DEPARTMENT OF COMMERCE AND LABOR

CIRCULAR

OF THE

BUREAU OF STANDARDS

S. W. STRATTON, Director

No. 36

THE TESTING AND PROPERTIES OF ELECTRIC CONDENSERS

[1st Edition]
Issued June 30, 1912

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I. INTRODUCTION

Since the organization of the Bureau of Standards, considerable attention has been given to the subject of electrical condensers, and several papers upon this subject have been published in the Bulletin. In addition to the results obtained in these investigations, much information has been accumulated as a result of the testing of a great many condensers. This Circular aims to give concisely the most important facts available concerning the most important types of condensers.

Within a few years the demand for condensers for commercial uses has increased many fold. At present they are extensively used in telephony, telegraphy, radiotelegraphy, in gas-engine practice, and for many other purposes. With this increased demand there has been a marked improvement in the quality of the condensers manufactured. This has been due not only to scientific researches and to tests which showed defects in the condensers, but also to the serious efforts of manufacturers to overcome the defects shown by the tests. As many of the facts concerning condensers are not readily accessible to all those who have occasion to use them, they have been brought together in this Circular in the hope that the manufacturers of condensers may still further improve their quality and that the users of condensers may more readily select those condensers which are adapted to their needs.

II. CLASSES OF CONDENSERS AND THEIR PROPERTIES

1. IDEAL CONDENSERS

An ideal condenser would have a constant capacity under all circumstances, with zero resistance in the leads and plates of the condenser, infinite resistance between the plates, and no absorption in the dielectric. The capacity of such a condenser would be independent of changes in the temperature, atmospheric pressure, or other external conditions, as well as independent of the voltage, frequency, length of charge and discharge, and all other modifications of the circumstances under which it is measured. When used on an alternating-current circuit, the current flowing through this ideal condenser would be 90° ahead of the simple harmonic electromotive force impressed upon the condenser, and therefore the energy loss would be zero. A well-constructed air condenser having heavy metal plates and suitable insulating supports approximates sufficiently well to an ideal condenser to be used as a primary standard of capacity.

2. AIR CONDENSERS

Air condensers are of two classes, (a) condensers of which the capacity can be accurately computed from the measurements of linear dimensions of the condenser, sometimes called absolute condensers, and (b) condensers of which the capacity is necessarily obtained by electrical measurements.

Absolute condensers must be of regular geometrical form, rigidly constructed, and capable of having their dimensions accurately measured. The simplest forms to construct which permit precise measurement and accurate calculation of the capacity are (a) two concentric spheres, (b) two coaxial cylinders, and (c) two parallel circular plates. In (b) guard rings are necessary at the ends of one of the cylinders, and in (c) a guard plate is necessary around one of the circular plates. Connecting wires for charging and discharging the condenser must be employed and correction made for their capacity.

Although the capacity of such condensers is necessarily small, absolute standards of high precision have been constructed.[1] Their use is, however, very limited, and, except for special purposes, standards of larger capacity are more convenient.

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[1] Rosa and Dorsey: Bulletin of the Bureau of Standards, 3, p. 433; 1907.

Air condensers the capacities of which are determined by electrical measurements rather than by calculation from their dimensions are indispensable in many kinds of experimental work. They should be so constructed that the resistance to the charging current is very small, that no other dielectric than air is concerned (no solid or liquid substance between the plates), and that the resistance between the two sets of plates is very high. Such a condenser shows no absorption, so that its capacity is independent of the method of measurement, except at excessively high frequencies or very high voltages. At high voltages there may be a brush discharge between the plates, so that the conduction through the dielectric becomes appreciable. At extremely high frequencies the resistance of the plates and their connections is appreciable in any condenser which can be constructed, so that the current will not be quite 90° ahead of the impressed emf, and hence the power factor will not be zero. For mechanical reasons the plates of an air condenser must be rather thick, and must be placed 1 or 2 millimeters apart. Hence, the capacity which can be secured by such a condenser is always small.

3. MICA AND PAPER CONDENSERS

The capacities required in many kinds of experimental work are much greater than can readily be secured with air condensers. Hence, condensers using (a) tin foil and mica, (b) silvered mica, or (c) tin foil and paraffined paper have long been employed, and a capacity perhaps ten thousand times as great as could be obtained with an air condenser of the same volume is secured. Such condensers, commonly called mica condensers, silvered-mica condensers, and paper condensers, respectively, are made and used in great numbers, and have been very thoroughly studied at the Bureau of Standards and elsewhere. Mica condensers are usually of much better quality than paper condensers, but even the best mica condensers do not approach as nearly to ideal condensers as do air condensers. If properly constructed, a mica condenser is only slightly influenced by changes of the temperature or of any other external condition. However, mica condensers do show absorption, so that the effective capacity depends on the method of measurement and the current flowing into the condenser is not quite 90° ahead of the impressed sinusoidal emf. But under any given condition of measurement the effective capacity and phase angle of a mica condenser are perfectly definite, so that they may be satisfactorily used as standards.

4. GLASS, OIL, AND COMPRESSED-AIR CONDENSERS

Where it is necessary to employ very high potentials, glass, oil, and compressed-air condensers are frequently used. The only advantage of a compressed-air condenser over an ordinary air condenser is its ability to stand higher voltages before a brush discharge begins. Oil condensers will stand much higher voltages than an air condenser with the same distance between the plates, and its capacity is about twice that of an air condenser of the same size. If a high-grade oil is used the absorption is very small.

The first condenser ever constructed was of glass, and the "Leyden jar" is familiar in all laboratories. It withstands very high voltages, but shows very pronounced absorption.

5. ABSORPTION IN CONDENSERS [2]

With the exception of air condensers, in all of the above types of condensers the phenomenon of absorption is to be found; that is, when a condenser is connected to a battery, in addition to the instantaneous charge there flows into the condenser for some time a small and continuously decreasing current which seems to be absorbed by the dielectric. Hence, the total quantity of electricity flowing into an absorbing condenser depends upon the time of charge. Similarly, the discharge is not instantaneous and the quantity discharged is greater with a long than with a short time of discharge. The relative amount of the absorbed charge varies greatly with the different types of condensers, as well as with different condensers of the same type. In the best mica and oil condensers the absorption is relatively small, while in paper and glass condensers it is much larger.

The quantity which flows into an absorbing condenser during an infinitely short charging period or which is discharged during an infinitely short discharge is called the free charge of the condenser. The ratio of this free charge to the potential difference between the plates of the condenser is called the geometric capacity.[3] It is very difficult in practice to make the time of charge or of discharge so short that only the free charge will be measured. Hence, the measured capacity is always larger than the geometric capacity by an amount which depends upon the length of charge or of discharge. But by several measurements of the capacity with different times of discharge or with different alternating-current frequencies, the geometric capacity can be obtained by extrapolation. Fig. 1 shows the method of obtaining the geometric capacity both by direct current and by alternating current.

If a condenser is rapidly charged and discharged, as is done in most of the methods for the absolute measurement of the capacity, the amount of the absorbed charge is relatively small and the capacity so measured will be only a little larger than the geometric capacity. However, in measurements of precision,[4] the absorption which takes place in a thousandth of a second or less may affect the result by an appreciable amount. Hence, it is important that the length of charge and of discharge shall be very definite. This is especially the case where the number of charges and discharges per second is relatively large, since the amount which is absorbed in the first thousandth of a second after making contact is much larger than in any equal interval afterwards, and likewise the rate at which the absorbed charge is given up decreases rapidly with the time. For example, if a condenser is charged and discharged a hundred times a second, the duration of each

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[2] A review of the various theories of absorption has been given by Grover, Bulletin of the Bureau of Standards, **7**, p. 518; Reprint 166.

[3] A. Zeleny, Phys. Rev., 22, p. 65, 1906; and Curtis, Bulletin of the Bureau of Standards, **6**, p. 478; Reprint 137.

[4] For data, see Bulletin of the Bureau of Standards, **6**, p. 434; Reprint 137.

charge and discharge is perhaps only three-thousandths of a second; and yet in this short interval the effect of absorption is shown, and the measured capacity will be appreciably different if the duration is one-thousandth of a second more or less than this.

In those methods of measurement where the time of charge and discharge is relatively long the absorbed charge is very often a considerable part of the total charge, so that care must be exercised if consistent results are to be obtained. For example, if the capacity is measured by charging the condenser by a key and then discharging it through a galvanometer, the duration of the charge and discharge and the interval between charge

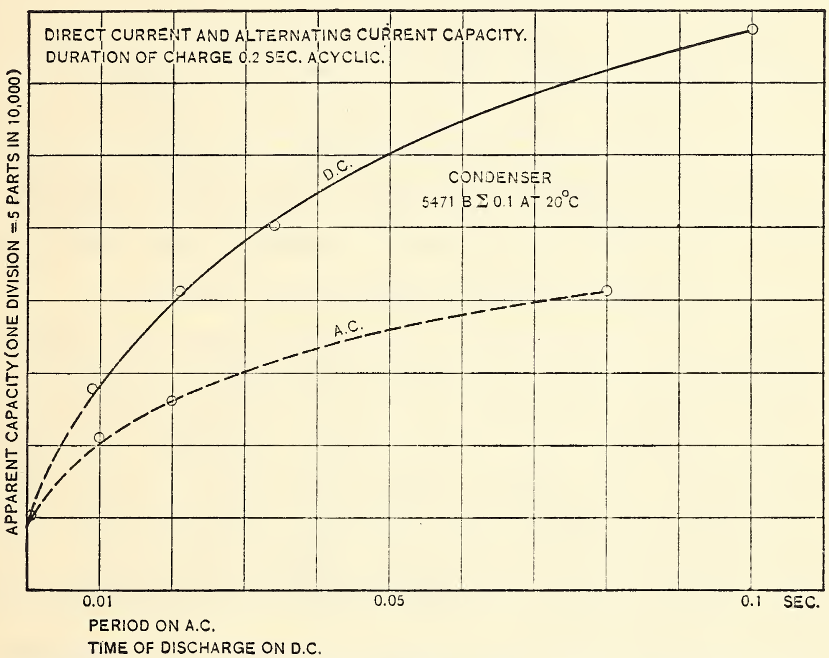

Fig. 1.—*Curves showing the method of determining the geometric capacity by extrapolation*

and discharge, as well as the interval of short circuit between discharge and a second charge, must all be carefully specified in order to be able to reproduce results, even with the accuracy obtaining with a ballistic galvanometer. Similarly, in comparing capacities by the method of mixtures,[5] the effects of absorption are so important that satisfactory results can not be obtained unless the various operations are performed with great regularity, though if two condensers could be found having identical absorption curves this would not be necessary.

[5] This method is described in Bulletin of the Bureau of Standards, 6, p. 441; Reprint 137.

In alternating-current measurements [6] the effect of absorption is to increase the measured capacity with respect to the geometric capacity and also to change the phase angle between the current and emf. The measured capacity decreases as the frequency increases, though this change is not large in the case of the best mica condensers. Also, since the time of charge and discharge is short, the capacity of a good condenser as measured by alternating current is never more than a few tenths of a per cent larger than the geometric capacity.

Since the effective capacity of an absorbing condenser depends upon the method of measurement, it is important that such a condenser should be standardized under the same conditions under which it is to be used. However, if the effective capacity is determined with three or more frequencies of alternating current, then from these values a curve can be constructed by means of which values at intermediate frequencies can be interpolated. Likewise, if the effective capacity is determined by direct current using different times of discharge, other conditions remaining constant, then values for intermediate times of discharge can be interpolated. Hence, a satisfactory knowledge of the effective capacity of a condenser under different conditions can be obtained by making several direct-current measurements and several alternating-current measurements.

6. TEMPERATURE COEFFICIENT OF THE CAPACITY

The capacity of a condenser will generally vary with the temperature. The temperature coefficient of the geometric capacity of a mica condenser [7] may readily be made very small. The Bureau possesses many condensers of which the temperature coefficient of the geometric capacity is smaller than one-hundredth of 1 per cent per degree centigrade. However, the absorption changes very rapidly with the temperature, so that with long times of charge and discharge, the temperature coefficient of the measured capacity may be quite different from that of the geometric capacity. Hence, where it is necessary to use a condenser at different temperatures, the temperature coefficient should be measured under the same conditions as those under which it is to be used.

Some condensers show slight changes of capacity with changes of the voltage used in measuring the capacity. Also, there may be slight changes of capacity due to variations in the barometric pressure. These effects are very small in a high-grade mica condenser, and need not be considered except in work of the highest precision.

7. ENERGY LOSSES IN CONDENSERS

In an ideal condenser there is no energy loss in the condenser and the current is 90° ahead of the impressed sinusoidal emf. With mica, paper, and all condensers other than air condensers, there is an energy loss

[6] For a discussion of alternating-current methods, see Grover, Bulletin of the Bureau of Standards, 3, p. 371, Reprint 64, and Curtis, same Bulletin, 6, p. 435; Reprint 137.

[7] Bulletin of the Bureau of Standards, 6, p. 447; Reprint 137.

in the condenser due to absorption, as well as that due to the resistance of the leads and plates and to conduction through the dielectric, so that the current is not quite 90° ahead of the impressed emf. The total loss of energy in a condenser may be determined by measuring the heat developed in it, but it can be obtained more readily by electrical measurements. The total energy loss in unit time is $2\pi n C E^2 \sin\theta$, where n is the frequency, E the impressed emf, C the capacity of the condenser and θ the phase difference (90° minus the phase angle). All of these quantities can be readily measured, and the total energy loss thus determined. It is more difficult, however, to separate the loss into its three components.

If the insulation resistance R is known, the energy loss in unit time due to conduction through the dielectric is $\frac{E^2}{R}$. For most condensers this is a negligible part of the total loss, and in all cases it is independent of the frequency. This part of the energy loss is readily determined, since the insulation resistance can be determined by direct-current measurements.

If the frequency is not so high as to affect the distribution of the charge on the plates, then the effective resistance of the leads and plates, r, is independent of the frequency. In this case the energy loss per second is I^2r or $4\pi^2n^2E^2C^2r$, which shows that the loss increases as the square of the frequency. For high frequency measurements this is very often the principal source of energy loss, though its accurate determination is difficult.[8]

The loss due to absorption does not obey a simple law. The loss per cycle decreases as the frequency increases, but with a given voltage the loss in unit time increases as the frequency increases. Hence, the phase difference of condensers with low plate resistance decreases as the frequency increases.

For a given condenser the per cent of the energy loss in unit time due to absorption varies with the frequency. At low frequencies the energy loss is largely due to absorption, but as the frequency increases the loss due to resistance in the leads and plates increases as the square of the frequency, while the loss due to absorption does not increase so rapidly. Hence, a point will be reached where the resistance loss will exceed the absorption loss. This is seen even in mica condensers with tinfoil plates, where the phase difference decreases until a frequency of several thousand is reached, when it begins to increase. However, the heating in a condenser always increases as the frequency increases, so that even a good condenser may become overheated when used on excessively high frequencies.

8. INSULATION RESISTANCE

For some kinds of measurements it is important that the insulation resistance of a condenser should be high. For instance, with direct current measurements it is important that no appreciable part of the charge should be lost in the interval between disconnecting from the battery and connecting

[8] A method of approximation is given in Bulletin of the Bureau of Standards, 7, p. 516, Reprint 166.

to the galvanometer. In alternating-current measurements the insulation resistance is usually so high that no appreciable part of the energy loss is due to conduction, though cases frequently arise where this is not the case.

If an absorbing condenser is connected to a battery, and the current flowing through the condenser is measured, this current decreases for some time, so that the true insulation resistance can only be obtained when the current reaches a steady state. In good condensers this will be reached in a few minutes, but in poor condensers it may require hours, or even days.

9. MAXIMUM VOLTAGE WHICH MAY BE SAFELY APPLIED TO CONDENSERS

In the case of condensers having a fluid dielectric no permanent damage results if a spark discharge takes place between the plates, but with a solid dielectric the condenser may be ruined. Hence, with glass, mica, and paper condensers it is necessary that the voltage should be kept below the value at which breakdown might occur. In some condensers discharge takes place around the edges of the plates with a lower voltage than is required to puncture them. Hence, it is impossible to formulate any rules which may be applied to all condensers.

The dielectric strength of glass and mica is high, while paper has a lower value. However, by using sufficient thickness of paper, a paper condenser can be constructed which will withstand high voltages. A paper condenser having two thicknesses of paper between the plates (as is usual in telephone condensers) will generally withstand 200 volts, alternating, without damage, provided the voltage is not applied for so long a time as to cause excessive heating. Frequently condensers are found which will withstand considerably higher voltages, but the above is considered to be the highest voltage to which the average paper condenser can be safely subjected.

The ordinary mica condenser may safely be used on 1000 volts, alternating, so long as there is not an excessive rise in temperature. In these condensers the mica is about 0.05 mm in thickness, and this does not puncture until a voltage of from 3000 to 5000 volts is applied. However, such condensers will frequently spark around the edge of the mica at 2000 volts.

Glass condensers usually have thick plates which will withstand 10 000 volts or more with safety.

With paper condensers, where the metal plates are very thin, accidental short circuits within the condenser can sometimes be remedied by applying a moderately high voltage for a short time. This causes a considerable generation of heat at the place of short circuit which melts the metal, causing it to recede by surface tension. In this way the condensers can again be made serviceable. The Mansbridge type of paper condensers has very thin plates, so that the above method is particularly applicable to them. It is even possible to stick a pin through such a condenser without doing serious damage to it.

III. AIR CONDENSERS [9]

Air condensers are extensively used where small capacities are desired. The largest values in common use are 0.02 μf. Below 0.005 μf, air condensers are frequently made so that one set of plates can be moved relatively to the other set, thus making a variable condenser. This may be accomplished by having each set of plates consist of half circles, one set of plates being pivoted to rotate about the common axis. Condensers of this type having a maximum capacity as small as 0.0001 μf and a minimum capacity of 0.00001 μf are sometimes used. In the range where it can be used, an air condenser has the following important advantages over a mica condenser.

1. An air condenser if properly constructed has negligible absorption, while a mica condenser of small value often shows relatively large absorption effects.

2. An air condenser can be made continuously variable, giving a large range of values in a single condenser.

3. The temperature coefficient of a well-constructed air condenser is only a few parts in a hundred thousand per degree, though with the larger sizes there may be buckling of the plates and other effects due to temperature changes which may cause an uncertainty of a few parts in ten thousand.

In the construction of air condensers certain precautions should be observed. The condenser should consist of an odd number of plates, so that the top and bottom plate belong to the same set, and the terminal to which this set is connected should be marked "earth." The whole condenser should be surrounded by a metal shield, which should be connected to the "earth" terminal. This will make the capacity independent of the presence of surrounding objects provided the condenser is properly connected while measurements are being taken. It is also important that no insulating material other than air should be allowed between the condenser plates. Otherwise there may be appreciable absorption. The resistance of all connections and contacts should be kept as low as possible. This is of especial importance in radiotelegraphy or other high frequency use, where the energy loss due to a small resistance may be troublesome.

In those variable condensers where the plates are half circles, the movable plates are not symmetrical about their axes of rotation. Hence, when such a condenser is being handled there may be danger that the movable plates will be thrown around violently, which may bend the pointer or otherwise change the adjustment. This may be prevented by using a friction washer or similar device. Three methods of overcoming this difficulty are in use. In one each set of plates consists of 90° sectors of circles. These are then arranged symmetrically with regard to the axis, so that the moving set of plates is balanced in all positions. This has the disadvantage that the scale is only one-half as long as when the plates are half circles and that the mimimum capacity is larger. Another method is to use half-circle plates, but to place half on one side of a plane through the axis and

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[9] A very thorough study of air condensers as standards has been made by Giebe. (See Zs. f. Instrk., 29, p. 269; 1909.)

half on the opposite side of this plane. This has the advantage of a 180° scale, but the minimum capacity is not as small as when the plates are all on the same side of the axis. The third method is to use half-circle plates all on one side of the axis and to counterbalance by a weight.

IV. MICA CONDENSERS

Mica condensers are almost invariably used as standards of capacity for values greater than 0.1 microfarad, and are often used in the range from 0.1 to 0.001 microfarad.

On account of this use as standards of capacity, their properties have been extensively studied. They may be divided into two classes: (1) Tinfoil and mica condensers, and (2) silvered mica condensers.

In the silvered-mica condensers, the thin sheets of mica are coated with a layer of silver in the manner used in coating a mirror. After removing the silver for a distance of about a centimeter from the edge, the sheets of silvered mica are laid up with sheets of tinfoil between them, and after clamping securely the whole is impregnated with paraffin, or other insulating material to prevent leakage around the edges.

The tinfoil and mica condensers are made in the same way except that the coating of silver is omitted and the insulating material is invariably paraffin. With these condensers it is important that all air and moisture should be removed, so that they are impregnated with paraffin either by boiling in paraffin in a vacuum or at atmospheric pressure. In this way the paraffin forms a layer between the tinfoil and mica, so that the dielectric consists of both mica and paraffin. For this reason they are sometimes referred to as paraffin-mica condensers. (The quantity of paraffin should be reduced to a minimum by squeezing out the surplus.) Silvered-mica condensers almost invariably show such changes in capacity with change of voltage,[10] that they can not be considered in selecting standards of the highest precision. Hence, paraffin-mica condensers are the more important class of mica condensers, and the following discussion will apply to them unless silvered-mica condensers are specifically mentioned.

1. ABSORPTION IN MICA CONDENSERS

The one thing that distinguishes the behavior of a mica condenser from that of an air condenser is the absorption which the mica condenser shows. Various theories of absorption have been advanced to account for the observed facts, but as yet they are all imperfect. However, it is very certain that any conducting particles in the dielectric will increase the absorption. In the manufacture of condensers, therefore, great care should be exercised to keep all extraneous materials out of the condenser, both by using the best mica and the highest grade of paraffin and by keeping the whole as free from moisture and other contamination as possible. But even with the greatest care all mica condensers will show some absorption.

[10] Bulletin of the Bureau of Standards, 6, p. 461; Reprint 137.

There are two factors which must be considered in dealing with absorption phenomena, viz, the total amount of electricity absorbed and the rate at which it is absorbed. This is illustrated by means of the curves of Fig. 2, which are typical curves, showing the rate of absorption of different condensers. It is supposed that the condensers are thoroughly discharged, then connected to a battery and allowed to charge. The absorbed charge is plotted against the time of connection to the battery. In *A* it will be seen that the charge is absorbed slowly at first but continues at nearly the

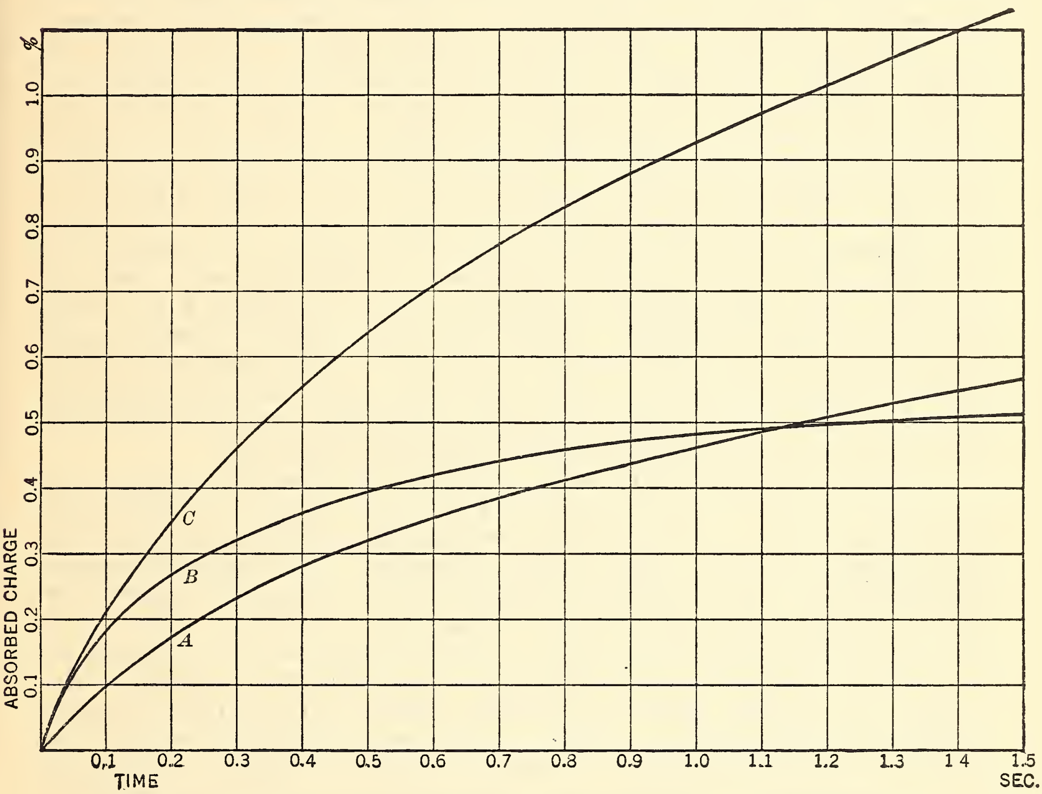

Fig. 2.—*Typical curves showing the rate at which condensers give up their absorbed charge*

same rate for some time, while *B* absorbes rapidly at first, but the rate decreases rather rapidly. For small times of charge and discharge, such as used in alternating-current measurements and in some absolute measurements, a condenser whose absorption curve is represented by *A* will be preferable, while with long times of charge and discharge, a condenser whose absorption curve is represented by *B* is to be preferred.

If the absorption curves of two different condensers were similar, as in the case represented by curves *A* and *C* of Fig. 2, where the absorption of C is always twice that of A, then if the condenser whose curve is A has been carefully studied, any one measurement in which the effect of the absorption of condenser C is involved would serve to show how the condenser would behave in any other measurement where absorption enters. But two such condensers are seldom or never found in practice. Hence, it is necessary to study each condenser independently, though approximate conclusions can sometimes be drawn from one or two measurements.

For direct-current work where relatively long times of charge and discharge are used, the following arbitrary method has been found to be of some service. Charge the condenser for 1 second, insulate it for 1 second, then short-circuit it for 1 second and insulate again. At the end of 30 seconds quickly discharge the accumulated residual charge through a ballistic galvanometer whose constant is known. Insulate again for 30 seconds and discharge through the galvanometer. Continue until five residuals have been measured. The ratio of the sum of the first five residuals to the original free charge is called the per cent absorption, and for a good mica condenser ranges from 0.2 per cent to 1.0 per cent. This does not represent the total absorbed charge of the condenser. A large part is lost during the second that the condenser is short-circuited. Also the absorbed charge will continue to come out of the condenser for a much longer time than 2.5 minutes. Cases have been observed where a good mica condenser which had been short-circuited for a week gave a measurable residual charge on standing on open circuit for only one minute; but the method of procedure described does give a comparative test for condensers which are to be used with long times of charge and discharge.

A method which seems to be more useful is to measure the capacity of the condenser with two or more times of discharge, using the same time of charge in each case. Then with these values of the capacity, together with the geometric capacity (most easily determined by alternating-current measurements) a curve is plotted which shows the change in capacity for different times of discharge but with the same time of charge. The curves of two condensers are shown in Fig. 3. These curves show the amount of the absorbed charge liberated in the first second after the condenser is discharged. For longer times of discharge, values of the capacity can be obtained by extrapolation. Curves of this same character can also be drawn for other times of charge, so that by means of a family of curves, the effect of absorption on direct-current measurements can be very completely expressed.

In the preceding paragraph it was assumed that the condenser was completely discharged between every set of measurements. This requires considerable time, so that for some kinds of measurement a more rapid method is to be desired. This has been accomplished at the Bureau of Standards by using a cyclic method of charging and discharging. In this method the condenser is charged and discharged at regular intervals. For instance, the condenser may be charged for 0.6 second, discharged for 0.5 second, left on open circuit for 0.9 second, then again charged for 0.6 second, etc., each process being repeated every 2 seconds. In this the absorbed

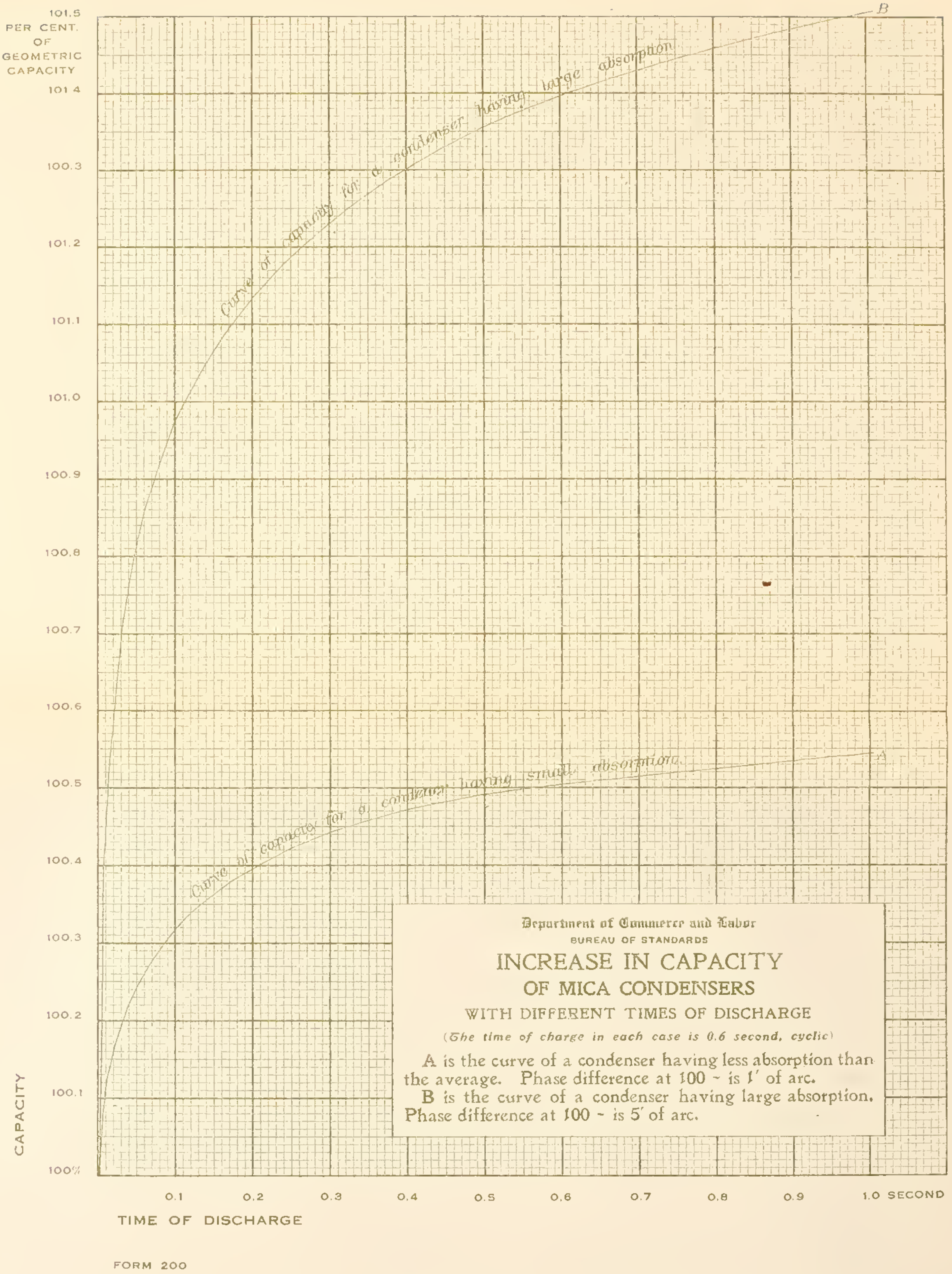

Fig. 3—*Curves showing the effective capacity of a good and a poor mica condenser with different times of discharge, the time of charge being 0.6 second, cyclic.*

NOTE.—A sheet identical with this, but having the results of the condenser under test plotted upon it, is furnished with each condenser tested according to the method indicated on page 25.

charge from one cycle is given up in the discharges of several following cycles. For a few cycles after the operation begins, the discharges increase, but they soon become stationary. It is evident that with the same time of charge and discharge in each case, the capacity determined from the discharge of a condenser which is being charged and discharged cyclicly will be greater than the capacity determined by the acyclic method where the condenser is completely discharged between readings.[11] Experience has shown that for good mica condensers the acyclic capacity using 1-second charge is nearly the same as the cyclic capacity using 0.6-second charge (the cycle being 2 seconds) for all times of discharge shorter than 1 second.

In alternating-current work absorption produces two effects; (1) it increases the phase difference and (2) it increases the effective capacity. While the resistance of the leads and plates as well as the insulation resistance between the plates produce an effect upon the phase difference, yet with good mica condensers these effects at ordinary frequencies are nearly, if not quite, negligible, so that the phase difference is an indication of the absorption with very short times of charge and discharge.

To show the possible effect of series resistance and leakage, it may be noted that if the insulation resistance of a microfarad condenser is as low as 300 megohms the phase difference due to leakage is only 1 second at 100 cycles, and that it would be less at higher frequencies. Also the addition of 0.01 ohm in series with a microfarad condenser increases the phase difference at 100 cycles by 1 second and the phase difference due to this resistance increases directly as the frequency. In high-frequency work this may become troublesome, but with a well-constructed condenser it is quite negligible at ordinary frequencies.

Since both the phase difference and the difference between the geometric capacity and the effective capacity depend at any frequency upon absorption phenomena taking place in the same interval of time, an attempt has been made at the Bureau of Standards to obtain a relation between these two quantities which will hold for all condensers. From measurements on a number of mica condensers the following empirical equation was determined:

$$\frac{(C_1-C)}{C_1}=0.000\,006\alpha;\ \text{or}\ C=C_1(1-0.000\,006\alpha)$$

Where C is the geometric capacity, C_1 the effective capacity at 100 cycles, and α the phase angle at 100 cycles (expressed in seconds of arc). For other frequencies the constant would be different. This gives an easy means of determining the geometric capacity from measurements of the capacity and phase angle at 100 cycles. With good mica condensers the error in the geometric capacity determined by the above formula will never be more than one-tenth of 1 per cent, and it will often be only one or two hundredths of 1 per cent.

[11] For curves showing the amount of this difference with different times of charge, see Bulletin of the Bureau of Standards, 6, p. 486; Reprint 137.

Various measurements in which absorption plays an important part are given for eight condensers in Table I.

TABLE I

Absorption Constants of Mica Condensers

Condenser	Temp.	Phase difference			Per cent absorption	Amount effective capacity is greater than geometric capacity in parts in 100 000					
						Alternating-current measurements			Direct-current measurements		
		50 cycles	100 cycles	1200 cycles		50~	100~	1200~	0.2-sec. charge, 0.1-sec. discharge	0.6-sec. charge, 0.1-sec. discharge	0.6-sec. charge, 1-sec. discharge
1038, 0.1	20°	1′ 30″	1′ 10″	50″	0.25%	112	96	14	252	372	629
1038, 0.2+0.2′	20	1 30	1 20	50	0.30	60	48	7	210	345	615
5471B, 0.1	20	1 30	1 20	40	0.25	132	85	10	195	319	541
5471B,Σ 0.1	20	2 50	2 0	1′ 0	0.62	213	153	18	330	535	1038
5471B,Σ 0.1	30	4 0	3 0	1 20	1.05	295	215	28	...	827	1552
5471A, 0.1	25	1 30	1 10	30	0.25	44	30	5	168	275	467
7377	20	55	30	. ..	0.25	20	10	2	128	205	391
No. 3	20	6 10	5 20	3 20	0.65	316	238	47	708	984	1510

The per cent absorption, the phase difference for three frequencies, and the increase of the effective capacity over the geometric capacity under different conditions are given for each condenser. In every case the geometric capacity was determined by plotting the values of the effective capacity at 50, 100, and 1200 cycles as ordinates with the period (reciprocal of the frequency) as abscissa and extrapolating to zero period. This gives the capacity independent of any absorption, so that the changes given in the table are those due to absorption. It should be noticed under the changes in capacity in direct-current measurements that the first two columns show the changes with the same time of discharge but different times of charge, while the last two columns show the changes with the same time of charge but different times of discharge.

These are all good mica condensers. Yet, an examination of the table shows how difficult it is to draw general conclusions. It has already been shown that an approximate relation holds between the phase difference and the change of capacity with frequency. Also the per cent absorption is relatively large with those condensers whose capacity changes rapidly when there is a change in the length of charge or of discharge. For a standard condenser it is very desirable that all of the constants due to absorption phenomena shall be as small as possible.

2. THE EFFECT OF TEMPERATURE

The effect of temperature changes upon the capacity of a mica condenser may be classed under two heads, viz, (a) permanent changes in the capacity caused by temperature changes and (b) changes which disappear when the condenser is returned to its original temperature.

(a) PERMANENT CHANGES

Formerly it was quite customary in the manufacture of condensers to depend upon the adhesive power of the paraffin between the plates to hold them together. Then, whenever the condenser was heated to near the melting point of paraffin there would be considerable readjustment, which would change the capacity very decidedly. This has been materially improved by clamping the condenser, preferably between plates of metal. But if this is done when the condenser is cold there will be a readjustment of strains when the condenser is warmed to the softening point of paraffin, and again there will be a change in capacity, in this case an increase. The best treatment, then, is to clamp the condenser while it is hot, and allow it to cool slowly. Also, if a paraffin having a high melting point is used there is less danger of any softening taking place in the ordinary range of temperatures to which a condenser is subjected.

(b) TEMPERATURE COEFFICIENT OF THE CAPACITY

In any condenser the geometric capacity depends on the dimensions of the plates and the thickness and dielectric constant of the dielectric. If the thermal expansion of all of the materials entering into the condenser was the same and alike in all directions, then the temperature coefficient of the geometric capacity would be positive and equal to the coefficient of linear expansion, provided, of course, that the dielectric constant does not change with temperature. This is readily seen from the formula for the capacity of a condenser of parallel plates, viz, $C = \frac{ka,}{4\pi d}$ where k is the dielectric constant, a the area of the plates, and d the thickness of the dielectric. If, now, the dielectric increases in thickness more rapidly than the plates increase in area, the temperature coefficient will be negative. This is what actually occurs in a paraffin-mica condenser where there is considerable paraffin between the plates, as the coefficient of expansion of paraffin is relatively large. However, if the condenser is tightly clamped while hot, a large part of the paraffin will be forced out from between the plates so that the increase in thickness of the dielectric is largely due to the expansion of the mica. With condensers prepared in this way, the temperature coefficient of the geometric capacity is always small, and may be either positive or negative. The coefficient of expansion of paraffin increases very rapidly when near the melting point; so that, if a condenser having considerable paraffin as a dielectric is heated sufficiently high, a temperature is reached above which its capacity decreases rapidly. The point at which this change takes place depends upon the grade of paraffin used in the manufacture of the condenser. It has been observed at as low a temperature as 22° C, but if a high melting-point paraffin is used it does not take place until a temperature of 35° or 40° C is reached.

The temperature coefficient of the effective capacity may be quite different from that of the geometric capacity, due to the fact that the absorption increases very rapidly with the temperature. This causes the temperature coefficient of the effective capacity to be always algebraically larger than the temperature coefficient of the geometric capacity, and the amount of this difference will depend on the absorption which the condenser shows as well as on the per cent change of absorption with temperature. Values of the mean temperature coefficient between 20° and 30°, as determined by six different methods, are given in Table II.

TABLE II

Mean Temperature coefficients between 20° and 30° under Different Conditions in Parts in 100 000

Condenser	1200 cycles	100 cycles	50 cycles	0.6-sec. charge, 0.1-sec. discharge	0.6-sec. charge, 0.5-sec. discharge	0.6-sec. charge, 1.0-sec. discharge
1038, 0.1	−20	−18	−17	0	+ 6	+ 6
1038, 0.2+0.2′	−23	−22	−21	− 2	+ 3	+ 5
5471B, 0.1	− 7	− 6	− 6	+ 1	+ 3	+ 4
5471B, Σ0.1	− 5	− 3	− 2	+17	+35	+42
7377	− 5	− 3	− 2	+10	+14	+16
No. 3	−10	− 7	− 5	+13	+23	+28

The temperature coefficient at 1200 cycles is sensibly the same as that of the geometric capacity, since only a very small amount of absorbed charge enters into this measurement. It should be noticed that these are the same condensers whose absorption constants are given in Table I, with the exception of 5471A, which was used as a reference condenser in the temperature coefficient determinations. It will be observed that those condensers which show the largest effects due to absorption show the greatest change in the temperature coefficient.

3. INSULATION RESISTANCE

The insulation resistance of a condenser depends upon the capacity of the condenser as well as on the specific resistance of the dielectric. This is easily seen from the formulas for capacity and resistance of a parallel plate condenser, viz,

$$C = \frac{ka}{4\pi d}$$

$$R = \frac{\rho d}{a}$$

where k is the dielectric constant, ρ the specific resistance, a the cross section, and d the thickness of the dielectric. From this it follows that $R=\frac{\rho k}{4\pi C}$ or $RC=\frac{\rho k}{4\pi}$. Hence, for any given class of condensers RC should not vary through wide limits and R should increase as C decreases. An examination of the results on a number of good condensers shows that in no case does the value of RC fall below 10^4 nor exceed 10^7, where R is measured in ohms and C in farads, or, what is equivalent, R in megohms and C in microfarads. The portion of the original charge which will leak through the condenser in a short time, t, is very approximately $\frac{t}{RC}$. Hence, it will be seen from the above that a good condenser should not lose more than one ten-thousandth of its charge per second. It has been pointed out before that the phase difference due to the leakage of a good condenser is entirely negligible.

4. CHANGE OF CAPACITY WITH VOLTAGE

For a range of voltages such as is used in ordinary testing a paraffin-mica condenser seldom shows any change in capacity with voltage, although occasionally such a change is observed. On the other hand, every silvered-mica condenser which has come to our notice does show a change in capacity with voltage, though in some cases the amount has been very small. For a change of 50 volts the change in capacity of a silvered-mica condenser has never been found to be more than 0.1 per cent. It is thought to be due to the presence of poorly conducting material underneath the flakes of mica which are often found on the surface of a sheet of mica.[12]

5. CAPACITY BETWEEN SECTIONS OF A SUBDIVIDED CONDENSER

If a condenser is to have a capacity which is independent of its surroundings, it is necessary that it should be surrounded by a metal sheath which is kept at constant potential during the measurements. This is accomplished in the case of a mica condenser by having the outside plates connected to the same terminal. If metal clamps are employed, these may be used as the outside plates of the condenser. This terminal should be marked "earth." If, then, two or more condensers are placed near each other in the same case, there will be no capacity between the sections, and the capacity in parallel will be the same as the sum of the individual capacities.

The capacity between the terminal blocks of a subdivided condenser is often an appreciable part of the total capacity. Hence, for precision work it is better to bring the terminals of each section to a separate binding post, each post being at a distance of several centimeters from any other post.

The above points are more important with condensers of small value than with condensers of large value, since the absolute value of the capacity

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[12] For data and curves, see Bulletin of the Bureau of Standards, 6, p. 462; Reprint 137.

between sections and of the capacity of the terminal blocks will be the same in any case. An idea of the magnitude of these capacities in some extreme cases may be obtained from the following figures: A box containing 10 0.1 μf sections was found to have an average capacity between sections of 0.1 per cent, or one ten-thousandth of a microfarad. The capacity between the terminal blocks in some of the common designs for a subdivided microfarad has been found to lie between two and six hundred-thousandths of a microfarad.

6. EFFECT OF CHANGES IN ATMOSPHERIC PRESSURE

Variations of barometric pressure tend to affect the capacity of a mica condenser, since an increase of pressure decreases the distance between the plates and hence increases the capacity.[13] This is more noticeable in condensers in which there is considerable paraffin, as paraffin is much more compressible than mica. However, ordinary changes of barometric pressure do not produce appreciable changes in the capacity, though extreme changes in pressure may do so.

7. CHANGES IN CAPACITY WITH TIME

Many condensers show a slow drift of the capacity with time. This is doubtless due to a slow readjustment of strains which are of necessity introduced in the manufacture of the condenser. The magnitude of these changes are usually small, though one condenser has changed at the rate of about 0.1 per cent per year for the two or three years it has been under observation. No method for artificially aging condensers has yet been devised.

V. PAPER CONDENSERS.

In a paper condenser the dielectric consists of a high-grade paper which is impregnated with some insulating material, usually paraffin. Two types may be distinguished, the tinfoil type and the Mansbridge type. In the tinfoil type the condenser may be built up by using alternate layers of tinfoil and paper in a manner analogous to that adopted in making mica condensers, or only two large sheets of tinfoil between which are inserted one or two thicknesses of paper may be used, and the whole rolled or folded into a convenient form. The first kind will have less internal resistance, while the second will require a little less material for the same capacity. Both kinds have been extensively used, but at the present time the great majority are of the second class.

In the Mansbridge[14] type, the tinfoil consists of a very thin coating of the metal deposited on the surface of a sheet of paper. To construct the condensers, two of these sheets of tinfoiled paper are rolled up with one or two sheets of paper between them. The whole is then impregnated

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[13] For data upon this effect, see Bulletin of the Bureau of Standards, **6**, p. 458; Reprint 137.
[14] Electr., **61**, p. 139, 1908.

with paraffin in the same manner as described above. In this form they have a very high resistance in the plates, which may give rise to an excessive energy loss when used with alternating currents of even moderate frequencies. To overcome this disadvantage, some manufacturers make frequent connections at the edge of the tinfoiled paper and in some cases even use a thin copper strip along one edge of the tinfoiled paper. This greatly reduces the plate resistance.

A paper condenser generally shows larger absorption than a mica condenser. With the best paper condensers this is not materially larger than with the poorer mica condensers, but in some cases it becomes very large. Condensers have been observed whose capacity is 100 per cent larger when measured by direct current, using long times of charge and discharge, than when measured by alternating current. Such a condenser has a very indefinite value when measured with direct current, since absorption plays so large a part in the effective capacity that it is impossible to reproduce conditions of measurement with sufficient exactness to obtain accurate results.

Paper condensers have two important uses: (1) They are used across the break of an inductive circuit to prevent sparking, and (2) they are used in alternating current circuits to alter the impedance of the circuit. Under the first heading the most important application is for use with induction coils, while under the second heading the greatest use is in telephone circuits.

For use across the break of an induction coil the condenser should have small absorption, as any energy absorbed in the condenser will decrease the energy of the spark. For the same reason the insulation resistance should be high.

For telephone work it is very desirable that the capacity should be independent of the frequency and that the energy loss should be small. This necessitates that both the absorption and the internal resistance be as low as practicable. It is seldom that a paper condenser is found in which there is an appreciable energy loss due to leakage when it is used with alternating currents.

The effect of temperature upon paper condensers [15] is very marked. The dielectric is largely paraffin, which expands rapidly and decreases the geometric capacity as the temperature increases. However, the absorption increases rapidly with the temperature, so that the temperature coefficient of the capacity of a condenser which shows large absorption measured even with alternating current is usually positive. In fact some condensers have been observed which have a positive temperature coefficient at 100 cycles and a negative coefficient at 900 cycles. The general principles underlying these phenomena are the same as those outlined under mica condensers, though both the effect due to expansion and that due to absorption are much larger with paper condensers than with mica condensers.

[15] For curves showing the effect of temperature upon the capacity of paper condensers, see Grover, Bulletin of the Bureau of Standards, 7, p. 553 et seq.; Reprint 166.

Manufacturers usually state the capacity and insulation resistance of their condensers. It would also seem desirable to state some constant which would indicate the magnitude of the absorption. Some manufacturers do this by stating the effective capacity both with alternating current and with direct current. It would seem simpler to give the phase difference at low frequency alternating current, as this is almost entirely due to absorption.

The results of measurements on some commercial paper condensers are given in the following table. The condensers are from several different manufacturers, and are representative of the commercial grade of paper condensers.

TABLE III

Constants of Paper Condensers

Condenser	Tinfoil type			Mansbridge type		
	21B	8A	25B	31K	38C	333B
Effective capacity (microfarads):						
2900 cycles	2.200	0.931	0.4041	1.018	0.907	0.906
1200 cycles	2.202	0.934	0.4086	1.025	0.921	0.915
100 cycles	2.214	0.942	0.4237	1.039	0.938	0.931
0.6-sec. charge, 1.0-sec. discharge	2.311	0.960	0.826	1.134	1.080	1.170
Maximum increase of capacity	5%	3%	105%	12%	20%	30%
Phase difference:						
2900 cycles	1° 21′	1° 38′	1° 41′	39′	9° 13′	5° 52′
1200 cycles	0° 42′ 30″	0° 51′	1° 28′	33′	4° 15′	2° 49′
100 cycles	0° 14′ 30″	0° 20′	2° 21′	31′	1° 6′	1° 5′
Apparent series resistance (ohms):						
2900 cycles	1.29	1.51	1.58	0.57	8.81	5.56
1200 cycles	1.55	1.92	3.32	1.21	9.78	6.45
100 cycles	5.43	7.66	67.74	14.62	28.68	28.20
Power factor:						
2900 cycles	2.4%	2.8%	2.9%	1.1%	6.0%	10.2%
1200 cycles	1.2	1.5	2.6	1.0	7.4	4.9
100 cycles	0.4	0.6	4.1	0.9	1.9	1.9
Insulation resistance (megohms)	140 000	1050	22	110	75	109

The first three (21B, 8A, and 25B) are of the tinfoil type, while the last three (31K, 38C, and 333B) are of the Mansbridge type. Of these last, one (31K) has connections made at several points along the edge of the tinfoiled paper.

In determining the relative amounts of absorption by the change in capacity, the capacity at 2900 cycles may be taken as sufficiently near the geometric capacity for purposes of comparison. The per cent increase in capacity is the increase between 2900 cycles and the direct-current measurement compared to the capacity at 2900 cycles.

It will be noticed that in some cases the phase difference increases with the frequency and in some cases decreases, depending on whether the series resistance or the absorption phenomena predominates. The actual series resistance is very approximately that given under 2900 cycles, as the absorption is small at that frequency. The increase in the apparent series resistance at low frequencies is due to absorption, and it will be seen that those condensers which show the greatest change in the effective capacity show the largest increase in the apparent resistance. The power factor is the fraction of the total energy of the condenser circuit which is converted into heat within the condenser when an alternating current is transmitted through the condenser. It will also be noticed that those condensers which are the best in other respects also have the highest insulation resistance, though in all cases the insulation resistance is sufficiently high for the purposes for which such condensers are ordinarily used.

VI. COMPRESSED-GAS CONDENSERS

As the voltage on an air condenser is increased a point is reached where there is a disruptive discharge between the plates, the actual voltage depending on the distance between the plates. But for considerably lower voltages than this there is a brush discharge which consumes energy. Hence, it is only at relatively low voltages that an ordinary air condenser can be considered to have negligible losses. To improve them in these respects, Fessenden, Wien,[16] and others have inclosed air condensers in a strong air-tight container into which gas under pressure is introduced. Wien found that the kind of gas used is immaterial and that it is somewhat easier to maintain the pressure with carbon dioxide than with air. For pressures up to 10 atmospheres the voltage necessary to produce disruptive discharge increases nearly as rapidly as the pressure, but above 10 atmospheres the increase is less rapid, and there is little advantage in going above 20 atmospheres. With high gas pressure the brush discharge becomes very much less troublesome than with low pressure. With such condensers, having a distance of 3 mm between the plates, Wien was unable to detect any energy loss in the condenser when 35 000 volts were applied. Such condensers are very heavy and expensive, and are necessarily limited to very small capacities, but are invaluable for certain kinds of work. It should be noted that the capacity is but slightly affected by the increased air pressure.

VII. OIL CONDENSERS

An oil condenser is easily made by placing an air condenser in a proper case which is filled with oil. Care should be taken that air bubbles are removed. The capacity is then more than twice that of the original air condenser and it will stand from two to four times as high a voltage before disruptive discharge takes place. The energy loss in such a condenser depends upon the kind of oil used. With the best paraffin oils the loss is very small,

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[16] Ann. d. Phys., **29**, p. 679, 1909.

but inferior oils may show a very large loss. The results of measurements on samples of four different oils are given in the following table:

Oil	Density at 20° C	Resistivity, ohms per cm cube	Phase difference		Dielectric constant
			100	1200	
Pratt's astral	0.7852	470. $\times 10^{12}$	2′ 0″	25″	2.34
Paraffin	0.8710	1100. $\times 10^{12}$	35	5	2.41
Transformer oil A	0.8793	0.49 $\times 10^{12}$	1° 5 0	5′ 10	2.51
Transformer oil B	0.8682	3.1 $\times 10^{12}$	30 0	5 30	2.47

The Pratt's astral is the best grade of commercial kerosene. The paraffin oil is a specially refined clear oil, somewhat heavier than kerosene. The transformer oils are commercial oils furnished by reputable transformer manufacturers.

It will be seen that the best oil condensers compare favorably with a mica condenser, and, owing to the increased loss of energy in the plates of a mica condenser at high frequency, the total loss is somewhat less in oil condensers at high frequency. However, the condensers with transformer oils show as much absorption as many paper condensers.

VIII. GLASS CONDENSERS

Glass condensers are most often made in the form of Leyden jars, and are much used for high-voltage work. The older form was made by pasting tin foil over the glass, but this left bubbles of air beneath the tin foil, and at these points the jar would puncture more readily than where the tinfoil was spread smoothly on the glass. Of late this has been overcome by depositing a coating of copper directly on the glass. It is then found that the glass always punctures at the edge of the coating. To obviate this the glass is sometimes thickened at this point, thus reducing the strain in the glass.[17]

The energy loss observed when using Leyden jars at high voltages, due to the brush discharge from the edges of the plates, is often much larger than the loss due to absorption. This brush discharge may be reduced by making the jar long and of small diameter, so that the coating has a shorter boundary. It may be entirely overcome by completely immersing the jar in oil. The energy loss due to absorption is relatively large, but varies greatly with the kind of glass. Flint glass is said to give the best results. Absorption data of some commercial condensers are given below:

5 – 0.002 μf condensers in parallel

Capacity		Phase difference	
100 cycles	1350 cycles	100 cycles	1350 cycles
0.010244	0.010205	17′	12′

[17] Moscick, Elect. Tech. Zs., 25, pp. 527, 549; 1904.

The temperature coefficient of a glass condenser is positive. Stöckly [18] found a value of 0.08 per cent. He also found that the losses increase rapidly with the temperature.

IX. TESTS UPON CONDENSERS

The Bureau of Standards is prepared to determine the effective capacity and phase difference of condensers at any frequency between 25 and 3000 cycles, though tests at 100 cycles can be made more easily than at any other frequency, and tests are more often made at this frequency. Also, the effective capacity with direct current using various times of charge and discharge can be determined. While almost any time of charge or discharge can be used, the apparatus employed at the Bureau is adapted to make tests with 0.2, 0.4, or 0.6 second charge and 0.1, 0.5, or 1.0 second discharge, the charging and discharging being performed cyclicly at intervals of two seconds. Where requested, the insulation resistance and absorption ratio will be determined. The temperature coefficient of the effective capacity for any method of measurement can be determined, but the temperature coefficient will be different for different methods of measurement.

Unless otherwise ordered, the test of a condenser will consist of the measurement at 20° C of the capacity and phase difference at 100 cycles alternating current, and the measurement of the capacity with direct current using 0.6 second charge and two different times of discharge (0.1 second and 1.0 second). From these values of the capacity a curve will be furnished which shows the increase of capacity as the length of discharge is increased. The curve will be plotted upon a sheet identical with that of Fig. 3, so that the relative quality of the condenser is easily seen.

The Bureau also makes special tests upon condensers where the results to be obtained appear to justify the work required:

X. PUBLICATIONS OF THE BUREAU CONCERNING ELECTRIC CONDENSERS

The following publications of the Bureau of Standards will be useful to those interested in the subject of electric condensers.

SCIENTIFIC PAPERS

10. The Aosolute Measurement of Capacity. .*E. B. Rosa and F. W. Grover*
64. Simultaneous Measurement of the Capacity and Power Factor of Condensers. . . . .*F. W. Grover*
65. A New Determination of the Ratio of the Electromagnetic to the Electrostatic Unit of Electricity. .*E. B. Rosa and N. E. Dorsey*
137. Mica Condensers as Standards of Capacity. . . . .*Harvey L. Curtis*
166. The Capacity and Phase Difference of Paraffined Paper Condensers as Functions of Temperature and Frequency. . . . .*Frederick W. Grover*

[18] Lum. Electrc., 7, p. 57; 1909.

BUREAU CIRCULARS

6. Fees for Electric, Magnetic, and Photometric Testing.
24. Publications of the Bureau of Standards.
36. The Testing and Properties of Electric Condensers.

Any of the above will be sent upon request.

S. W. STRATTON,
Director.

Approved:
CHARLES EARL,
Acting Secretary.