indicating the current through the direct electrode path, as has been explained in paragraph 18 of this report. The value of dielectric constant may be measured as described in the preceding paragraph. The other unknown factor in equation (8) is the frequency, which may easily be measured. In this manner, the magnitude of the radio frequency electric field was determined.

21. Tests to determine the effect of field intensity upon dielectric power loss were conducted with the apparatus shown in Plate 3, used in a circuit arrangement as shown in Plate 2, together with equipment for measuring the temperature rise of the test specimen. The procedure used in testing a material consisted in placing the material between the electrode system as illustrated in Plate 1, adjusting electrode spacing until resonance occurs, exposing the material to the field for a certain period of time, and then measuring the resulting temperature rise with a contact thermocouple. The time of exposure was determined from the results of a few trial runs, and was fixed at a period which did not permit a temperature rise large enough to allow too great a loss of heat. The precautions necessary to prevent an appreciable heat loss have already been discussed in paragraph 11 of this report. The period of time which the materials were exposed to the field will be shown subsequently in this report. All tests conducted in field intensity-power loss relationship investigation were made at 30 megacycles. Variation in field intensity was obtained by adjustment of the radio frequency current through the test specimen. The magnitude of the applied radio frequency field was determined by the means described in the preceding paragraph. Materials were tested over a range in field intensity variation of about 2 to 1, although the maximum field applied to various materials was not always the same, but governed somewhat by the dielectric constant of the material and the maximum power output of the radio frequency power supply. The observed temperature changes in the various materials were reduced to the same time of exposure basis (temperature rise per second) for comparative purposes. The applied field intensity and the corresponding temperature rise (in degrees Centigrade per second) were plotted along logarithmic coordinates, in the manner described in paragraph 10 of this report, in order to determine the relationship between dielectric power loss and applied field intensity.

22. Tests to determine the effect of frequency upon dielectric power loss were conducted with the apparatus described in the preceding paragraph, in much the same manner. The temperature rise of the materials was measured at a fixed value of field intensity at various frequencies. This investigation was conducted over a frequency range of 15 to 60 megacycles, temperature rise measurements being taken at intervals of 7.5 megacycles. The field intensity applied to the test specimen was fixed at 1000 volts per centimeter, which was adjusted by control of the radio frequency current through the specimen. The results of the test, that is, the frequencies and corresponding temperature rises (in the form of temperature rise per second) were plotted on linear cross-section paper, in order to establish the relationship between

frequency and power loss. All precautions necessary to correctly measure the temperature rise, which have been discussed in paragraph 11 of this report, were observed in these tests.

23. Tests to determine the effect of the subjection of a material to an intense radio frequency field for a considerable period of time were conducted with the same equipment which has been used in all other high frequency tests. The test frequency used was 30 megacycles and the materials were subjected to a field intensity of 1000 volts per centimeter. Each material was exposed to this field for various periods of time, the temperature rise at the end of each exposure being determined. The duration of the exposure was increased until either a temperature measurement indicated that temperature equilibrium had been established, or deterioration of the material occurred. At the termination of each test the specimen was examined for defects or other signs of deterioration. In some cases materials were exposed to the field for a period as great as 20 minutes. The time of exposure and corresponding temperature rise for each of the materials tested were plotted on cross-section paper in order to illustrate the observed rise in temperature.

24. In a report recently submitted to the Bureau, reference (f), it was shown that frequency errors of considerable magnitude are present in ordinary thermal ammeters over the range of frequencies used in the high frequency dielectric tests. All instruments used in this investigation were calibrated at various radio frequencies by the method described in reference (f). Four ranges of instruments were necessary to measure the various required values of radio frequency current, the current ranges being 6, 10, 15 and 20 amperes, a pair of instruments of each range being necessary, as reference to Plate 2 indicates that two instruments are used simultaneously. Two instruments were used to provide a circuit mechanically symmetrical, and in addition, the two instruments were useful in checking the electrical symmetry of the circuit. In Plates 7 and 8, curves are shown by which the true radio frequency current may be obtained from the instrument reading at any of the test frequencies. The "multiplying factor" of an instrument is a number which is multiplied by the instrument reading in order to obtain the true radio frequency current. The question may arise as to the reason why the multiplying factors of the 6 and 10 ampere instruments are not approximately unity at a very low frequency. These instruments are unlike commonly used thermal ammeters, in that they were specially calibrated (by calculation) by the manufacturer to indicate correctly at 30 megacycles. For further information concerning this class of instrument, see reference (f), paragraph 20.

25. In Plate 9, a wiring diagram of the equipment used in the measurement of temperature rise of the insulating material test specimens is shown. The materials used in making the thermocouple were Copel and Chromel wire, two junctions being used on each end. The temperature of one pair of junctions was held constant by immersion in an ice water bath. The means of termination of the other pair of junctions is shown in Plate 10, and, in addition, the manner in which the terminating parts are mounted is illustrated. The terminating parts are made of brass, constructed so that the junction may be inserted and soldered. In order to make a temperature measurement, the test specimen was placed on the arrangement

shown in Plate 10 in such a manner that the thermocouple terminating parts make firm contact with the surface of the specimen at or near the center. The terminating parts are so mounted that they project above the other parts, in order that they will maintain firm mechanical contact with the test specimen. The arrangement shown in Plate 10 was selected because it afforded a uniform thermal contact between a test specimen and a thermocouple from time to time. The indication of temperature with the apparatus shown in Plate 9 is provided by the deflection of the galvanometer. The procedure in measuring the temperature rise of a test specimen is first, to place the material on the thermocouple, then to adjust the slide wire potentiometer until the galvanometer reads zero, thereby balancing out the initial temperature of the test specimen. Next, the material is subjected to the required radio frequency test, and at the end of the test, the specimen is placed again on the thermocouple and the change in temperature determined by the galvanometer deflection. The attenuator shown in Plate 9 is used as a galvanometer shunting device, which permits a multi-range temperature rise indicating mechanism. A measurement of temperature by means of a thermocouple relies upon the conduction of a portion of the heat within the substance to the junction of the thermocouple, and when the material has a very low coefficient of thermal conductivity, the possibility of errors in temperature measurements must not be overlooked. Investigation showed that it was necessary to calibrate the thermocouple in terms of each of the various type of insulating materials. Calibration was accomplished by raising the temperature of the specimens in a temperature controlled chamber a known amount, and then finding the corresponding galvanometer deflection. For any material the galvanometer deflection was found to be directly proportional to the temperature rise, although the same temperature rise in materials varying considerably in thermal properties did not produce even comparable galvanometer deflections. In order to illustrate the differing temperature measurement characteristics of the various materials, a relative comparison factor has been provided, which is expressed in terms of the deflection produced by the application of an aluminum block to the thermocouple. This factor may be designated as a "temperature correction factor" which is defined as the ratio of the galvanometer deflection produced by the aluminum block to that by a test specimen, when the temperature of each above the ambient is the same. Temperature correction factors for each of the materials will be shown subsequently in order to illustrate how great the difference is between various materials.

26. The specimens of insulating material were also tested by conventional methods at a low frequency to determine if there was any correlation between the high and low frequency test data. The well known "parallel substitution method" was used in conducting these tests, which is described in reference (g), paragraph 7(a). The test frequency was approximately 400 kilocycles, measurements of dielectric constant and power factor being taken on all specimens. From the product of these two quantities, the loss factor was determined. The loss factor of a material is proportional to the power loss, and is the unit commonly used in comparison of dielectric materials.

27. Tests were conducted to determine the effect of moisture upon insulating materials. The materials were soaked in distilled water at room temperature for a period of four days. At the end of this period, the low frequency loss factor was determined after the surfaces had been thoroughly dried with a clean cloth. After the low frequency test, the specimen was subjected to a field of 1000 volts per centimeter at a frequency of 30 megacycles and the temperature rise measured. By comparison of the dry and wet test data, the effects of moisture upon the material may be established.

28. In this report, all values of voltage, current, power, capacity, etc., are expressed in practical units. Reference is made to the system of units employed, as some textbooks and published articles utilize electrostatic units in matters pertaining to dielectric investigation. The c.g.s. system of units is used in this report in expressing all quantities except the electrical ones.

#### DATA OBTAINED

29. Values of dielectric constant for each of the eight representative samples at seven test frequencies between 15 and 60 megacycles, are shown in Table 2. In addition, the dielectric constant of each of the materials determined by conventional methods at 400 kilocycles is shown for comparison. Values of dielectric constant were found to be independent of field intensity over the range of impressed high frequency fields, the maximum field in each instances being approximately the same as that which will subsequently be shown for each material in the data illustrating the relationship between dielectric power loss and field intensity (Plate 11). The data observed in making a dielectric constant measurement at 30 megacycles are shown in Table 3, in order to illustrate the nature of such data.

30. Test data to establish the relationship between dielectric power loss and field intensity, that between power loss and frequency, and the effect of prolonged exposure of a material to an intense high frequency field are shown in Plate 11, Plates 12 to 14, and Plates 15 to 18, respectively. A recapitulation of all these data is shown in Plate 19 for comparison purposes. In Plate 19 a few of the curves are shown by dotted lines, the purpose being to distinguish them more clearly from other curves in the same region.

31. Low frequency loss factor test data, both with the materials dry, and after immersion in distilled water for a period of four days, are shown in Table 4. Such data are furnished for every test specimen of each of the materials listed in Table 1.

32. Each of the products listed in Table 1 received high frequency tests after immersion in water as described in paragraph 27 of this report. Except in the case of Product 19, no substantial difference between the results of the high frequency wet tests and the dry ones were noted. The power loss in Product 19 (as indicated by relative changes in temperature under identical conditions) after immersion was approximately 6 times as great as when dry. All subsequent high frequency test data, either graphical or tabular, were taken with the test specimens dry.

## DISCUSSION OF PROBABLE ERRORS

33. In the data taken for the purpose of determining the effect of field intensity upon dielectric power loss, frequency upon power loss, etc., some absolute error is, of course, introduced. From a relative standpoint, such data are indicative of the various laws governing the characteristics of insulating materials at high frequencies, and any fixed error present may be ignored in forming conclusions. When any of the properties of a material (power loss per unit volume, for example) are computed, a rough estimate of the probable error is desirable. Into such a computation two types of error are introduced, one from inaccuracies in the evaluation of field intensity, and the other in the determination of temperature rise. Since in any power evaluation, the square of the field intensity is introduced, any error in the value of field intensity will introduce an error into the final result approximately twice as great in percentage. Errors in field intensity may be introduced by error in measurement of current (due to inaccuracy in the calibration of the thermal ammeters and due to the fact that the current may not exactly divide as predicted by a low frequency capacity measurement), and error in determination of dielectric constant. In arriving at any conclusions regarding probable error in the measurements, it should also be considered that an accurate measurement involving heat is, in general, very difficult to make. It is estimated that quantitative high frequency dielectric properties computed from the foregoing test data are accurate to within about 25%. The properties of the low loss materials may be inaccurate to a somewhat greater percentage, and the high loss ones are likely to have a smaller error. It is estimated that probable error in the low frequency loss factor measurements is approximately 25% for the low loss materials, and 12% for the ones of high losses, intermediate grades of materials falling between these two estimated percentages.

## RESULTS

34. Reference to Table 2 indicates that the dielectric constant of a material is not materially affected by frequency over a frequency range of 15 to 60 megacycles and is substantially the same at a frequency of 400 kilocycles, or the dielectric constant of a material is not a function of frequency. Neither is it a function of field intensity, as was indicated in paragraph 29 of this report. An examination of the graphical data in Plate 11 illustrates that the relationship between field intensity and dielectric power loss is in the nature of a square law. A straight line whose slope is approximately 2 may be approximately drawn through all observed points for any particular product, thereby proving the foregoing statement to be true. The relationships between frequency and power loss are not similar in all of the eight representative samples, as a study of the curves in Plates 12 to 14, inclusive, will show. In the case of Products 2, 3, 12a, and 19, the power loss is proportional to the frequency over the test frequency range, since in each case, a straight line may be drawn through the average of the points, which, when extended, passes approximately through the origin. This indicates that over this frequency band the power factor is a constant, or the power loss per cycle is constant at a fixed

field intensity. The relationship between frequency and power loss in the other four representative samples (Products 5a, 6, 7a, and 20) is not so simple. The power loss in these materials increases with frequency, and appears to increase somewhat faster than the frequency over the test frequency band. Probably some equation could be formulated which would express the power loss as a function of frequency in these materials, although such a formula would likely be of little value. It has been shown that all of the eight representative samples obey the ordinary electrical laws at any particular frequency, although the effect of frequency upon power loss is not the same in all of the materials. In order to compare materials their properties may be computed at some particular frequency, and in general, such information will be indicative of the performance of the materials over the test frequency range. A comparison at one frequency is not, in a strict sense, a complete one, as reference to temperature rise vs. frequency curves in Plate 19 shows that the relative standings of Products 7a and 13a are interchanged between 15 and 60 megacycles. All quantitative dielectric properties were computed at 30 megacycles which falls approximately at the mid-point of the test frequency range.

35. The means by which the dielectric power loss may be computed from the temperature rise will be discussed. When a material is subjected to a radio frequency field, the quantity of heat added may be expressed in terms of temperature rise, specific heat, and density of the material. From the principles of physics, the number of calories of heat added per unit volume when the material undergoes a change in temperature, is expressed by the following formula:

$$H = D \cdot S \cdot \Delta T \quad (9)$$

where H = Quantity of heat added to material in calories per unit volume.

D = Density of material in grams per unit volume.

S = Specific heat of material in calories per gram per °C.

ΔT = Temperature rise of material in °C.

The energy added, which is in the form of heat may also be expressed in terms of the electrical energy unit, the joule. Since one joule is equal to 4.18 calories, the following equation expresses the added energy in electrical units:

$$W = 4.18 H = 4.18 DS \cdot \Delta T \quad (10)$$

where W = Energy added to material in joules per unit volume.

The time rate at which energy is added to the material, or at which power is dissipated therein, is expressed by the following equation:

$$\frac{W}{t} = \frac{4.18 DS \cdot \Delta T}{t} = P \quad (11)$$

where t = Interval of time during which energy was added, in seconds.

P = Power loss in material in watts per unit volume.

The power loss per unit volume may be computed by means of equation (11), as the other terms of the equation may be readily found. The density may be found from the weight and volume of the test specimen. The specific heat may be found by means of the well known method of mixtures. The term  $\Delta T/t$  may be found for any of the eight representative samples at any value of field intensity from the data shown in Plate 11. In this manner, the power loss at any applied field intensity may be determined. In order to compare all materials on the same basis, their losses should be computed at the same field intensity. A field intensity of 1000 volts per centimeter would be satisfactory as the one chosen for comparison, for the magnitude of the field impressed upon an insulator in a high power transmitter is of this order.

36. The power factor of a material may also be computed from the temperature rise of the material and the impressed field. Power factor is defined as the ratio of power to volt-amperes in a circuit. In the preceding paragraph, a means has been described for determining the dielectric power loss per unit volume. A means of determining the volt-amperes per unit volume will be shown, thereby providing a means of computing the power factor. The capacity between opposite faces of a unit cube of material, entirely surrounded by the same material, may be computed by the following formula:

$$C_v = 0.0885 K \cdot 10^{-12} \quad (12)$$

where  $C_v$  = Capacity of unit cube in farads.  
 $K$  = Dielectric constant of material.

The capacitative reactance between opposite faces of the unit cube may be computed as follows:

$$X_v = \frac{1}{\omega C_v} = \frac{10^{12}}{0.0885 K \omega} \quad (13)$$

where  $X_v$  = Capacitative reactance of unit cube in ohms.  
 $\omega = 2\pi f$  = Angular velocity of impressed voltage in radians per second.  
 $f$  = Frequency in cycles per second.

If the material is subjected to a field intensity  $E$ , the voltage across opposite faces of the cube will also be  $E$ . The current flowing through the unit cube may be found from the voltage across and the reactance of the cube, as indicated in the following equation:

$$I_v = E\omega C_v = 0.0885 EK\omega \cdot 10^{-12} \quad (14)$$

where  $I_v$  = Current through unit cube in amperes.

The volt-amperes per unit volume may be found from the product of the current through the cube and the voltage across its faces, as is shown by the following equation:

$$U = EI_v = 0.0885 E^2 K\omega \cdot 10^{-12} \quad (15)$$

where U = Volt-amperes per unit volume.

The power factor of the material may then be computed as follows:

$$\psi = \frac{P}{U} \cdot 100 \quad (16)$$

where  $\psi$  = Power factor of material in per cent.

P = Power loss in material in watts per unit volume.

The means by which the value of the term P in the above equation may be found has been described in the preceding paragraph. In using the above equation to express power factor it is, of course, necessary to substitute power loss and volt-ampere values taken at equal values of field intensity. The value of U shown in equation (15) may be substituted in equation (16), and as comparisons will be conducted at a frequency of 30 megacycles, at a field intensity of 1000 volts per centimeter, equation (16) may be further simplified as follows:

$$\psi' = \frac{6 P'}{K} \quad (17)$$

where  $\psi'$  = Power factor of material in per cent at a frequency of 30 megacycles.

P' = Power loss of material in watts per unit volume at 30 megacycles with an impressed field of 1000 volts per centimeter.

The loss factor may be computed from the product of the power factor and dielectric constant. Data concerning the high frequency properties of the insulating materials will subsequently be furnished in tabular form.

37. Regarding the effect of exposure of insulating materials to a high frequency field for a considerable period of time, reference to Plates 15 to 18, inclusive, indicates that the materials undergo a gradual rise in temperature, which is in the nature of an exponential relationship in every instance except in the case of Product 3. The results in this instance, are illustrative of a condition (which was discussed as a possibility in paragraph 13) in which the temperature rise due to a prolonged exposure becomes great enough to damage the material. Obviously, a material with the physical properties of Product 3 could not be used as radio frequency insulation in a transmitter, if normal use may cause a temperature rise of 145°C. During the test the surface of the material became discolored, the test specimen warped to some extent, and during the last period of exposure to the field, a noticeable quantity of obnoxious fumes were liberated from the test specimen. Likewise, Product 6 would not be considered suitable for use as radio frequency insulation in a transmitter. The final test on this material caused large blisters to form on both surfaces of the test specimen, which exploded, liberating a considerable quantity of blue smoke having a phenolic odor. This material reached a temperature of 216°C. after a period of four minutes, at which point the test was terminated. All other of the eight representative

samples withstood the impressed field both without damage and without undergoing an excessive temperature rise. The temperature rise vs. time of exposure curves in Plate 19 may be used in comparison of results on all eight of the representative samples. A considerable time is required to make such a curve on a material, and any way of reducing the time required in testing a material is desirable. It may be noted that when a material is subjected to the field for a period of 15 minutes, either temperature equilibrium is reached, the temperature rise has progressed to a point unsafe for using the material, or the material has become damaged during the test. Other materials may therefore be tested once for a period of 15 minutes in order to determine the effect of prolonged subjection to the field. The temperature rise may be observed at the end of this period in order to determine if it has become too great for the particular material, and also for the purpose of comparison with other materials. The rise in temperature produced by exposure to a field of 1000 volts per centimeter for a period of 15 minutes in one sample of each product listed in Table 1, will subsequently be shown in this report.

38. The high frequency properties of the various materials at 30 megacycles are listed in Table 5. Those of the eight representative samples as well as those of all other of the samples listed in Table 1 are given. The temperature rise data used in computation of the properties of the representative samples were taken from the curves in Plate 11, the temperature rise at 1000 volts per centimeter being used in the calculation. The temperature rise data on other ones was determined by one exposure to a field at an intensity of 1000 volts per centimeter. In addition, the temperature rise produced by subjection of a material to the same field for a period of 15 minutes is shown. The loss factor at 400 kilocycles is also shown for comparison with that obtained at 30 megacycles. If the properties undergo no change with frequency (or if the loss per cycle is constant at the two frequencies, other factors being equal) the loss factors would be the same at both frequencies. Observed differences in characteristics may also be illustrated in this manner. It is necessary to consider probable error in arriving at any conclusions regarding dielectric properties at the two frequencies. There is listed in Table 6 some additional data necessary in making the computations of high frequency power loss and power factor.

39. For the purpose of more easily analyzing the observed data, the materials have been listed in the order of their relative merits both at 400 kilocycles and 30 megacycles. This information is shown in Tables 7 and 8. The only difference between these tables is that one designates the materials by symbol only and the other uses actual trade names, the purpose of the latter table being to show at a glance the properties of materials at both frequencies. The number following the names of the material in Table 8 is the symbol shown in Table 1, and is furnished to show the grade or type of material referred to. If it is necessary to withhold the identity of the materials, Table 8 as well as Table 1, should be removed from this report. Where more than one sample of a material was used, the test data on each was averaged, and the data shown for each material in Tables 7 and 8 is the average.

40. Reference to Table 7 or 8 indicates that the relative standings of the materials at the two frequencies, while not identical, are much the

same. The greatest change in relative standing occurs in the case of Product 8, which occupies the eighth place (from the top) in the high frequency list, and the twelfth place in the other. The loss factor of this material at 400 kilocycles is nearly three times as great as it is at 30 megacycles, the discrepancy being too great to be the result of experimental error. From this it appears that the characteristics of this material have undergone a change with frequency. In contrast, the loss factor of Product 6, a phenolic material, has increased 2-1/2 times between 400 kilocycles and 30 megacycles. The relative characteristics of the materials having a very low loss (the first three or four materials at the top of the lists in Tables 7 and 8) should not be given much consideration in forming conclusions regarding change in properties with frequency, because considerable experimental error may be introduced into these measurements. The high frequency properties of the rest of the materials (with the exception of those noted above, and ignoring test data on the very low loss materials) appear to be very nearly the same at the two frequencies, when probable error is considered. Thus, it may be concluded that, in general, the properties of an insulator do not change with frequency, but that there are exceptions to the rule.

41. Regarding the matter of qualification tests for insulating materials for use at high frequencies, the question naturally arises as to whether materials should receive certain of the high frequency tests discussed in this report (in addition to any others) before being considered suitable for use in the Naval Service. As has been shown in Tables 7 and 8, the relative standing of materials is approximately the same at both 400 kilocycles and 30 megacycles, no particular advantage would result from measurement of the dielectric properties at the high frequency, for measurements taken at the low frequency are sufficiently indicative of performance. Some type of high frequency endurance test would be desirable. Reference to Table 7 shows that Products 3 and 5 have approximately the same loss factors both at 400 kilocycles and 30 megacycles, and from this fact it might appear that from a standpoint of power loss either material could be used equally well. However, a comparison of their changes in temperature when they are subjected to prolonged exposure to a high frequency field, shows that the relative merits of the materials are not at all the same. Reference to the temperature rise vs. time of exposure curves in Plate 19 plainly indicates this fact. It may be noted that the temperature rise of Product 5 is not at all excessive, considering the type of material, whereas that of Product 3 is much greater, and the final value reached is great enough to actually damage the material. Thus the need for some type of endurance test is demonstrated. No radio frequency insulating material should be considered suitable for use in the Naval Service unless it will successfully withstand a radio frequency field of 1000 volts per centimeter, at a frequency of 30 megacycles, for a period of 15 minutes, without breakdown, damage, or deterioration in any other form.

#### DISCUSSION

42. The question may arise as to why immersion in water does not substantially change the high frequency properties of materials

(except in one case, which has been discussed in paragraph 32), whereas reference to Table 4 indicates that, in many instances, the low frequency loss factor is materially increased by such treatment. A possible explanation will be offered as to the reason why water soaking affects the low frequency measurements to a much greater extent. Surface moisture may contribute materially to the increase in low frequency loss factor, especially when it is considered that in the low frequency tests, the electrodes completely cover the opposite faces of the test specimen, which allows a fairly short path across the edges of the specimen between the electrodes. From a consideration of the physical arrangement of the high frequency electrode system, surface moisture on the edges will have an imperceptible effect on the measurements. Surface moisture on the faces of the test specimen would likely produce a small effect upon the high frequency tests, because the application of the field would likely cause the surface moisture quickly to evaporate. It has been demonstrated that the high frequency loss of a material increases if its structure is such that moisture can penetrate the material. The losses in a sample of porous porcelain increased more than 12 times after the material had been soaked in water one minute. The reason why the various products show no marked difference in high frequency properties, before and after immersion in water, is probably because their structure is such that they are impervious to moisture, and that surface moisture produces no substantial effect upon the properties of the material. A low frequency qualification test conducted after the soaking of a material in water is considered desirable, for in many Naval applications, the material will be used in a fairly weak field, insufficient to dry the surface moisture.

43. In reference (a), paragraph 4, the question arose as to the desirability of reducing the maximum allowable loss factors for both F and G grades of radio frequency insulation. The specifications, reference (b), permit maximum loss factors of 1% and 7% for F and G grades, respectively, the measurements being conducted after the material had been immersed in water four days. Reference to the "wet test data" in Table 4 indicates only four of the materials tested (which are physically suitable to conform to the specifications), Products 2, 13, 14 and 18, would qualify. In addition, the cost of one of these materials (Product 2) and the mechanical properties of two others (Products 13 and 14) make these materials unsuited to many Naval uses. Thus, of 13 commercial products tested which are physically and mechanically suited to conform to the specifications, only one of these (Product 18), qualifies for grade G material in so far as its radio frequency properties are concerned. Thus it appears undesirable to reduce the maximum allowable loss factor for grade G materials. As grade F materials are usually employed in transmitters covering only the low or intermediate frequency bands, it does not appear that much would be gained by a reduction in the maximum allowable loss factor tolerance.

44. Subsequently, a high frequency endurance test will be recommended, which all materials should conform with before receiving Navy type approval. Such qualification tests could be conducted by any Inspector of Naval Material, equipped with suitable apparatus.

## RECOMMENDATIONS

45. It is recommended that the existing Navy specifications, reference (b), for radio frequency insulating materials be supplemented with a high frequency endurance test. A requirement that such materials withstand without breakdown or deterioration, the application of a radio frequency electric field at a frequency of 30 megacycles, at a field intensity of 1000 volts per centimeter, appears to be suitable for this purpose.

## CONCLUSIONS

46. Navy specifications, reference (b), for radio frequency ceramic insulation are considered adequate at the present time, provided they are augmented with a suitable high frequency endurance test. A suitable test of this nature has been recommended in the preceding paragraph.

47. In regard to the properties of dielectric materials, it may be stated that, in general, no great frequency change in characteristics occurs, although there are exceptions to this statement.

TABLE 1

## List of Materials Tested.

Note: If necessary to withhold identity of materials, Table 8 in addition to this table should be removed.

<u>NRL Symbol Product</u>	<u>Material</u>	<u>Manufacturer</u>	<u>Mfr.'s Grade</u>	<u>Number of Samples Tested</u>
1	Alsimag	American Lava Corp.	35	2
2	Fused quartz	General Electric Co.	-	1
3	Hard rubber	American Hard Rubber Co.	1113	1
4	Hard rubber	American Hard Rubber Co.	1117	1
5	Isolantite	Isolantite, Inc.	-	3
6	Lamicoid	Mica Insulator Corp.	6022	1
7	Mycalex	General Electric Co.	-	3
8	Mycalex	Mycalex Corp. of America	-	3
9	Paraffin	-	-	1
10	Plate glass	-	-	1
11	Porcelain	Westinghouse Elec. Mfg. Co.	-	2
12	Porcelain	Porcelain Products Co.	-	2
13	Pyrex glass	Corning Glass Works	776	3
14	Pyrex glass	Corning Glass Works	707	3
15	Pyrex glass	Corning Glass Works	064	3
16	Sillimanite	Champion Spark Plug Corp.	-	1
17	Steatite	Dielectric Products Corp.	352-N	3
18	Ultra-steatite	Dielectric Products Corp.	444-B	3
19	Sulphur	-	-	1
20	Victron	Dielectric Products Corp.	AA	1
21	Victron	Dielectric Products Corp.	G	1

Product 6 is a phenolic insulating material.

Product 8 is commonly known as "British Mycalex."

Product 9 - The test specimen was made from The Texas Co.'s "Texwax."

Product 10 is ordinary plate window glass.

Product 15 - This glass is of the opaque variety; all other glasses are clear.

Product 19 - The test specimen was composed of ordinary cast sulphur.

TABLE 2

Dielectric Constant Measurements  
at Various Frequencies.

<u>Material Product</u>	<u>400 Kcs.*</u>	<u>15 Mcs.</u>	<u>22.5 Mcs.</u>	<u>30 Mcs.</u>	<u>37.5 Mcs.</u>	<u>45 Mcs.</u>	<u>52.5 Mcs.</u>	<u>60 Mcs.</u>
2	3.8	3.9	3.8	3.8	3.8	3.7	3.8	3.7
3	3.2	3.3	3.2	3.2	3.1	3.1	3.2	3.1
5a	5.4	5.7	5.6	5.6	5.5	5.6	5.6	5.6
6	4.2	4.7	4.6	4.7	4.6	4.7	4.8	4.8
7a	7.9	7.8	7.7	7.7	<b>7.8</b>	7.7	7.8	7.7
13a	4.0	4.0	4.0	3.9	3.9	3.9	4.0	3.9
19	3.5	3.8	3.7	3.8	3.8	3.8	3.7	3.7
20	2.6	2.6	2.5	2.5	2.5	2.4	2.5	2.5

\* Measurements in this column made by substitution method. All others made by means of method described in paragraph 19 of this report.

TABLE 3

Dielectric Constant Measurement Data.

30 Mcs.

<u>Material Product</u>	<u>Spacing with Material Inserted</u>	<u>Change in Electrode Spacing</u>	<u>Thickness of Test Specimen</u>	<u>Dielectric Constant</u>
2	0.802 cm.	0.517 cm.	0.70 cm.	3.8
3	0.729	0.444	0.65	3.2
5a	0.802	0.517	0.63	5.6
6	0.803	0.518	0.66	4.7
7a	0.798	0.513	0.59	7.7
13a	0.740	0.455	0.61	3.9
19	0.757	0.472	0.64	3.8
20	0.801	0.392	0.66	2.5

See Equation (1) for formula used in computation.

TABLE 4

## Loss Factor Test Data

400 Kcs.

Material Product	Dry Test Data			Wet Test Data		
	Dielectric Constant	Power Factor	Loss Factor	Dielectric Constant	Power Factor	Loss Factor
1a*	5.5	0.20%	1.1%	5.6	0.36%	2.0%
1b*	5.5	0.21	1.2	5.5	1.14	6.3
2	3.8	0.01	0.04	3.8	0.01	0.04
3	3.2	0.53	1.7	3.1	0.56	1.7
4	3.1	0.44	1.4	3.0	0.70	2.1
5a	5.4	0.28	1.5	5.4	0.50	2.7
5b	5.4	0.27	1.5	5.3	0.56	3.0
5c	5.4	0.28	1.5	5.5	0.47	2.6
6	4.2	2.58	10.8	4.1	2.66	10.9
7a	7.9	0.10	0.79	7.6	0.49	3.7
7b	7.9	0.10	0.79	7.6	0.29	2.2
7c	7.8	0.10	0.78	7.5	0.53	4.0
8a	5.5	0.17	0.94	5.5	0.38	2.1
8b	5.6	0.27	1.5	5.5	0.41	2.3
8c	5.5	0.29	1.6	5.7	0.55	3.1
9	1.9	0.004	0.008	2.1	0.007	0.015
10	6.8	0.59	4.0	7.0	0.61	4.3
11a	6.0	0.68	4.1	6.0	0.65	3.9
11b	5.5	0.63	3.5	5.6	0.58	3.3
12a	5.8	0.56	3.2	6.0	1.20	7.2
12b	5.9	0.59	3.5	6.0	0.89	5.3
13a	4.0	0.04	0.16	4.0	0.10	0.40
13b	4.0	0.03	0.12	4.0	0.11	0.44
13c	4.0	0.04	0.16	4.0	0.12	0.48
14a	4.2	0.17	0.71	4.4	0.20	0.88
14b	4.2	0.15	0.63	4.3	0.21	0.90
14c	4.3	0.19	0.82	4.3	0.17	0.73
15a	4.5	0.10	0.45	4.8	0.23	1.1
15b	4.5	0.10	0.45	4.5	0.26	1.2
15c	4.5	0.10	0.45	4.5	0.19	0.86
16	5.8	0.33	1.9	5.8	0.33	1.9
17a	5.7	0.25	1.4	5.5	0.24	1.3
17b	5.5	0.25	1.4	5.6	0.28	1.6
17c	5.6	0.25	1.4	5.5	0.24	1.3
18a	5.9	0.17	1.0	5.8	0.18	1.0
18b	6.0	0.18	1.1	5.9	0.19	1.1
18c	5.9	0.17	1.0	5.9	0.17	1.0
19	3.5	0.005	0.017	3.5	0.52	1.8
20	2.6	0.08	0.21	2.6	0.11	0.29
21	2.6	0.02	0.05	2.6	0.06	0.16

\* For tests on other samples of this material, see NRL Report No. R-1245.

TABLE 5

## Loss Factor Test Data - 30 Mcs.

Note: All data taken at 30 mcs. except that in right hand column.  
See Table 6 for other pertinent data.

Material Product	Temp.Rise* °C./Sec.	Dielectric Constant	Power Loss** (Watts)	Power Factor	Temp.Rise* 15 Min. Exp. to Field	Loss Factor	Loss Factor (Dry) 400 Kcs.
1a	0.086	5.1	0.173	0.204%	44.3°C	1.0%	1.1%
1b	0.083	5.2	0.167	0.192	-	1.0	1.2
2	0.005	3.8	0.009	0.014	1.7	0.05	0.04
3	0.164	3.2	0.26	0.487	145.0	1.6	1.7
4	0.118	3.1	0.204	0.392	87.0	1.2	1.4
5a	0.10	5.6	0.253	0.271	42.0	1.5	1.5
5b	0.11	5.6	0.278	0.297	-	1.7	1.5
5c	0.097	5.5	0.245	0.266	-	1.5	1.5
6	2.53	4.7	4.57	5.82	#	27.4	10.8
7a	0.029	7.7	0.063	0.049	12.7	0.38	0.79
7b	0.028	7.7	0.06	0.047	-	0.36	0.79
7c	0.03	7.9	0.065	0.049	-	0.39	0.78
8a	0.042	5.3	0.078	0.088	-	0.47	0.94
8b	0.045	5.5	0.083	0.09	-	0.50	1.5
8c	0.049	5.6	0.09	0.096	22.5	0.54	1.6
9	0.004	2.0	0.009	0.03	2.7	0.06	0.008
10	0.237	6.5	0.521	0.482	87.0	3.1	4.0
11a	0.276	5.8	0.651	0.672	103.0	3.9	4.1
11b	0.258	5.5	0.608	0.661	-	3.6	3.5
12a	0.27	5.3	0.637	0.72	-	3.8	3.2
12b	0.274	5.4	0.647	0.719	187.0	3.9	3.5
13a	0.029	3.9	0.057	0.088	10.5	0.34	0.16
13b	0.028	3.9	0.055	0.085	-	0.33	0.12
13c	0.027	3.9	0.053	0.082	-	0.32	0.16
14a	0.058	4.4	0.11	0.15	-	0.66	0.71
14b	0.058	4.4	0.11	0.15	-	0.66	0.63
14c	0.064	4.5	0.121	0.161	23.7	0.73	0.82
15a	0.05	4.5	0.092	0.123	-	0.55	0.45
15b	0.05	4.6	0.092	0.129	23.2	0.59	0.45
15c	0.047	4.5	0.087	0.116	-	0.52	0.45
16	0.087	5.0	0.202	0.242	29.0	1.2	1.9
17a	0.097	5.5	0.234	0.254	-	1.4	1.4
17b	0.10	5.7	0.241	0.252	-	1.4	1.4
17c	0.10	6.0	0.241	0.241	44.3	1.5	1.4
18a	0.053	6.0	0.131	0.131	-	0.79	1.0
18b	0.043	5.6	0.106	0.113	-	0.63	1.1
18c	0.059	5.8	0.146	0.151	18.4	0.88	1.0
19	0.004	3.8	0.006	0.0095	1.5	0.036	0.017
20	0.019	2.5	0.028	0.067	11.5	0.17	0.21
21	0.014	2.6	0.02	0.046	6.1	0.12	0.05

\* Temperature rise at 1000 V./Cm.

\*\* Power loss per unit volume at 1000 V./Cm.

# Material became defective after 4 minute exposure, and the temperature rise at the end of this period was 216°C.

TABLE 6

Density and Specific Heat of Materials,  
and Other Pertinent Information  
Concerning High Frequency  
Insulation Tests.

<u>Material Product</u>	<u>Density</u>	<u>Specific Heat</u>	<u>Temperature Correction Factor*</u>	<u>Time of Exposure to Field**</u>
1	2.41	0.20	1.39	30 Sec.
2	2.20	0.20	1.55	120
3	1.22	0.31	1.85	30
4	1.38	0.30	1.77	30
5	2.52	0.24	1.40	60
6	1.35	0.32	1.80	5
7	3.44	0.15	1.27	120
8	2.32	0.19	1.51	90
9	0.82	0.69	1.85	120
10	2.50	0.21	1.40	30
11	2.56	0.22	1.38	30
12	2.35	0.24	1.42	30
13	2.12	0.22	1.55	90
14	2.26	0.20	1.56	60
15	2.21	0.20	1.54	60
16	2.41	0.23	1.45	60
17	2.62	0.22	1.35	60
18	2.82	0.21	1.33	90
19	1.99	0.18	1.60	120
20	1.05	0.33	2.00	60
21	1.06	0.32	1.95	60

\* See paragraph 25 for significance of this factor.

\*\* The time of exposure is that used in obtaining information in "Temperature Rise - °C./Sec." column in Table 5.

TABLE 7

Relative Standings of Materials.

400 Kcs. and 30 Mcs.

Materials Designated by Symbols.

<u>400 Kcs. (Dry)</u>		<u>30 Mcs.</u>		
<u>Material</u>	<u>Loss</u>	<u>Material</u>	<u>Loss</u>	<u>Power</u>
<u>Product</u>	<u>Factor</u>	<u>Product</u>	<u>Factor</u>	<u>Loss*</u>
9	0.008%	19	0.036%	0.006
19	0.017	2	0.05	0.009
2	0.04	9	0.06	0.009
21	0.05	21	0.12	0.02
13	0.15	20	0.17	0.028
20	0.21	13	0.33	0.055
15	0.45	7	0.38	0.063
14	0.73	8	0.5	0.084
7	0.79	15	0.55	0.09
18	1.0	14	0.68	0.11
1	1.2	18	0.77	0.13
8	1.4	1	1.0	0.17
17	1.4	4	1.2	0.2
4	1.4	16	1.2	0.2
5	1.5	17	1.4	0.24
3	1.7	5	1.6	0.26
16	1.9	3	1.6	0.26
12	3.4	10	3.1	0.52
11	3.8	11	3.8	0.62
10	4.0	12	3.9	0.64
6	10.8	6	27.4	4.57

\* Power loss expressed in watts per cubic cm. at a field intensity of 1000 V./Cm.

TABLE 8

Relative Standings of Materials.

400 Kcs. and 30 Mcs.

Materials Designated by Trade Names.

400 Kcs. (Dry)		30 Mcs.		
Material	Loss Factor	Material	Loss Factor	Power Loss*
Paraffin - 9	0.008%	Sulphur - 19	0.036%	0.006
Sulphur - 19	0.017	Fused quartz - 2	0.05	0.009
Fused quartz - 2	0.04	Paraffin - 9	0.06	0.009
Victron - 21	0.05	Victron - 21	0.12	0.02
Pyrex - 13	0.15	Victron - 20	0.17	0.028
Victron - 20	0.21	Pyrex - 13	0.33	0.055
Pyrex - 15	0.45	Mycalex - 7	0.38	0.063
Pyrex - 14	0.73	Mycalex - 8	0.5	0.084
Mycalex - 7	0.79	Pyrex - 15	0.55	0.09
Ultra-steatite - 18	1.0	Pyrex - 14	0.68	0.11
Alsimag - 1	1.2	Ultra-steatite - 18	0.77	0.13
Mycalex - 8	1.4	Alsimag - 1	1.0	0.17
Steatite - 17	1.4	Hard rubber - 4	1.2	0.2
Hard rubber - 4	1.4	Sillimanite - 16	1.2	0.2
Isolantite - 5	1.5	Steatite - 17	1.4	0.24
Hard rubber - 3	1.7	Isolantite - 5	1.6	0.26
Sillimanite - 16	1.9	Hard rubber - 3	1.6	0.26
Porcelain - 12	3.4	Plate glass - 10	3.1	0.52
Porcelain - 11	3.8	Porcelain - 11	3.8	0.62
Plate glass - 10	4.0	Porcelain - 12	3.9	0.64
Lamicoid - 6	10.8	Lamicoid - 6	27.4	4.57

\* Power loss expressed in watts per cubic cm. at a field intensity of 1000 V./Cm.

SIDE VIEW

MEANS OF APPLICATION OF R. F. FIELD TO TEST SPECIMEN OF INSULATING MATERIAL

PLATE I

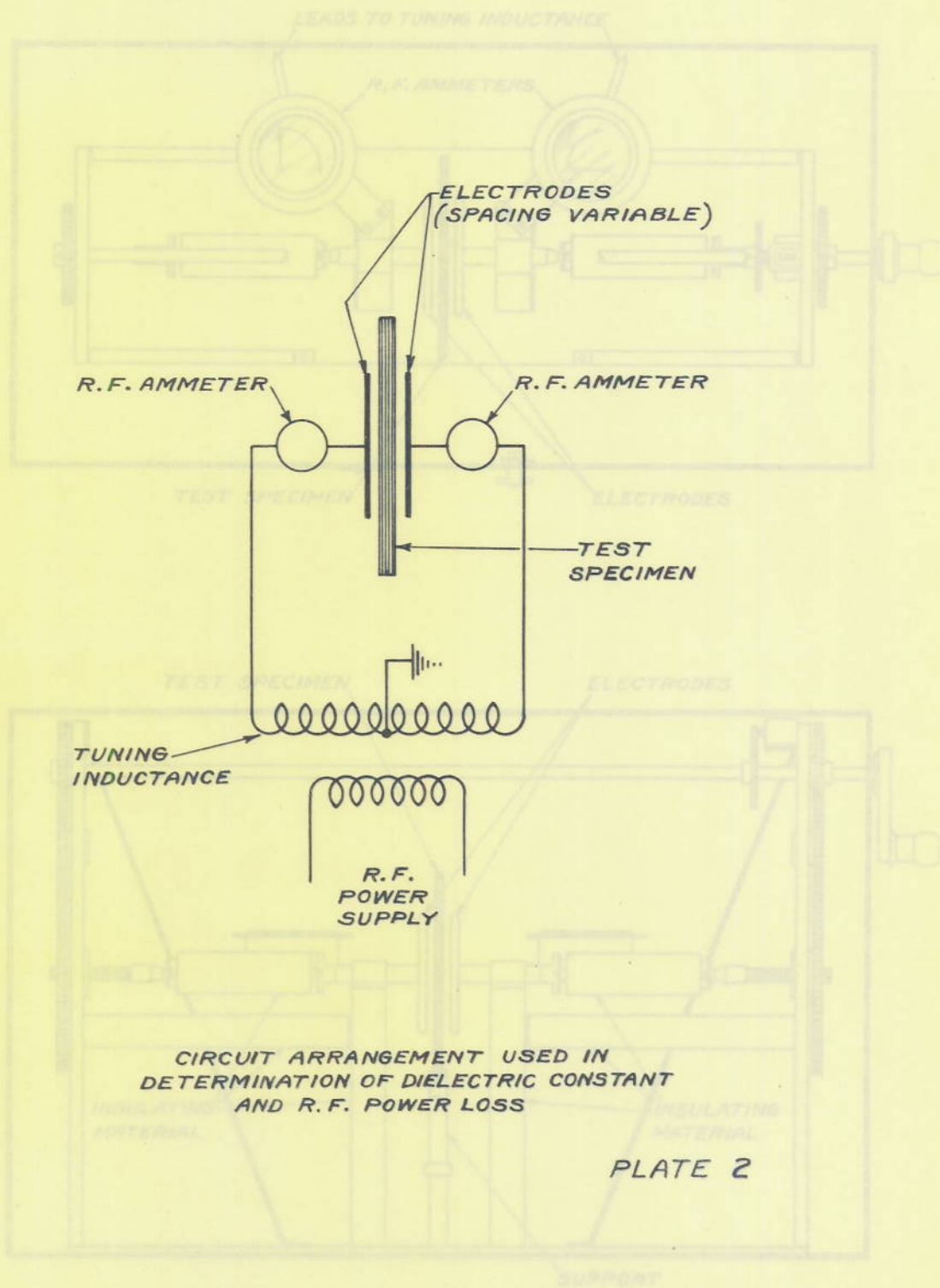
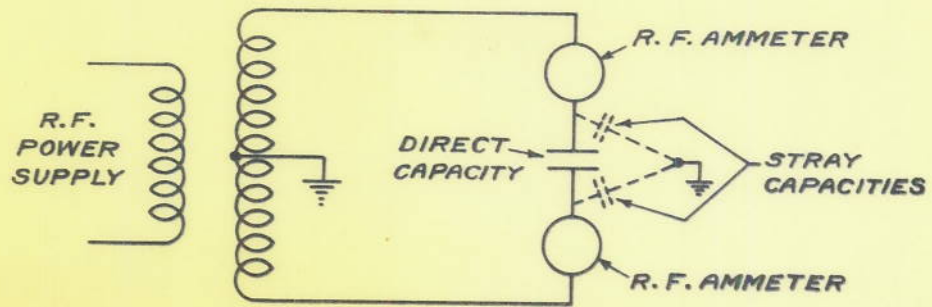


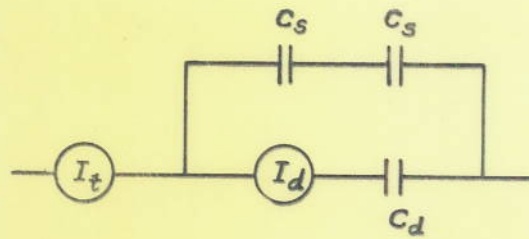
PLATE 2

APPARATUS USED IN TESTING INSULATING MATERIALS

PLATE 3

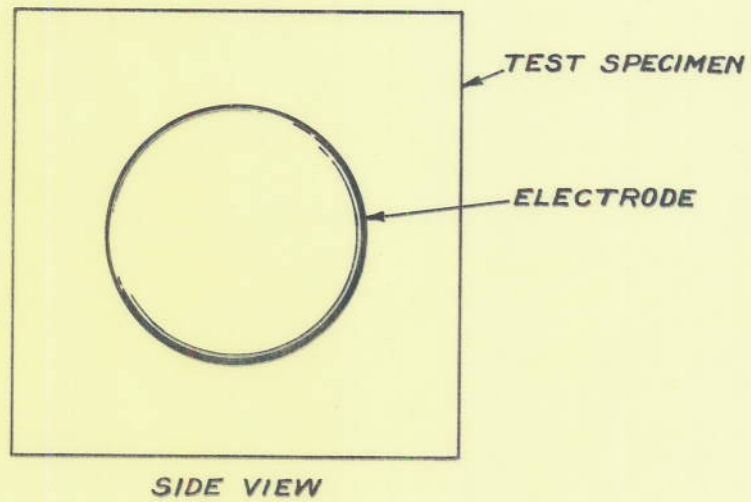
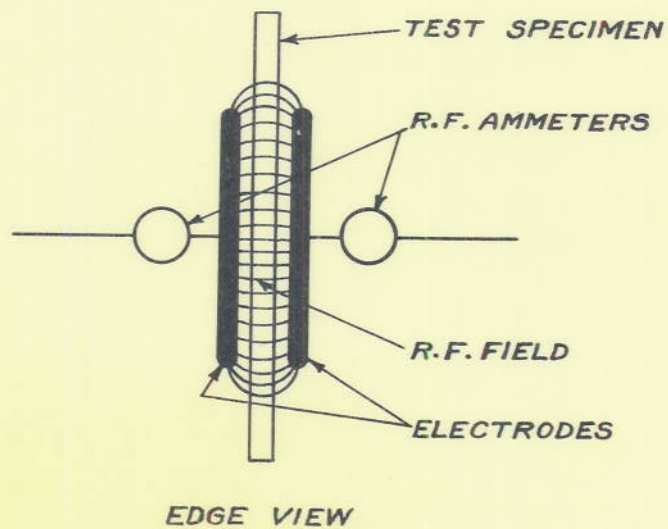


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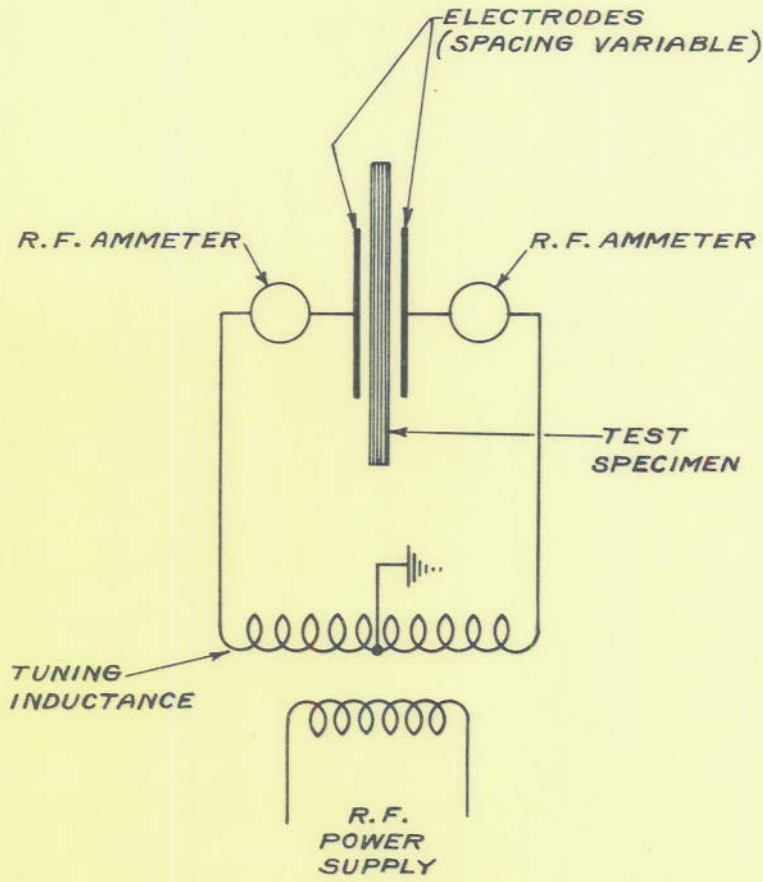


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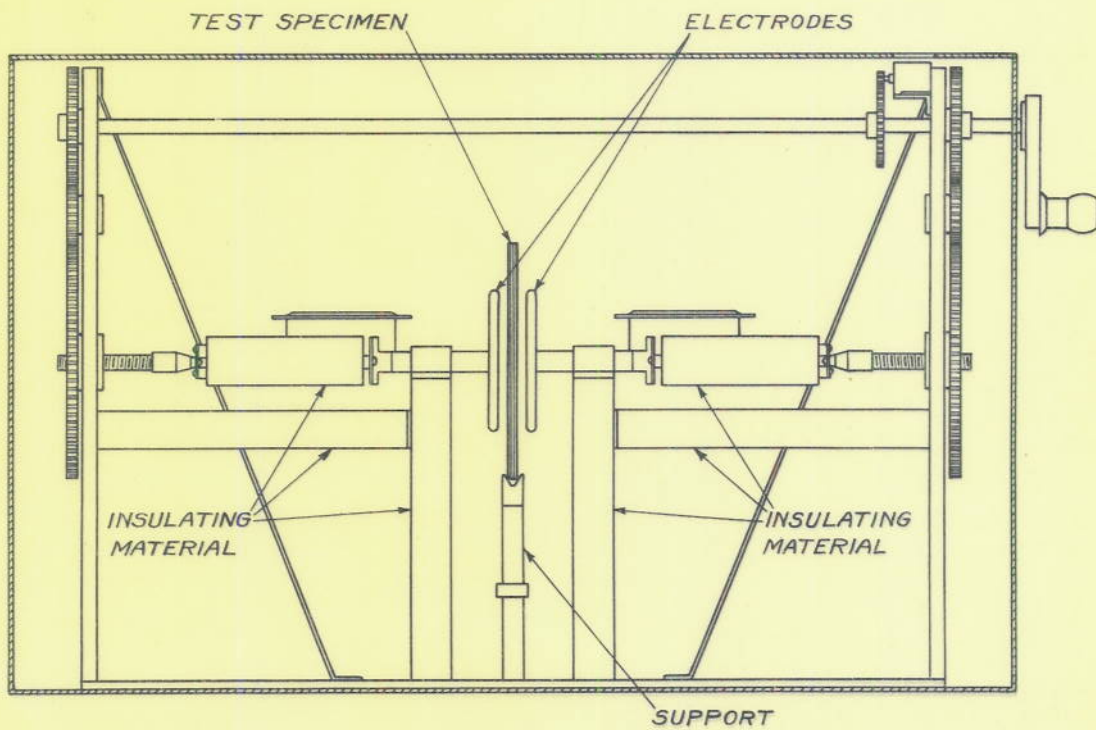
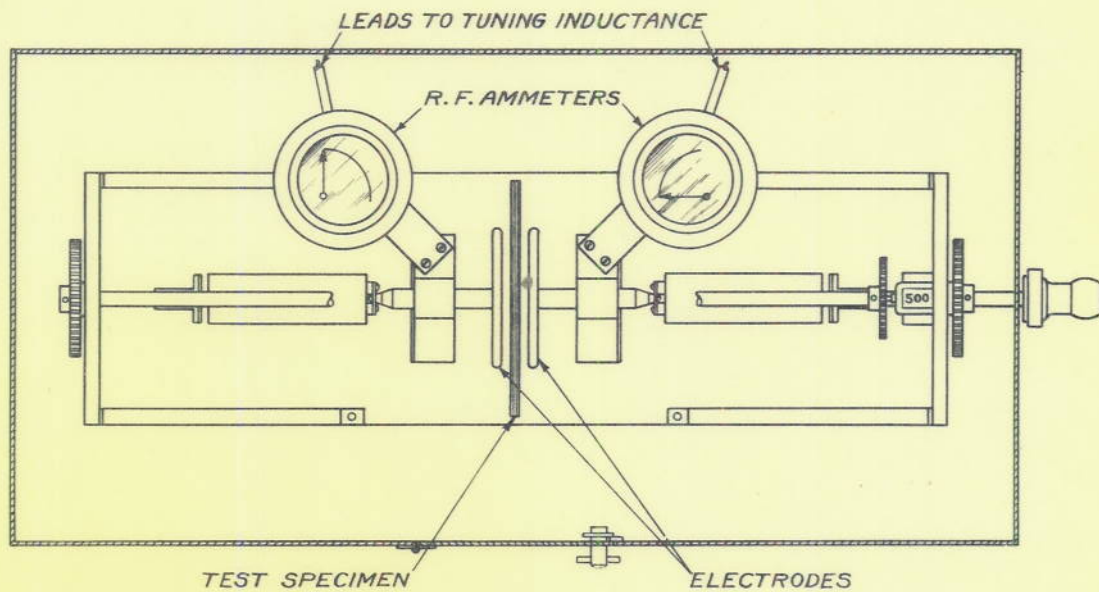
DIRECT AND STRAY CAPACITY CIRCUITS  
OF ELECTRODE SYSTEM



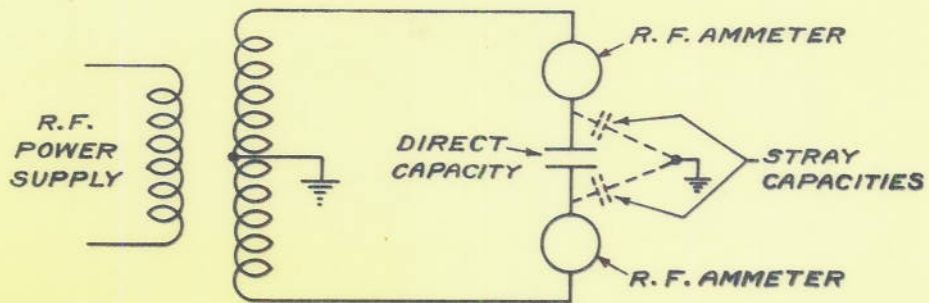
MEANS OF APPLICATION OF R. F. FIELD  
TO TEST SPECIMEN OF INSULATING MATERIAL



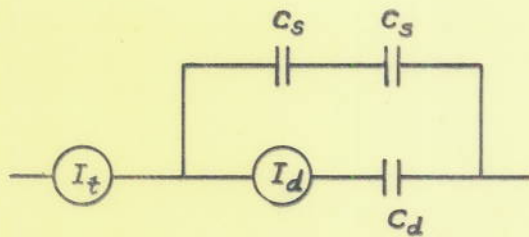
CIRCUIT ARRANGEMENT USED IN  
DETERMINATION OF DIELECTRIC CONSTANT  
AND R.F. POWER LOSS



APPARATUS USED IN TESTING INSULATING MATERIALS



(A)



(B)

**DIRECT AND STRAY CAPACITY CIRCUITS  
OF ELECTRODE SYSTEM**

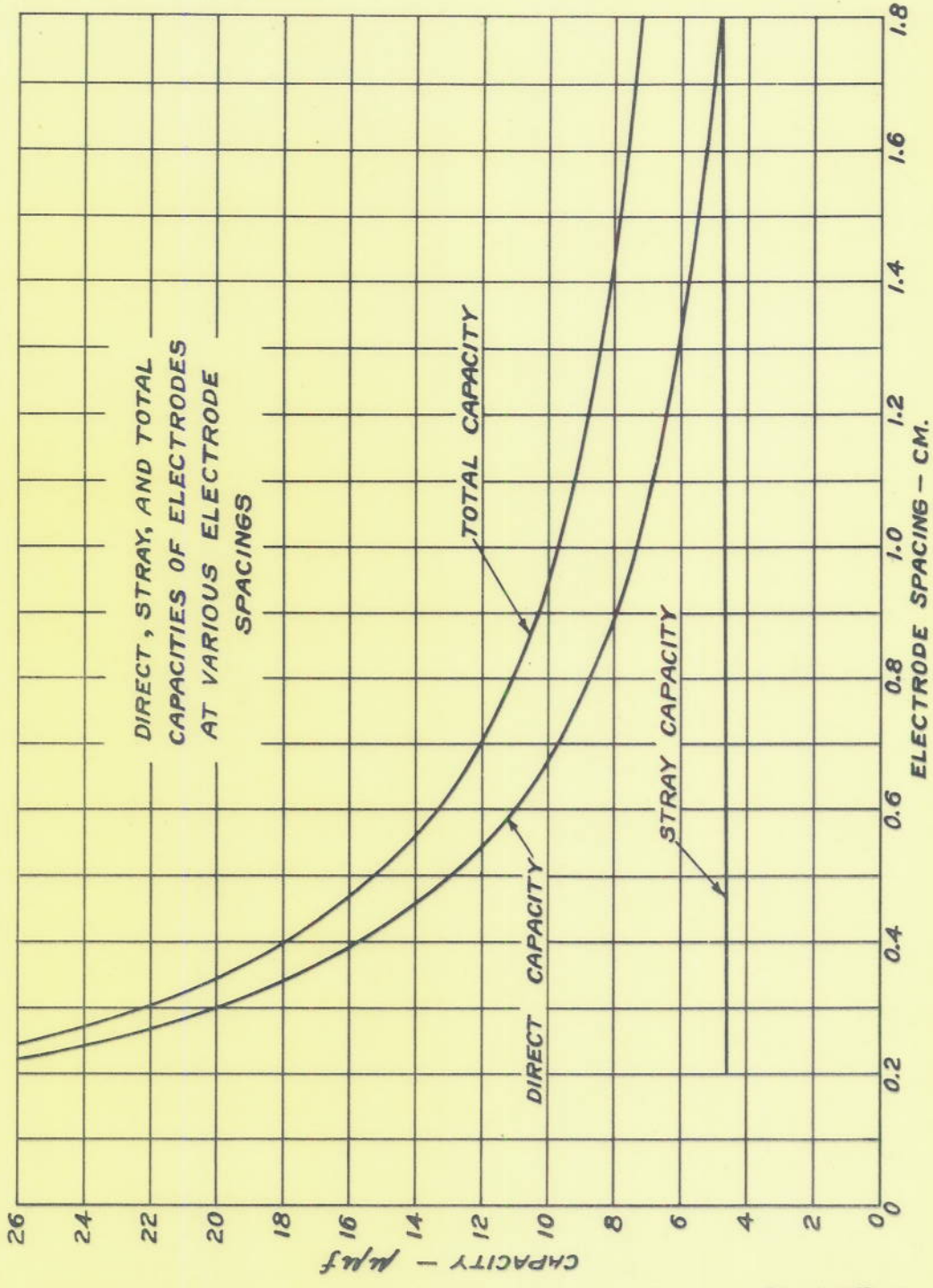
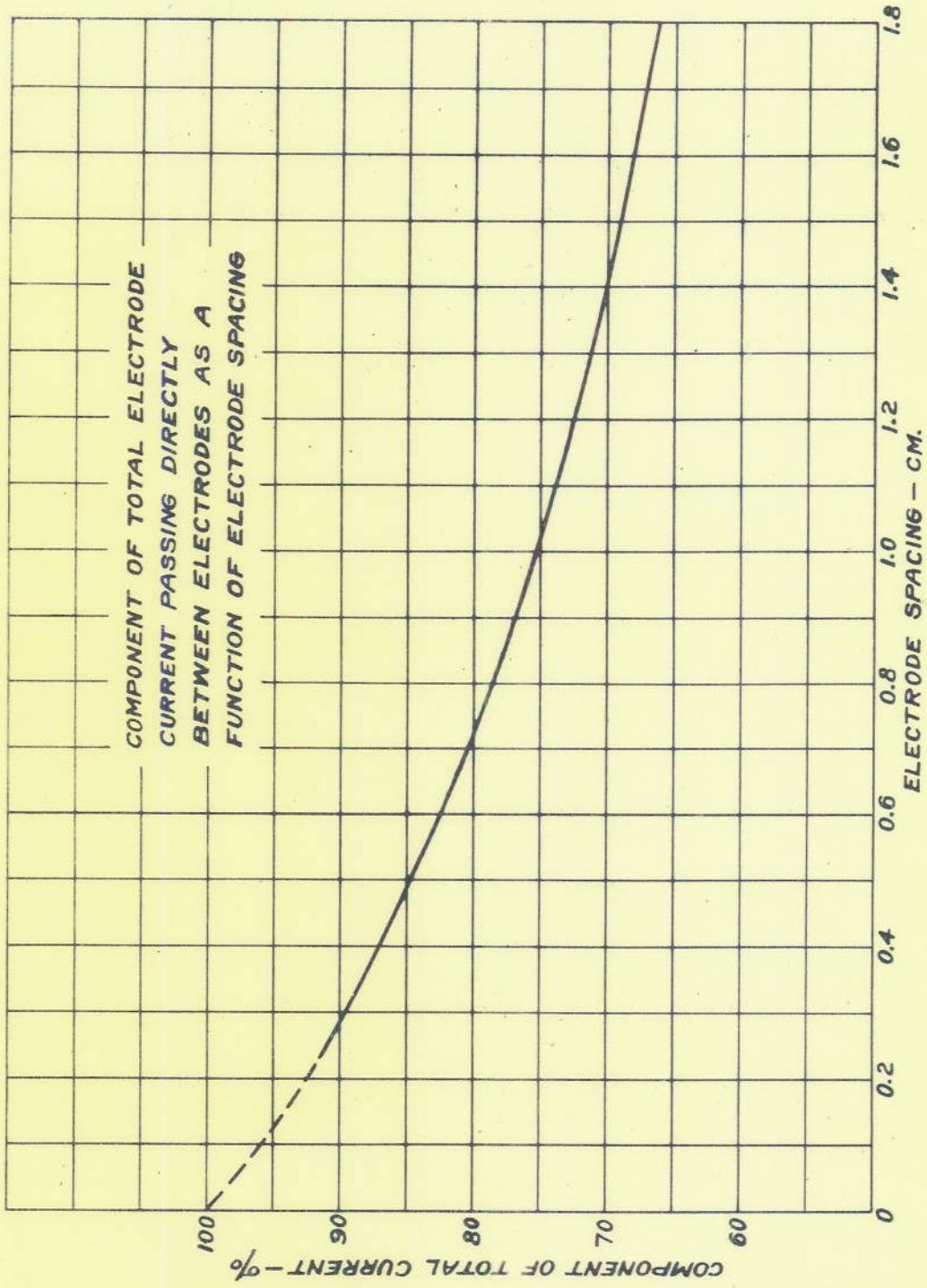
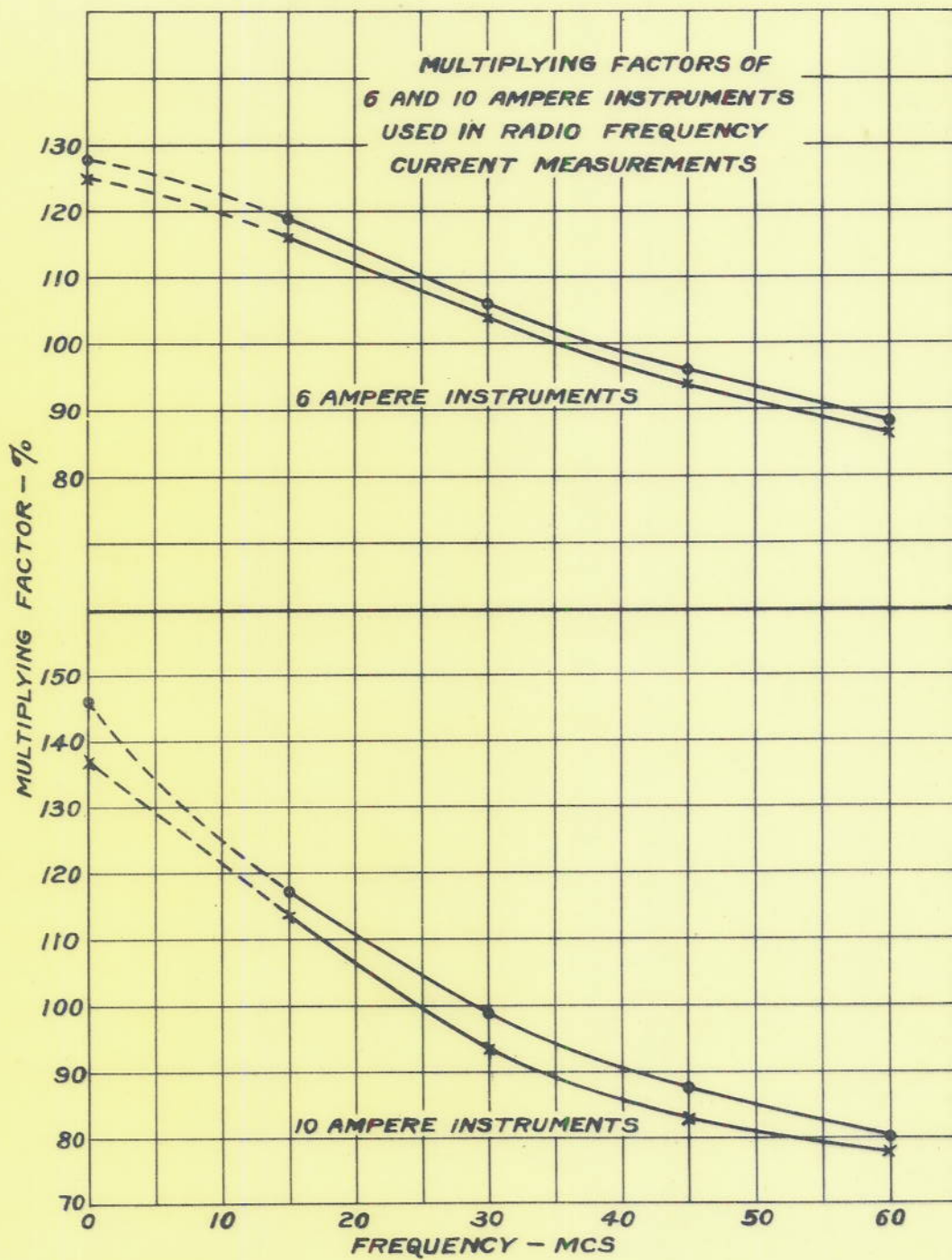
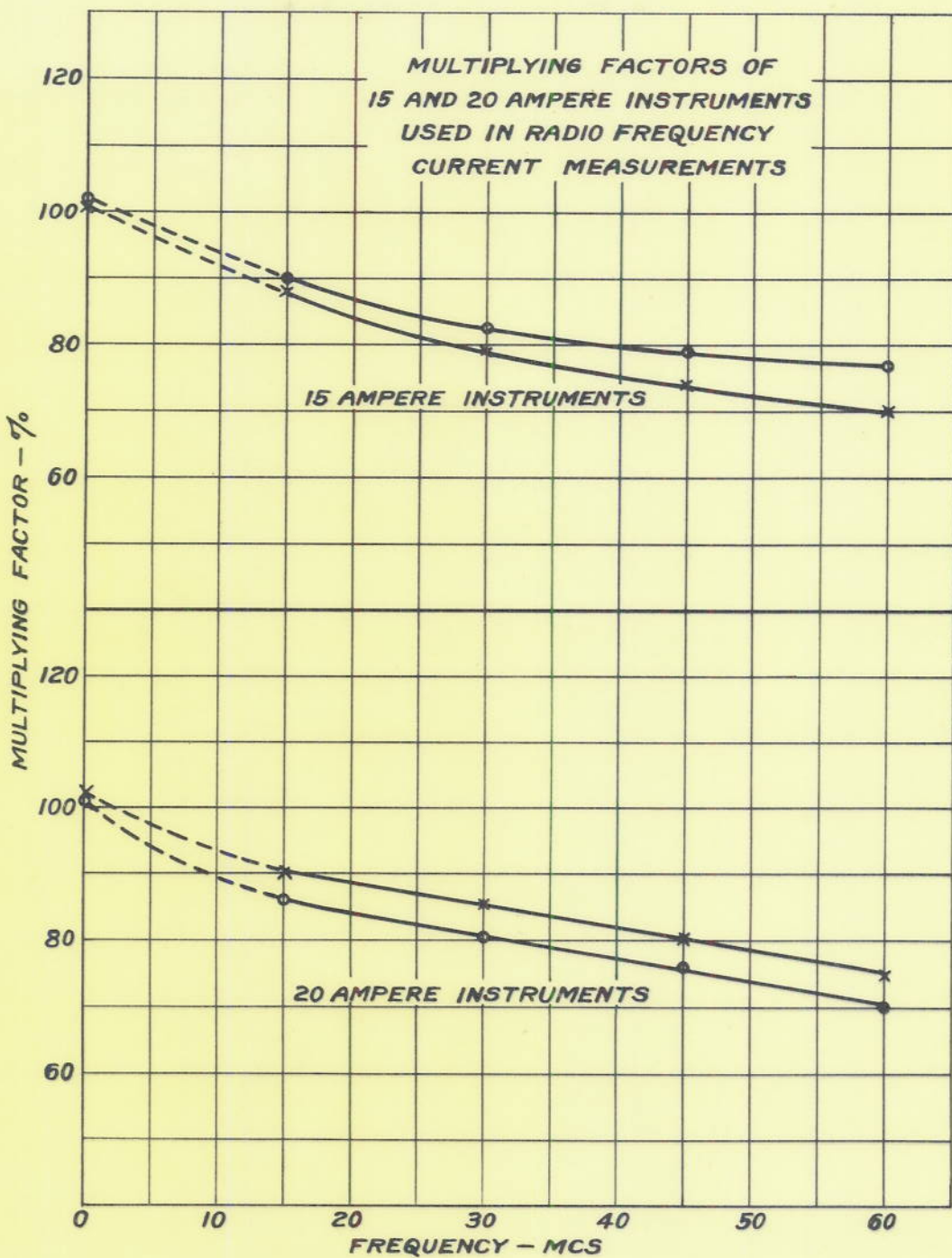


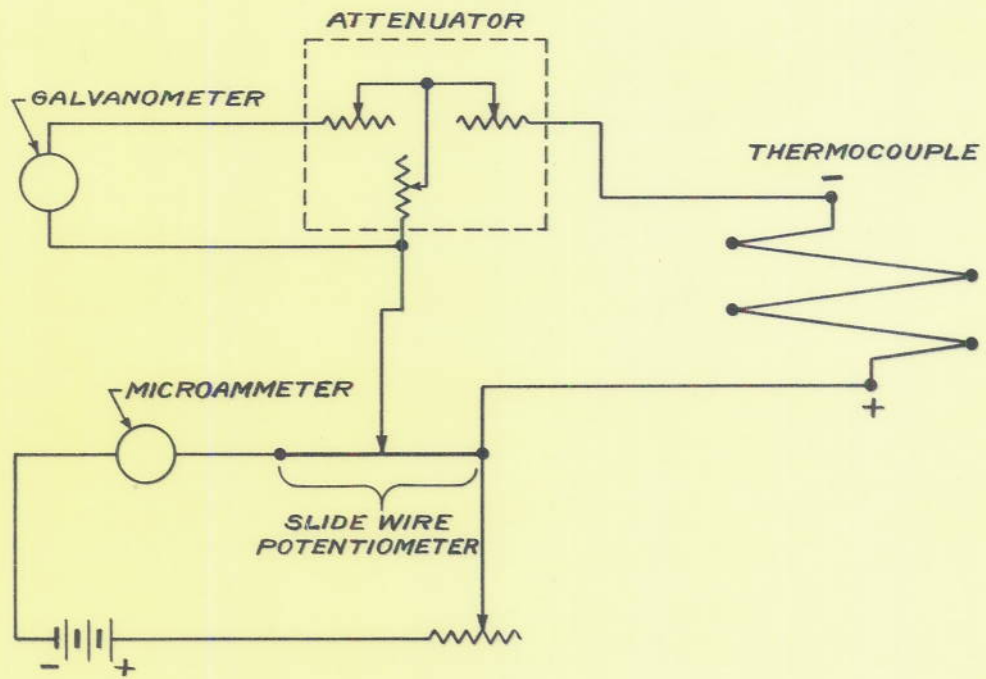
PLATE 5



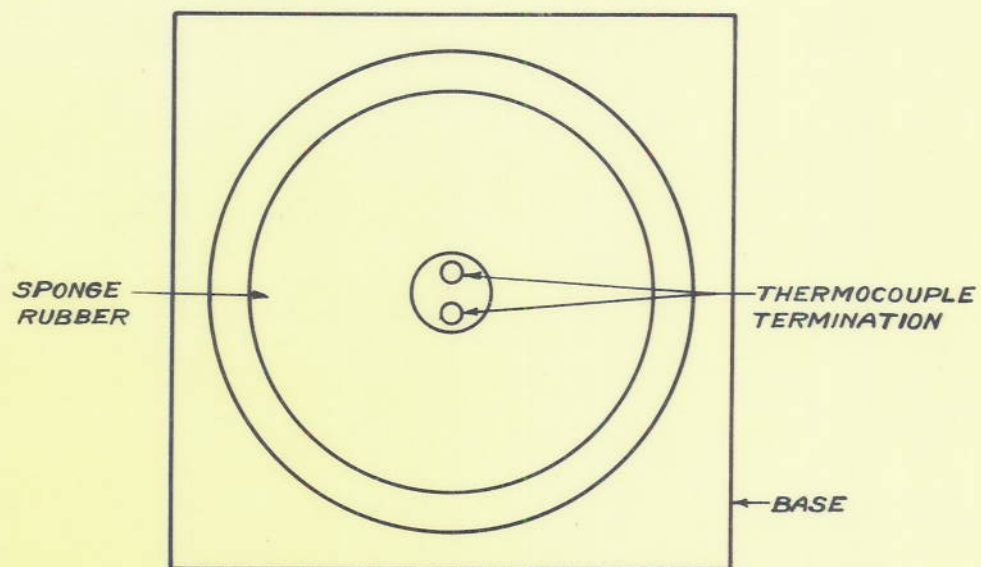
9 PLATE 6



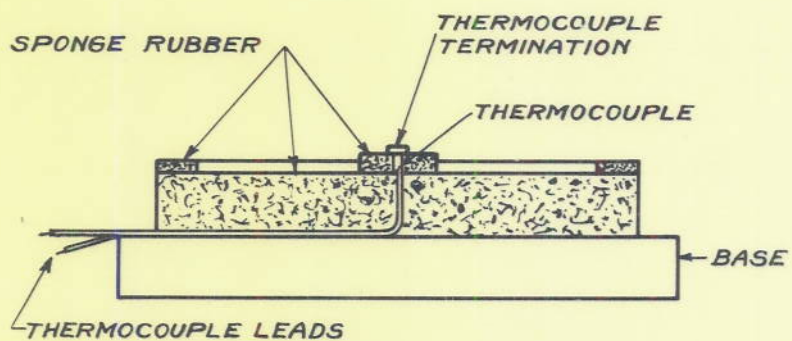




CIRCUIT OF EQUIPMENT USED IN MEASUREMENT OF TEMPERATURE RISE



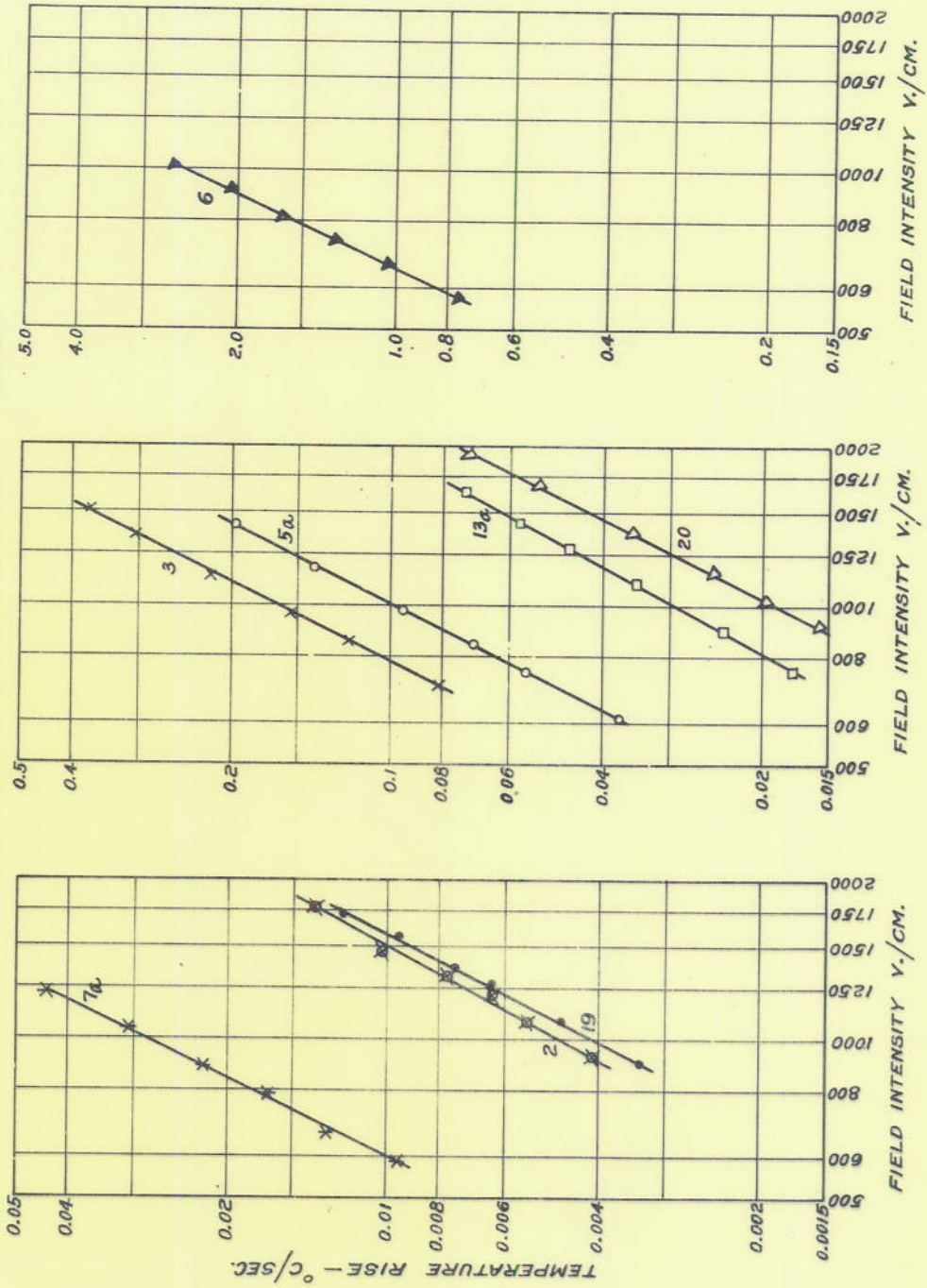
TOP VIEW

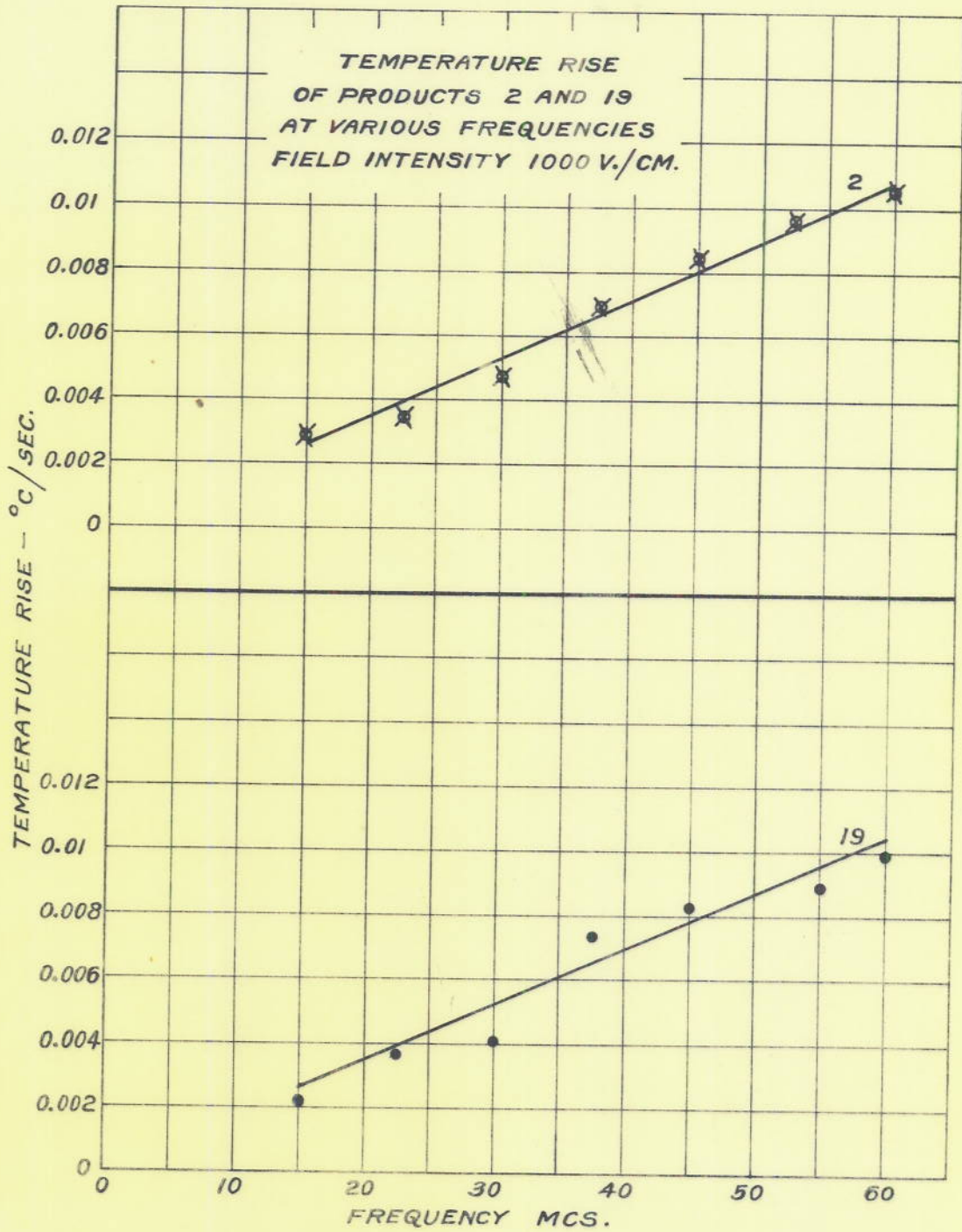


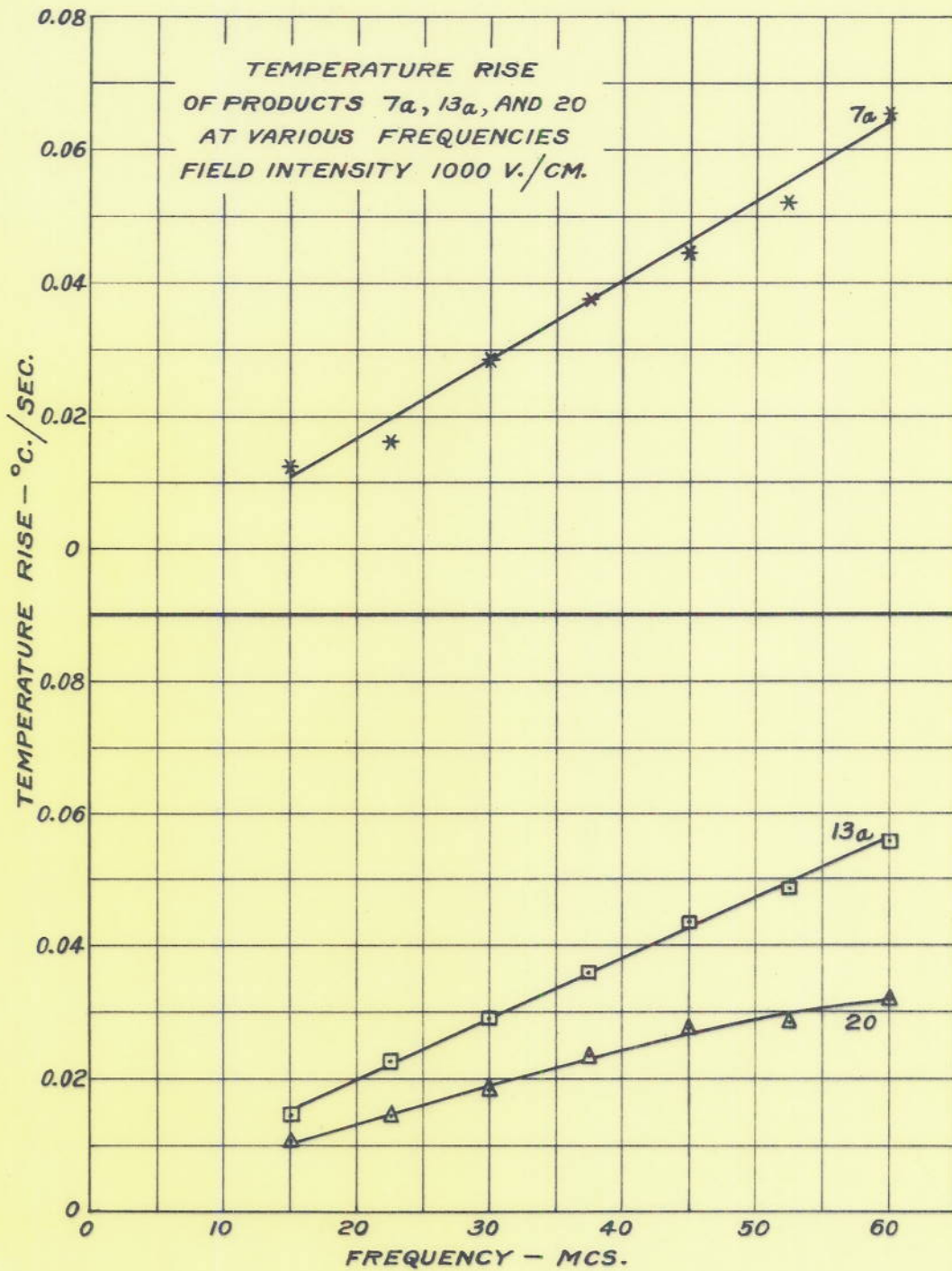
SECTIONAL VIEW

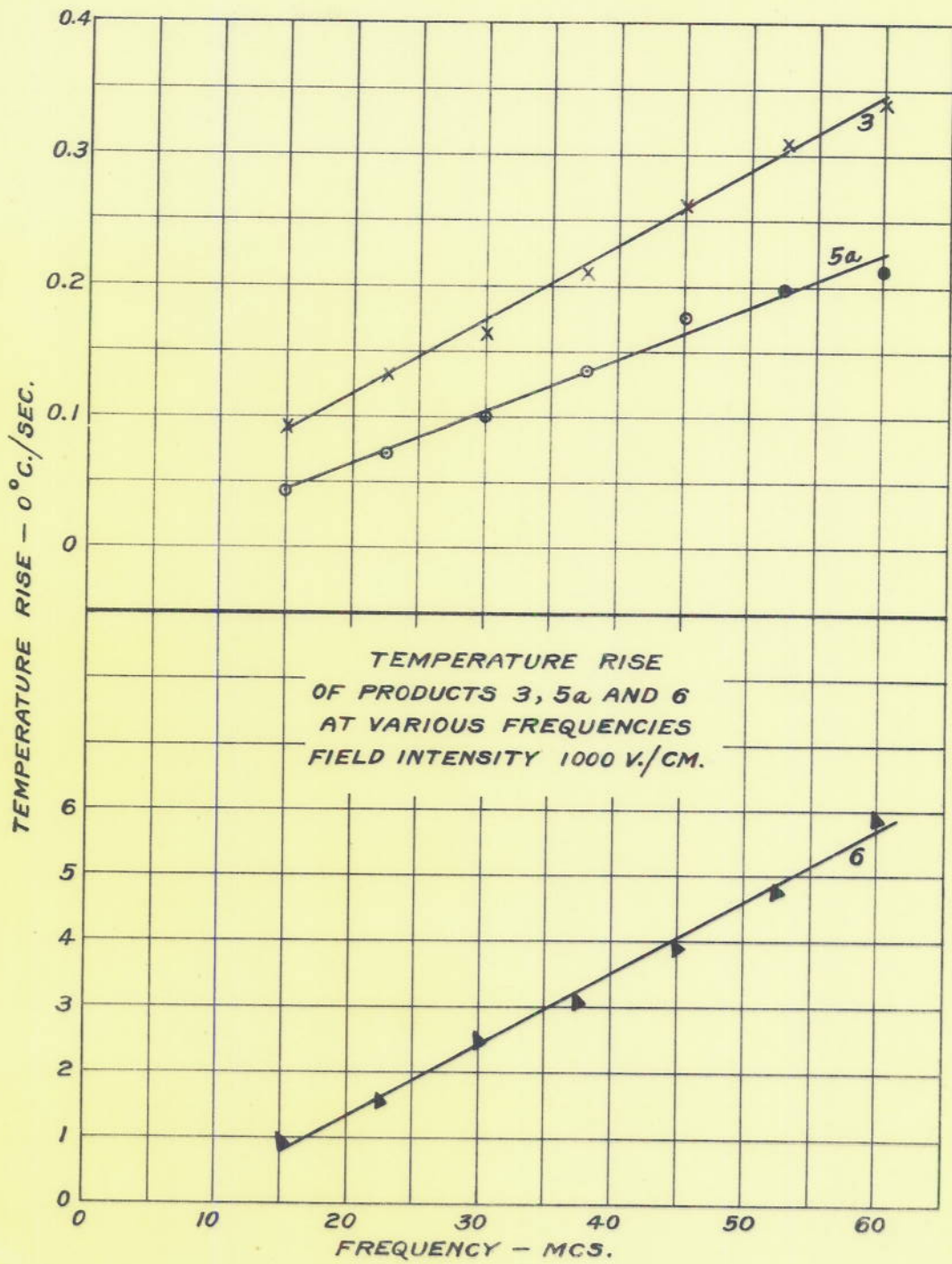
TERMINATION AND MEANS OF MOUNTING THERMOCOUPLE

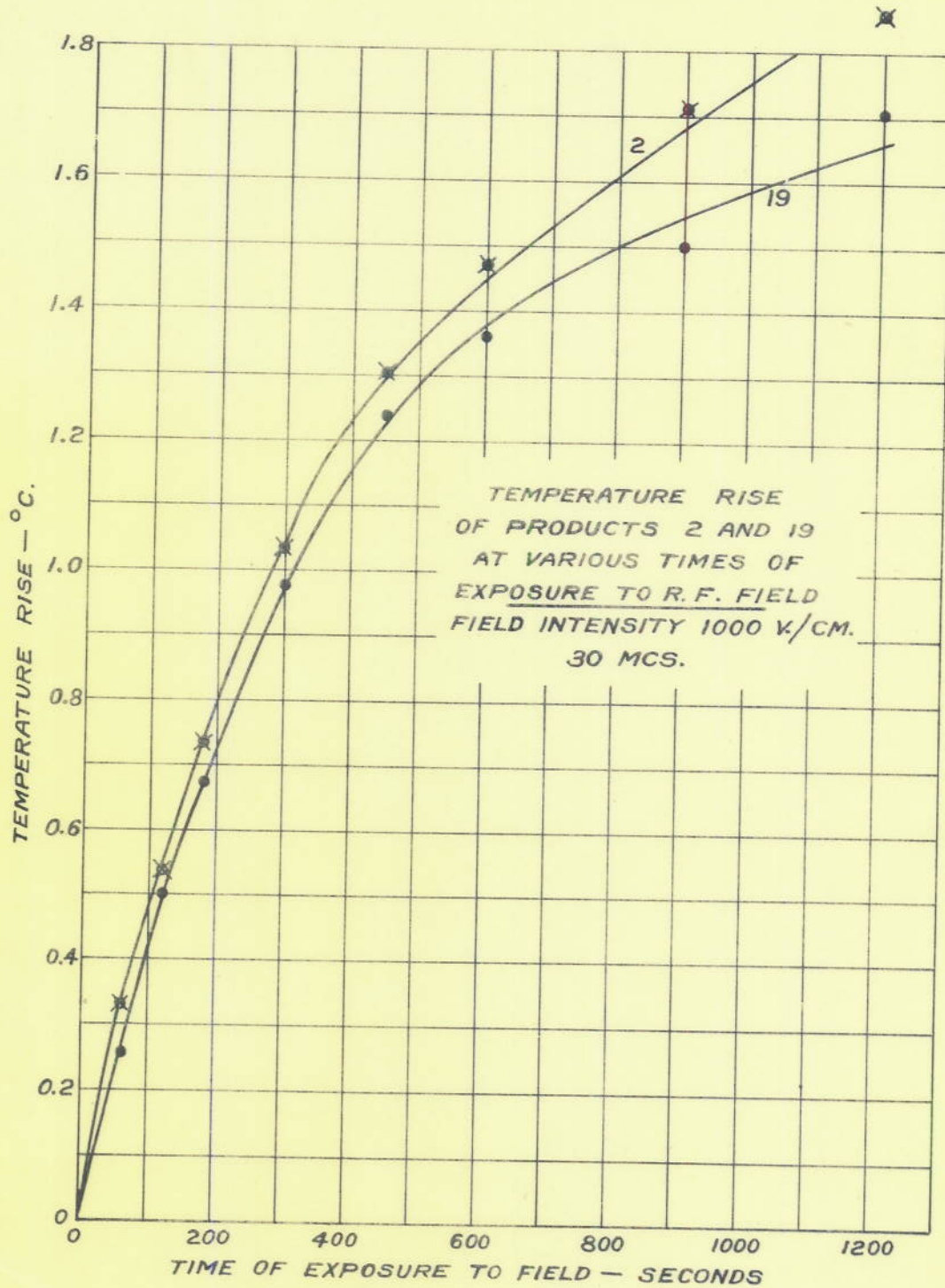
TEMPERATURE RISE OF SEVERAL MATERIALS AT VARIOUS VALUES OF FIELD INTENSITY — 30 MCS.

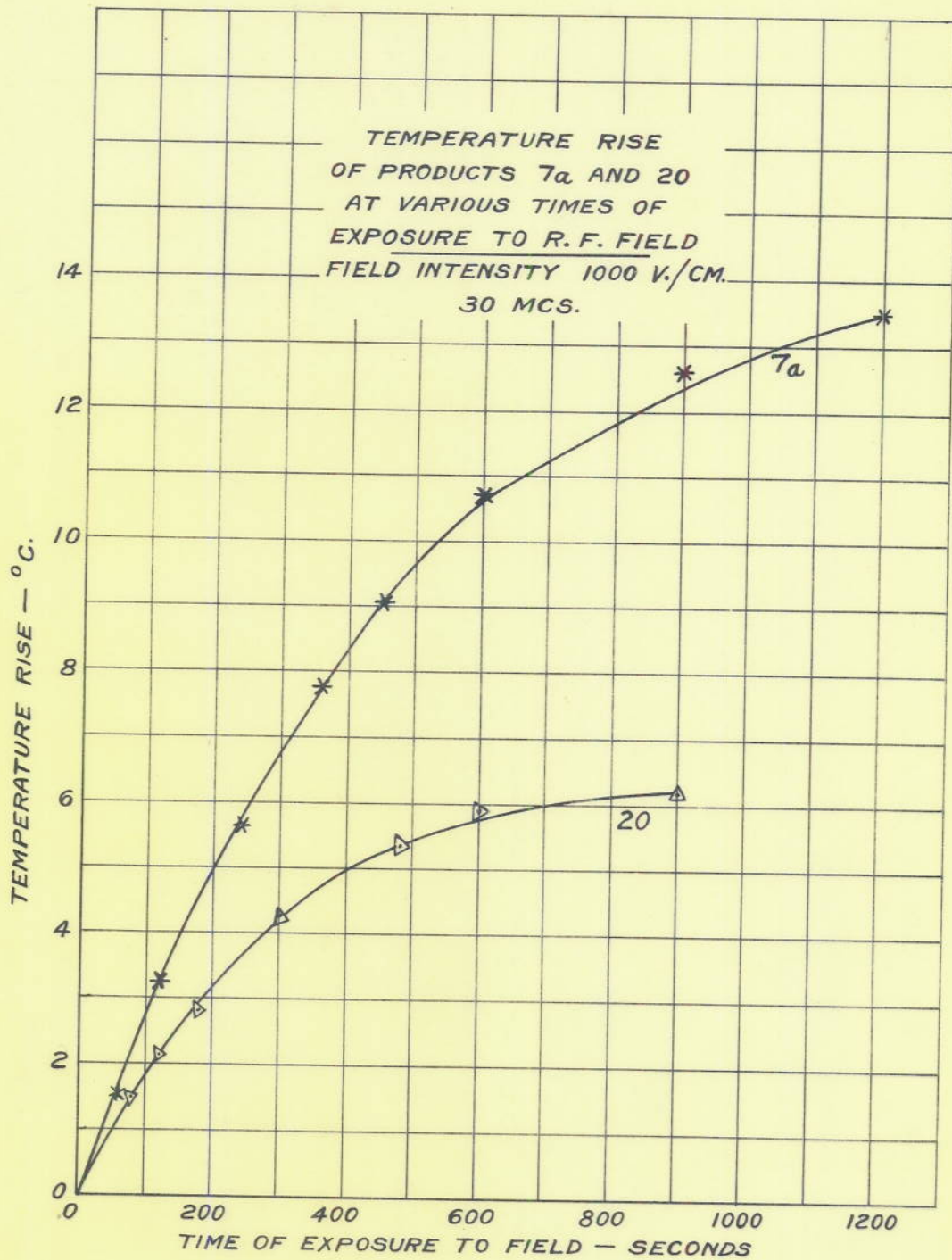




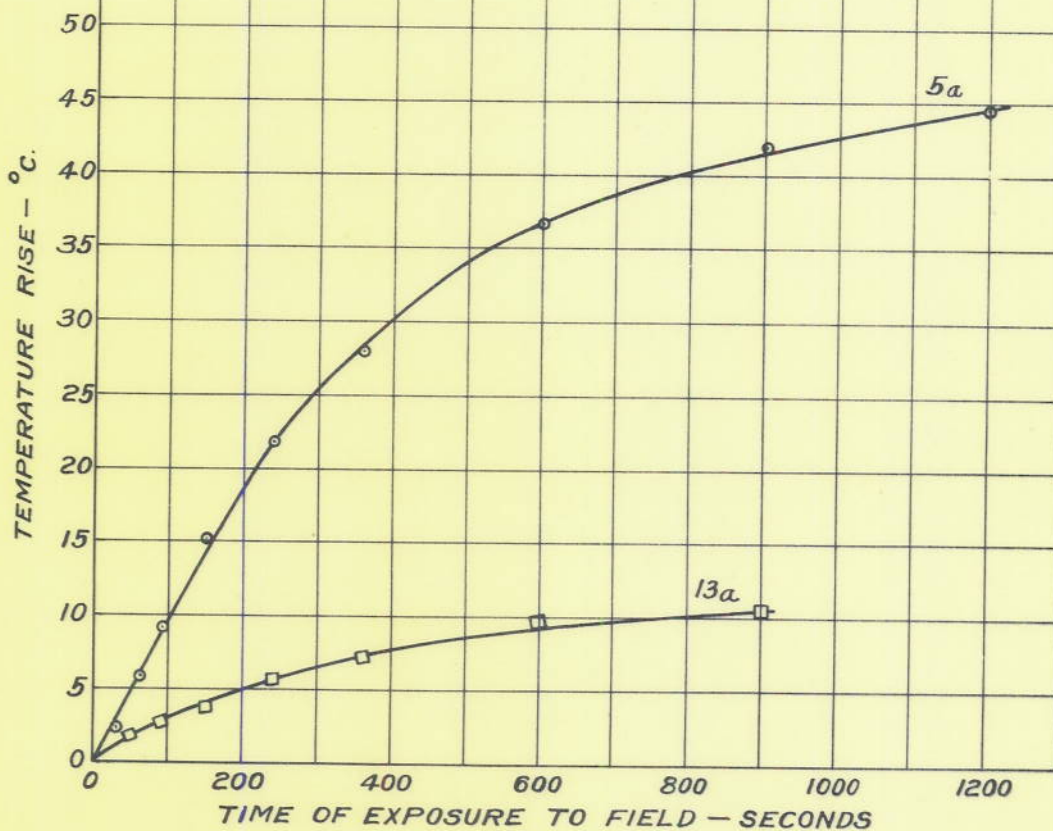








TEMPERATURE RISE  
OF PRODUCTS 5a AND 13a  
AT VARIOUS TIMES OF  
EXPOSURE TO R. F. FIELD  
FIELD INTENSITY 1000 V./CM.  
30 MCS.



TEMPERATURE RISE  
OF PRODUCTS 3 AND 6  
AT VARIOUS TIMES OF  
EXPOSURE TO R.F. FIELD  
FIELD INTENSITY 1000 V./CM.  
30 MCS.

