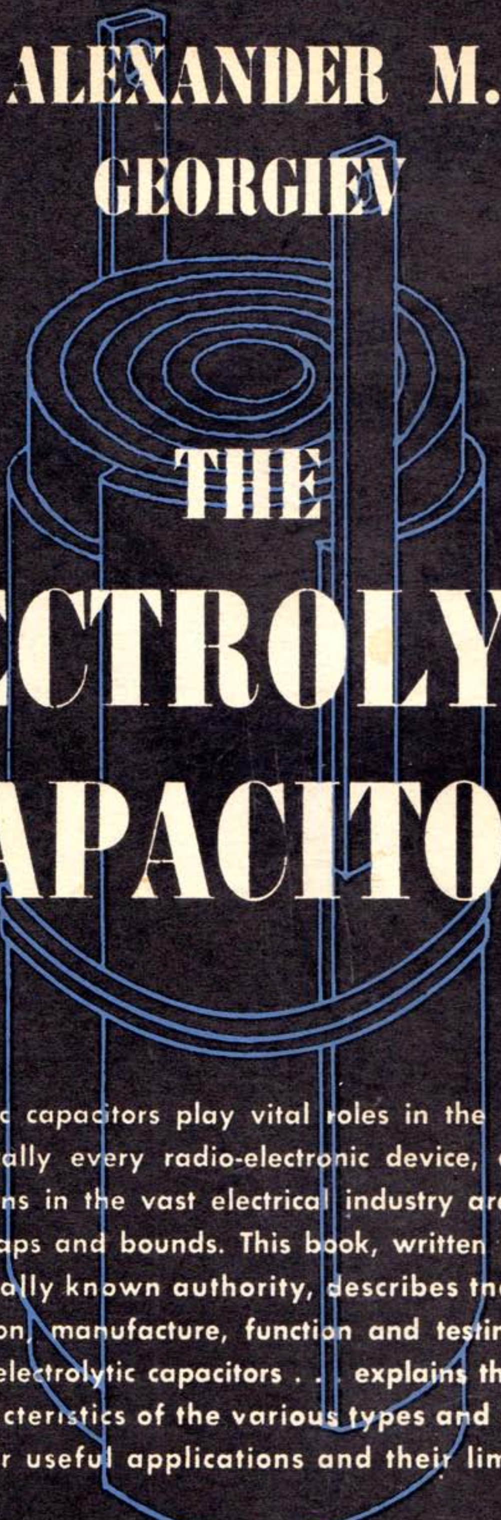
ALEXANDER M. GEORGIEV

THE ELECTROLYTIC CAPACITOR



Electrolytic capacitors play vital roles in the operation of practically every radio-electronic device, and their applications in the vast electrical industry are increasing by leaps and bounds. This book, written by an internationally known authority, describes the design, construction, manufacture, function and testing of dry and wet electrolytic capacitors . . . explains the operating characteristics of the various types and indicates both their useful applications and their limitations.

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THE ELECTROLYTIC CAPACITOR

by

ALEXANDER M. GEORGIEV

Member, American Institute
of Electrical Engineers

This is a practical book which will be of value not only to engineers concerned with the actual design and manufacture of electrolytic capacitors (annual production now amounts to tens of millions) but also to that larger group of engineers, technicians, and maintenance men concerned with equipment in which electrolytic capacitors are used, e.g., radio receivers and transmitters; sound systems and other electronic apparatus; telephone circuits; electric welding equipment; and single-phase induction motors such as those used in refrigerators, air-conditioning units, pumps, oil burners, washing machines, etc. It will also be a useful reference book for academic and industrial research workers in the electrical and electrochemical field, and physicists and chemists may find of interest the recorded observations and experimental data on electrolytic cells.

The author's primary objective is to describe the design, construction, manufacture, function, and testing of dry and wet electrolytic capacitors, to explain the operating characteristics of various types, and to indicate both their useful applications and their limitations. In addition,

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The Electrolytic Capacitor

ALEXANDER M. GEORGIEV
Member, American Institute
of Electrical Engineers

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Preface

The origin of the electrolytic capacitor or condenser can be traced to the second half of the 19th century when the discovery was made (Wheatstone, Buff, Ducretet) that a film can be formed on aluminum electrochemically and that it will exhibit unidirectional electrical conductance and other peculiar properties. One of the early attempted applications of the electrolytic capacitor was in conjunction with the starting of single-phase induction motors; efforts were also made to utilize it for power factor correction in alternating current circuits. It appears that no extensive use had been made of this device until the early twenties, when its utility in filter circuits supplying rectified plate current to radio tubes was definitely established. These capacitors were "polarized" and of the "wet" type. Several years later "dry" electrolytic condensers of a low voltage rating and large capacitance found a limited application in A-battery eliminators (comprising a rectifier and a filter circuit) which furnished filament current for d.c. radio tubes. By 1929 the high-voltage dry electrolytic capacitor was developed and soon found very extensive and diversified applications in several fields. The annual production of dry and wet electrolytic capacitors amounts now to tens of millions and they are used in radio receivers and transmitters, sound systems and other electronic apparatus, in telephone circuits, in conjunction with electric motors and, to a smaller extent, in a number of other applications.

The main object of this book is to describe the construction, manufacture, function and testing of dry and wet electrolytic capacitors, to explain the operating characteristics of the various types and to indicate both their useful applications and their limitations. To make clearer the peculiarities of these devices, a comparison has been drawn between them and the nonelectrolytic capacitors, the latter being known for a much longer time. It has been endeavored, otherwise, to limit this text to the subject matter that is specifically related to the electrolytic type. The discussion of the theory underlying capacitors in general (electrolytic and nonelectrolytic) has been omitted, as far as possible, because it is covered by the literature on this subject.

Several of the known theories on the nature of the dielectric film have been briefly outlined. The properties of the film, however, have been treated in detail, as they determine to a very large extent the characteristics of the electrolytic capacitor.

Only a few commercial dry and wet capacitors have been described, but they are typical and representative of most electrolytic capacitors now in use. The description of the numerous minor constructional variations has been considered unnecessary.

In writing this book, the author has used extensively his observations and experience acquired in the development and manufacture of electrolytic capacitors during the past fifteen years. It is hoped that the information presented in the text will be of interest to manufacturers and users of electrolytic capacitors and also to workers concerned with the development of capacitors and related apparatus.

There are many patents on electrolytic capacitors and a list of some of the more interesting among them has been appended.[1]

The author wishes to express his appreciation to Delco Products and Delco-Remy Divisions of General Motors Corporation, The Crosley Corporation, The Aluminum Research Laboratories, The Aerovox Corporation, P. R. Mallory & Co., Inc., Sprague Electric Company, and the Solar Manufacturing Corporation for the illustrations they have furnished him.

A. M. G.

Dayton, Ohio
January, 1945

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[1] A few of the listed patents do not specifically refer to electrolytic capacitors. However, the subject matter presented therein is directly or indirectly related to such capacitors.

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I

General Information on Capacitors

The capacitor may be considered as a device for storing static electricity. The essential parts of a capacitor are two electrodes, which consist of conducting members, closely spaced by a dielectric or insulating medium. The electrodes are usually metallic plates or foils, while the dielectric may be vacuum, gases (for instance, air), liquids (like mineral or vegetable oils), or solids (like mica, glass, wax-impregnated paper, and so on).

Another classification of capacitors depends upon the positioning of the electrodes and the dielectric. If they are permanently positioned with respect to each other, the condenser is designated as *fixed,* and its capacitance remains substantially unchanged. If the electrodes can be moved relative to each other or the dielectric displaced, the capacitance may be changed and the condenser is then of the *variable* class. Fig. 1 illustrates the simplest form of a fixed capacitor.

The capacitance of a condenser is a measure of the quantity of electricity that can be stored in it at a given potential (voltage). The unit of capacitance is the *farad* and it corresponds to a charge of one coulomb at one volt pressure across the terminals of the device. These relations are expressed by the formulae:

$$Q = CE \qquad (1)$$

or

$$C = \frac{Q}{E} \qquad (2)$$

where C = farads,
E = volts,
Q = coulombs.

As the farad is too great a unit for practical purposes, the microfarad (MF)—one millionth of one farad—or its subdivisions are ordinarily used.

The energy in joules, stored in a capacitor, equals ½ CE^2. **(3)**

The capacitance of a condenser is directly proportional to the area of the electrodes spaced by the dielectric and is inversely proportional to the thickness of the latter. The nature of the dielectric is the third determining factor for the capacitance. If this dielectric medium is a mineral oil, the capacitance of the condenser may be, for instance, twice as great as it would be with air, everything else being the same. With castor oil the capacitance will be about five times as great as with air. The ratio of the capacitance of a condenser with a given dielectric medium between the electrodes to the capacitance of the same condenser with air (or, more accurately, vacuum) as a dielectric is designated as the dielectric constant of the medium or its specific

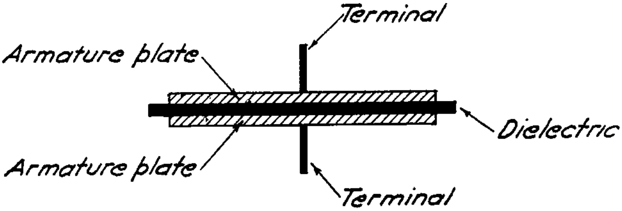

FIG. 1.—Two-plate fixed capacitor.

TABLE I

DIELECTRIC CONSTANTS OF VARIOUS MATERIALS[1]

Glass	3–10,	depending on the grade
Hard rubber	2–3	depending on their composition
Mica	5–10	
Bakelite	5–7	
Paraffin wax	2–2.5	
Transformer oil	2.2–2.5	
Castor oil	4.7	
Ethyl alcohol	26.5	
Glycerin	36–44,	depending on the water content, on the temperature and also on the frequency of the test current
Nitrobenzene	36	
Water[2]	57–83,	depending on the temperature

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[1] It appears that a relationship exists in solvents between dielectric constant, resistivity and power to ionize dissolved substances. Higher dielectric constants are associated with lower resistivities and with a greater power to ionize.

[2] There are also solid materials (titanium dioxide—TiO^2—and other ceramics) that possess very high dielectric constants, of the order of 80 and even greater.

The dielectric constants are strongly affected (increase) if the materials are contaminated with moisture.

Unless otherwise specified, the constants in this table refer to measurements at commercial frequencies.

TABLE II

Dielectric Strength of Various Insulating Materials[3]

(Thin layers[4] used for specimens)

Mica	500–2000	and higher (values given are volts RMS per mil thickness), depending on its grade
Untreated paper	150–500	
Treated paper	up to 700	
Glass	200–500	depending on its composition
Wax	200–500	depending on the grade and purity
Insulating oil	250–700	

inductive capacitance. The dielectric constant of a vacuum is taken as unity and that of air is very close to it. The approximate dielectric constants of a few materials, some of which are used in capacitors, are listed in Table I. These constants depend on the composition and purity of the material, are more or less affected by the temperature and vary also with the frequency of the impressed voltage. Table II gives information on the dielectric strength of several insulating materials; the breakdown voltage drops with the increase of the temperature of the insulator.

The capacitance of a parallel-plate condenser as shown in Fig. 1 is computed from the formula

$$C = \frac{8.84 \times KA}{10^8 \times D} \tag{4}$$

where C = capacitance in microfarads,
K = the dielectric constant,
A = area of one side of one of the electrodes in square centimeters,
D = thickness of the dielectric in centimeters.

To increase the capacitance of the condenser and make it compact, a plurality of electrode plates or foils (every second plate connected to the one terminal and the rest of the plates to the second terminal) interleaved with layers of dielectric, like waxed paper or mica sheets,

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[3] The dielectric strength and the insulation resistance are reduced if moisture is present in the material.

The constants in this table were determined at commercial frequencies.

The natural film on aluminum is exceedingly thin, highly refractive, provides a fairly good protection for the underlying metal against many corrosive agents, but is mechanically weak and has very poor dielectric characteristics.

[4] Of the order of several thousandths of an inch.

can be stacked in a pile. The capacitance of such multiplate condensers is computed from the modified formula

$$C = \frac{8.84\,KA\,(n\text{-}1)}{10^8 \times D} \tag{5}$$

where n is the total number of electrode plates.

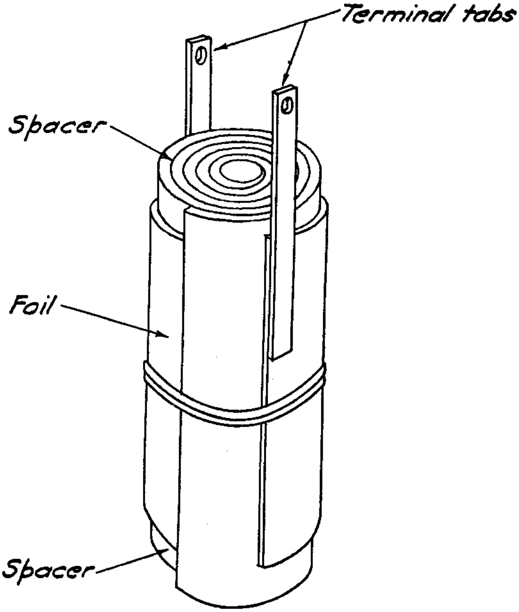

Fig. 2.—Wound capacitor section.

In a wound type of condenser (Figs. 2 and 5), consisting of two electrode foils with insulating separators on both sides of the foils, the capacitance is substantially doubled as compared with the unit of Fig. 1, because both surfaces of the foils are active.

II

Electrolytic vs. Nonelectrolytic Capacitors

Electrolytic capacitors constitute one of the several classes of capacitors. To differentiate between the electrolytic and all other classes we shall designate the latter in this text as "nonelectrolytic."

The structure of the electrolytic capacitor comprises the fundamentally important component parts present in any capacitor—the electrodes and the dielectric between them. It also performs the characteristic function of storing and releasing electrostatic charges. However, the electrolytic capacitor possesses in addition some very distinct structural and functional features which justify placing it in a class of its own. Some of these features permit the classification of this device as an electrolytic cell and a relationship between it and other electrolytic cells, like the electrolytic rectifier and lightning arrester, will be brought out later.

The essential difference between the electrolytic and nonelectrolytic capacitor resides in the nature and thickness of the respective dielectrics and in the presence or absence of an ionic conducting medium (the electrolyte) between the metallic electrodes. In the nonelectrolytic capacitor the thickness of the dielectric is usually not less than the gauge of a thin sheet of paper, while in the electrolytic capacitor the dielectric is many times thinner. In the former class of capacitors the dielectric is made of materials of well-known compositions, like mica, wax- or oil-impregnated paper, glass, oil, and the like, while in the latter class the true nature of the effective dielectric has not been definitely established. We know, however, that the dielectric in electrolytic capacitors is intimately associated with the surface of the electrode and that its existence is correlated with the formation of an oxide film on the latter.

Another important characteristic of the electrolytic capacitor is the marked ionic conductivity of the medium positioned between the metallic electrodes, in contrast to the highly insulating material (mica, oil, and the like) between the electrodes in nonelectrolytic capacitors.

From the point of view of usage, it is typical of the electrolytic capacitor that it combines some remarkably valuable advantages with several grave shortcomings which will be brought out while comparing it with the nonelectrolytic type. The most outstanding advantage of the electrolytic condenser resides in the *great,* in some cases even enormous, *capacitance* per unit of electrode area which it exhibits at moderate (100–600 V), but particularly at low voltages (down to a few volts). At higher voltages, and especially when the amplitude of the voltage fluctuations is considerable or the voltage is alternating, this advantage exists usually to a much smaller degree, if at all, as series combinations of two or more sections then become necessary with the resulting drastic reduction in capacitance per unit of volume and weight of the condenser assembly.[1]

The following example may illustrate the great compactness of the low-voltage electrolytic capacitor as compared with an equivalent wax-paper capacitor. A unit of the former class designed for use in a unidirectional circuit and rated for 2,000 MF at 5 to 10 volts (depending on the ripple voltage) can be housed in a container of about 10 cubic inches, while the capacitance of the lowest voltage condenser of the latter class, occupying the same space, will be of the order of only a few MF's. Consequently, the bulk, weight and also the cost of the electrolytic capacitor are in this case less to a very great degree.

The cause of this impressive difference between the two kinds of capacitors will be discussed in the following paragraphs. As already stated, for a given type of dielectric, the less its thickness the greater the capacitance per unit electrode area. The limit for increasing the capacitance by this expedient in nonelectrolytic condensers is determined by the gauge of the thinnest available insulators which will provide the required dielectric strength. For example, it is difficult to make condenser paper thinner than 0.0003″, and it is the usual practice in the manufacture of wax- or oil-paper capacitors to place at least two layers of paper between the foils, to prevent breakdowns due to unavoidable pinholes and conducting particles (metallic specks, and the like) in the paper. Thus, 0.0006″ between the electrodes appears to be the minimum spacing. But even if a chance were taken with a single layer of paper between the foils of a condenser for very low voltages, the ultimate minimum spacing would be 0.0003″, which would

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[1] If two or more condensers are connected in parallel, the resulting capacitance is equal to the sum of the capacitances of the individual condensers. If two condensers are connected in series, the capacitance is computed from formula (8), Chapter XV. If n condensers of equal value are in series, the capacitance is $=\frac{C}{n}$. **(6)**

also set the limit to the capacitance per unit area for this type of dielectric, no matter how low the voltage rating of the unit. Thus, whether the latter were intended for 5 volts or 25 volts, it could not occupy a space less than that required for the housing of a section of the required capacitance wound with a 0.0003″ paper between the foils.

With the electrolytic capacitor, however, such limitations do not exist as the minimum thickness of the dielectric is not determined by the gauge of the layer or spacer placed between the electrodes. The almost intangible dielectric of the electrolytic capacitor is formed electrochemically on the electrode surface, and the accurate control of its thickness, down to less than one millionth of an inch, can be readily effected. Thus, by the simple expedient of varying the filming voltage, which governs the thickness of the dielectric, one may produce condensers, within wide voltage and capacitance ranges, which can be housed in containers of the same dimensions. For example, a container of 10 cubic inches will be suitable for the assembly of a capacitor rated for 100 MF and formed at 100 V or of a capacitor of 400 MF at 25 V. Hence, the electrolytic capacitor exhibits a *remarkable adaptability* to the *operating voltages.*

The upper voltage limits for single-section electrolytic capacitors are established by a number of factors (among them the operating conditions) discussed in Chapter XVIII. But even those units which are to be operated with unidirectional potentials and small ripple voltages only, i.e., under favorable conditions, are seldom rated for more than 500 or 600 V peak. For higher voltages and where the service conditions are severe, two or more capacitors are connected in series.

Electrolytic capacitors excel the usual paper-wound nonelectrolytic capacitors with respect to their *self-healing properties.* By this is meant that after an instantaneous voltage surge or short-lasting overload, which may cause a breakdown of the dielectric, the dry electrolytic capacitor is more likely to recover than a wax- or oil-paper capacitor. The wet electrolytic is in this respect far superior even to the dry electrolytic capacitor, as it is practically always healed after the transient overload has ceased.

In the neighborhood of its forming voltage the electrolytic capacitor exhibits an abrupt and great rise in leakage current—Fig. 3 (curve A); this is the critical voltage of the device. If the voltage is lowered, the leakage rapidly drops to its normal level. This effect occurs with regularity and the voltage at which the "yielding" of the dielectric takes place can be *predetermined.* The yielding may serve as a warning that potentials dangerous to the capacitor are being approached. Nonelectrolytic capacitors do not give such a definite warning as to the approach of the critical voltage and they are likely to break down suddenly and at a voltage which cannot be predicted. The "yielding" feature also enables the electrolytic capacitor to absorb electric shocks and thus to *protect* other component parts of the circuit from the harmful effects of *surges.*

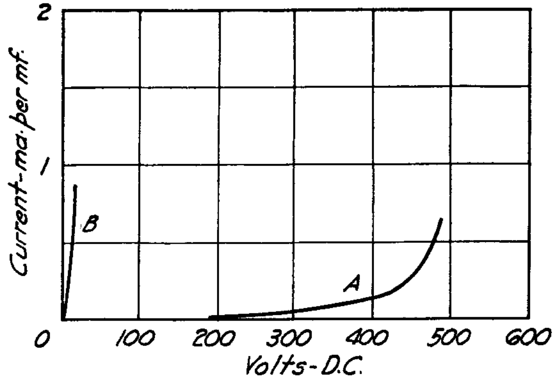


FIG. 3.—Leakage current vs. impressed voltage. The anode of the polarized capacitor was formed at about 400 V.
A—correct polarity application.
B—reversed polarity.

Finally, the unilateral properties of the film (or its conductance in one direction only) make it possible to use electrolytic capacitors for the blocking of direct current in the undesired direction. The unilateral feature makes the electrolytic capacitor also more adaptable to circuits in which unidirectional pulsating currents are flowing; in such cases, by making the condenser polarized or asymmetric in its action, its bulk and cost can be substantially halved without reducing its capacitance. Contrasting with this, nonelectrolytic condensers are always symmetric and no analogous economy is feasible when they are used on pulsating current, nor can they be employed to block or restrict the flow of d.c. in one direction only.

In other respects, however, the electrolytic capacitor is inferior to the nonelectrolytic, as will be pointed out here. The leakage current (per MF), when a continuous potential is applied, is much greater in the former than in the latter; this is equivalent to saying that the insulation resistance per MF in electrolytic capacitors is much smaller. Thus, the insulation resistance of nonelectrolytic capacitors may be of the order of hundreds and even thousands of megohms per MF, while the resistance of electrolytic capacitors usually amounts to only a few megohms per MF. This peculiarity of the electrolytic capacitor is particularly pronounced after prolonged periods of idleness and is then designated as "deforming." The initial leakage after such idling may be quite substantial. However, in some particular cases the high *initial* leakage is taken advantage of for the protection of the circuit, as outlined in Chapter III.

The electrical losses in electrolytic capacitors, as expressed by the power factor, are much greater. While the power factor of a wax-paper capacitor, for example, is usually less than 1 per cent, it is several per cent for the best electrolytic capacitor and often approaches 10 per cent. Formerly, electrolytic capacitors, especially of the wet type, used to have much higher power factors—around 25 per cent and even greater.

The temperature characteristics of electrolytic capacitors in general and of the wet type in particular, are inferior. The capacitance, power factor and leakage current are markedly affected by the temperature; at very low temperatures the capacitance may be reduced to a small fraction of its normal value; wet condensers become inoperative when their electrolyte freezes.

The comparatively high power losses in electrolytic capacitors combined with their poor temperature characteristics limit their application in many fields. The losses cause heating of the capacitor which tends to weaken the dielectric film and this in turn increases the leakage current and the losses in general, resulting in more heating; thus, the effect is cumulative and may eventually lead to the failure of the device. For this reason the employment of electrolytic capacitors should be avoided where the ambient temperature is high or the alternating current component excessive, as the latter is apt to generate more heat than is permissible. If the electrolytic capacitor carries pure a.c., its operation will be ordinarily limited to an intermittent service, allowing it to cool and recuperate between duty cycles.

The evaporation of some of the constituents of the electrolyte and electrolysis effects may cause a reduction in capacitance, increase of power factor and sometimes failure of the electrolytic condenser. The gas and vapor pressure in these condensers may be at times considerable and even excessive, thus necessitating the provision of a vent arrangement, which complicates the construction and may eventually present inconveniences in operation.

Most of the electrolytic capacitors are of the polarized or asymmetric type and can be used only if the voltage impressed across their terminals is unidirectional. Furthermore, they *must* be connected with the *proper polarity,* or damage to the capacitor and associated apparatus may result. The unidirectional feature, however, may be turned into an advantage in special cases as has been pointed out in the foregoing. The electrolytic capacitor can even be made semipolarized to block the flow of d.c. in one direction and to *restrict* it to a predetermined value in the opposite direction, as described in Chapter XVIII.

Nonelectrolytic capacitor sections or units can be built for much higher operating voltages than is practicable for the electrolytic type. Furthermore, the nonelectrolytic capacitor can be operated continuously on alternating current at its rated voltage.

III

Dry vs. Wet Electrolytic Capacitors

Both types of capacitors depend for their operation on the presence of the dielectric film and also on the electrolyte interposed between the electrodes. Although substantially alike in the principles of their construction, they differ considerably in the embodiment of these principles and in a number of functional characteristics.

In the wet capacitor shown in Fig. 4, the electrodes are ordinarily rigid and self-supporting bodies, sufficiently spaced from each other to prevent contact between them. In many of the commercial wet capacitors there is also a thin, perforated sheet of celluloid or hard rubber positioned between the electrodes. This separator precludes the short-circuiting of the device even in case of an accidental displacement of the electrodes. The spacing between the electrodes is usually nonuniform and in some regions amounts to large fractions of an inch (or even more), as can be seen from the schematic drawing in

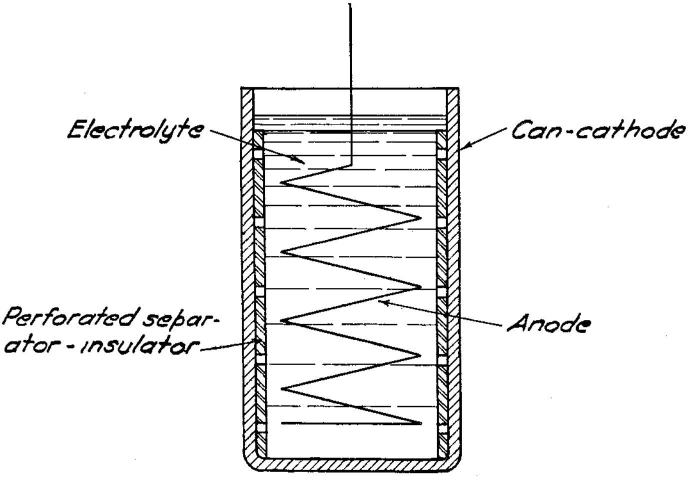


FIG. 4.—Schematic drawing of a wet electrolytic capacitor.

Fig. 4. These appreciable distances between the electrodes represent paths of considerable resistance for the current flow. To prevent excessive I^2R losses due to the long paths, an electrolyte of comparatively low resistivity must be employed. The substantial thickness of the electrodes and their rather wide spacing are limiting factors with respect to the accommodation in a given container of the largest possible electrode surface exposed to the electrolyte, which is required for obtaining the maximum of electrostatic capacitance. This limitation is somewhat offset by an appreciably greater capacitance per unit electrode area, for a given voltage, in wet as compared with dry condensers.

As mentioned previously, the construction of the wet capacitor renders it almost immune to permanent short circuits because of the distance between the electrodes. Furthermore, occasional sparks at the electrodes are not likely to put out of commission the component parts of the device. For these reasons, wet electrolytic capacitors lend themselves eminently to use in circuits where frequent voltage surges and short-lasting overloads are apt to occur, i.e., in filter circuits, immediately next to the rectifier tube.

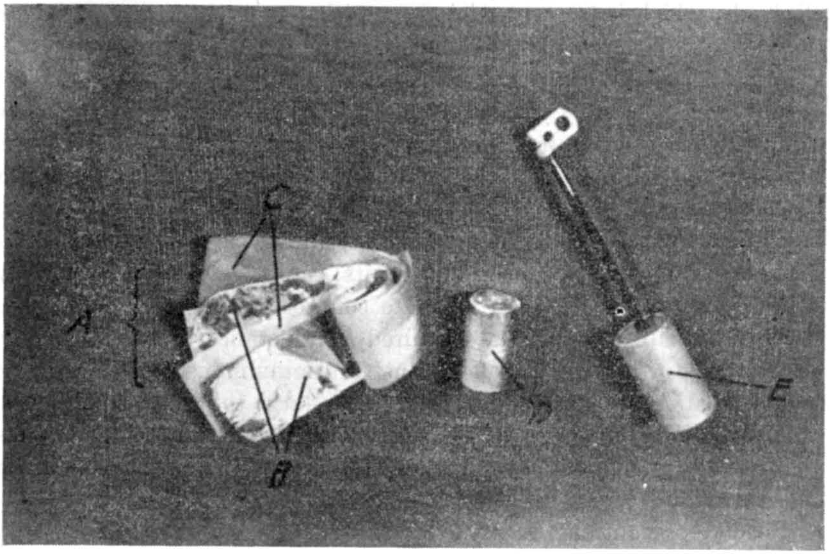
As a rule, the leakage current of the wet capacitor is greater, particularly after periods of idleness. This appreciable "deforming" is generally considered as a drawback, since it entails increased electrical losses and an extra load upon the source of the current supply (transformer, rectifier, and so on). In certain cases, however, this effect serves a useful purpose. For instance, the excessive leakage current through the capacitor, during the first minute or so after a radio set is turned on and while the tubes (of the indirectly heated type) are being heated, results in the depression of the voltage on the tubes and associated component parts. Thus, while the capacitor is "re-forming" it is protecting the various pieces of apparatus from excessive voltages which are otherwise likely to prevail during this warming-up period. The leakage characteristics can be even deliberately enhanced and so adjusted that the device may serve in certain circuits as a capacitor and voltage regulator and at the same time provide a by-pass path for rather severe voltage surges (reminiscent of the action of a lightning arrester). These applications require the formation on the anode of such a dielectric which will withstand effectively potentials up to the normal operating value and above that value will substantially yield to the electric pressure and permit a rather high leakage. However, as soon as the overvoltage ceases, the film will regain its dielectric properties and the leakage will drop to its usual low level.

Wet capacitors are ordinarily of the polarized type, i.e., only one electrode, which is connected to the positive side of the circuit, called the *anode,* is covered with the dielectric film. The unfilmed electrode, known as the *cathode,* is connected to the negative side of the circuit; in most wet capacitors the can serves as a cathode. The latter feature contributes to the simplicity and economy of the construction, although it is partly responsible for the nonuniform and rather long paths for the passage of the current between the electrodes. The utilization of the can as an active electrode is made possible in polarized wet capacitors (as ordinarily used in filter circuits) since even a comparatively small *cathode* area when in intimate contact with the low resistance electrolyte will provide the required conductance. To reduce the obstruction to the passage of current to a minimum, the separator, if such is used, is so perforated as to secure a large total open space. The electrolyte is ordinarily very fluid at room temperature and remains *unabsorbed* in the container; it consists of an aqueous solution of an ionizable, film-forming substance.

Special precautions in the construction of the wet capacitor and its mounting in the place of operation are required to make sure that the fluid electrolyte will not leak out in storage, transportation or use, as otherwise the device may lose some or all of its capacitance. The same trouble may result from excessive evaporation or electrolytic decomposition of the electrolyte due to prolonged overloading or high ambient temperature. Furthermore, to obtain the full rated capacitance from the wet condenser, it must be so mounted that the entire active surface of the anode is covered with electrolyte. The installation of the capacitor must also permit an unobstructed functioning of its vent.

If wet capacitors are to be used at low ambient temperatures, provisions are necessary to prevent the freezing and consequent loss of conductivity of the electrolyte which would render the device temporarily inoperative. After melting, however, the conductivity of the electrolyte is restored and the capacitance regained. In general, the limitations for the use of wet capacitors in the various fields are much greater than is the case for the dry type.

The conventional dry electrolytic capacitor (Fig. 5–B) comprises a winding very similar in its appearance to that of a wax- or oil-paper nonelectrolytic capacitor, as illustrated by Fig. 5–A. The winding consists of two foils of which at least one must be of a film-forming metal; in commercial electrolytic capacitors both foils are practically without exception of aluminum. They are interleaved with paper layers impregnated in a suitable electrolyte. The latter is known as nonaqueous, as it contains not more than a few per cent of water. As a rule, *no unabsorbed* electrolyte is present in the container and it is due to this



(Courtesy Delco Remy Division of General Motors Corporation.)

FIG. 5–A.—Wax-impregnated paper capacitor, ignition type.
A—partly unwound capacitor section.
B—foils.
C—papers.
D—completed capacitor section.
E—capacitor assembled in can.

fact that these spacer-wound capacitors are designated as "dry," regardless of the fluidity or solidity of the impregnant.

Since the foils are very closely spaced, usually between 0.001″ and 0.006″, the resistivity of the electrolyte may be comparatively high without unduly increasing the resistance of the path for the current flow. The rather high resistivity is inherent in most nonaqueous electrolytes commonly used in dry capacitors and is advantageous in this

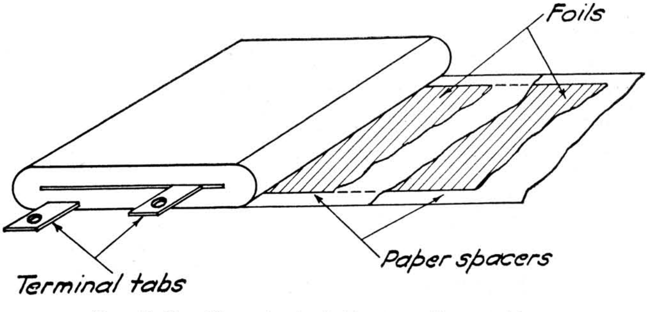


FIG. 5–B.—Dry electrolytic capacitor section.

application, as it improves the breakdown characteristics of the unit. Enough electrolyte is used to saturate the paper spacer thoroughly, but an excess or unabsorbed impregnant is undesirable as it would not improve the performance of the capacitor while it would make more difficult the prevention of its oozing out of the container.

Because of the close spacing of the electrode foils and the thin gauge of the latter (down to 0.0005″), the dry capacitor can be built very compactly, saving space and weight. Furthermore, two or even more sections of the same or of widely different voltage ratings can be assembled in one container, as shown in Fig. 6, without interference among the sections, as the latter can be effectively insulated from one another. But even if a leakage path were accidentally established from section to section through the electrolyte, the stray currents would be greatly attenuated because of the high resistivity of the nonaqueous electrolyte. With wet capacitors, the possible flow of stray currents of a substantial magnitude through the low-resistance aqueous electrolyte makes much more difficult the mounting of several sections in one container, particularly so when there is a considerable potential difference among them.

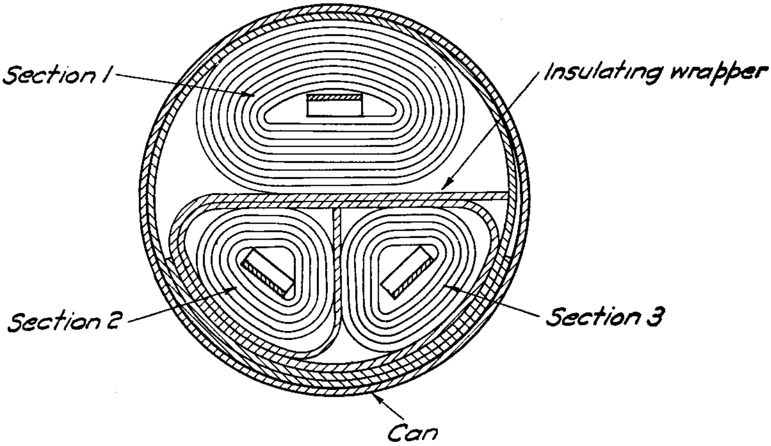
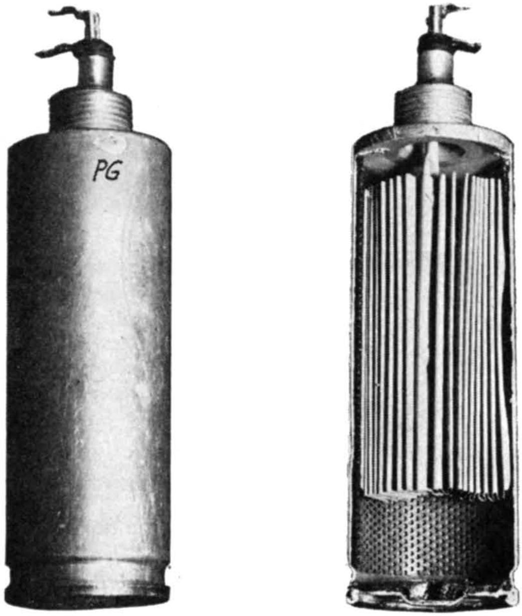


FIG. 6—Three-section dry electrolytic capacitor.

An outstanding advantage of the dry type is its adaptability to the various operating and installation requisites. Because of the exceedingly close and uniform spacing of the foils, the resistance to the current flow is low and consequently the I^2R losses within the electrolyte-impregnated spacers are small. This feature makes the dry capacitor usable even where the current density at the foils is great, as is the case with low voltage units rated for a high amperage.[1] The latter type is, for instance, employed in filtering the commutator ripples of low-voltage d.c. generators for which condensers of enormous capacities are sometimes required. Because of their extreme compactness, dry electrolytic capacitors of 20,000 MF and greater, but rated for a very low voltage, can be mounted in boxes of the size of an ordinary automobile storage battery.

The dry capacitor is also more suited for high-voltage circuits. Single dry sections for up to 600 V d.c. are available, while wet capacitors are mostly rated for less than 500 V. When capacitors of a rating in excess of 600 V are required, or the operating conditions are particularly severe, series combinations of dry sections are usable and readily accommodated within one container.



(Courtesy Aerovox Corporation.)

FIG. 7.—Polarized wet electrolytic capacitor.

In a.c. circuits, for instance for the starting of single-phase induction motors, dry capacitors are almost exclusively used. This is due

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[1] By this is meant that the d.c. component of the voltage applied to the condenser is low and therefore the film is formed at a correspondingly low voltage; this in turn results in a great capacitance per unit area and permits the flow of a large alternating current component (or ripple).

to their moderate electrical losses, as expressed in a comparatively low power factor, to their satisfactory operation at rather high and low ambient temperatures and in any position—upright, inverted or otherwise. Moreover, they are inexpensive and compact and can be assembled in containers of diversified materials designed to fit into spaces of practically any configuration—cylindrical, rectangular, deep or shallow, and so on, as suggested in Figs. 46–47.

There is little danger of the dry condenser leaking, and even if that should occasionally happen, the device will not lose its capacitance (provided the electrolyte is properly compounded) as the oozed portion represents an *excess* of the impregnating material.

Although the dry type is by far more adaptable mechanically and electrically to various service conditions and therefore its application is more extensive and diversified, it is inferior to the wet type when it comes to frequent and severe voltage surges and short-lasting overloads (neither type is safe if the overloads are prolonged). An overvoltage may cause arcing-over between the foils, puncturing the paper spacer. Although the resulting short circuit is frequently automatically healed, sometimes the damage is permanent and puts the unit out of commission. The operation of the dry capacitor at or above the critical voltage of the film results in minute sparks, which cause pitting of the foil (particularly at the terminal tabs) and may, in the long run, sever it and render the device inoperative. The little sparks have also a tendency to produce dry or carbonized spots on the paper spacer, which may eventually facilitate a flashover in case of a surge.

IV

The Electrodes of Electrolytic Capacitors

The true cathode of the electrolytic capacitor is the electrolyte (or, more accurately, its ions, which thus play the part of one of the electrodes), the film is the dielectric and the anode is the second electrode represented by the metallic member on the surface of which the film is formed. However, to establish a good contact between the electrolyte and the external circuit, a second metallic member is required; the latter is in intimate contact with the electrolyte and is called in practice the cathode, although it serves primarily to distribute the current over, or pick it up from, the electrolyte. This arrangement, as illustrated by Figs. 4, 7, 8, is characteristic of *polarized* or *asymmetric* capacitors, intended for operation with unidirectional potentials. For such use a single dielectric film is sufficient and the second electrode—the cathode—does not have to be necessarily of a film-forming metal. It is essential, however, to select for its construction a material which is not attacked by the electrolyte and which will not contaminate the latter. It must, of course, meet the usual structural requirements and be of moderate cost. The cathode foils of dry electrolytic capacitors are made of aluminum, though of a lower grade than required for the anodes, a purity of about 99% being satisfactory. Aluminum has been preferred for the cathode foil because of its comparatively low price, light weight and consequently great coverage, ease of fabrication and

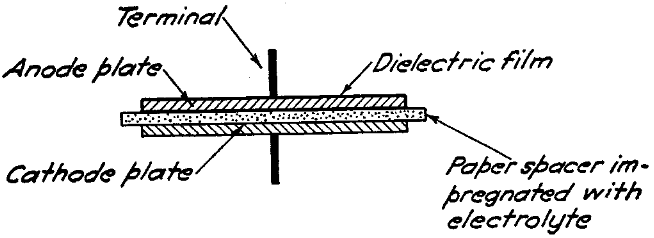

FIG. 8.—The essential component parts of a dry polarized electrolytic capacitor.

winding. It is not apt to corrode while in storage and is not attacked by the usual electrolytes, nor does it contaminate them.

In wet capacitors, where the can serves commonly as the cathode, copper has been used in competition with aluminum. In fact, when aluminum cans are employed, chromium plating of the latter is frequently resorted to in order to prevent the formation of a film on the cathode by the ripple current in the course of the operation of the device. The dielectric film on the cathode may be objectionable because it is in series with the film on the anode and thus tends to reduce the effective capacitance of the condenser (simulating the setup in a nonpolarized unit).

In *nonpolarized* or *symmetric* capacitors, used in a.c. circuits, the electrolyte is again the true cathode, but in this case two aluminum electrodes, both provided with dielectric films, must be used, as shown in Fig. 60–B. Each of the films, however, is fully effective only while it is subjected to a positive potential, i.e., during the respective positive half cycles. On the negative half cycles the dielectric properties of the films are alternately reduced to a small value and during that time the foils on which they are formed serve to distribute the current over the electrolyte by conduction. The arrangement in this capacitor is equivalent to the series-opposition connection of two polarized units, as in Fig. 60–A. With this combination the two units become alternately effective and substantially ineffective as the polarity is reversed. In both analogous cases, as the voltage alternates, the electric charges are being shifted from the one film to the other back and forth. It must be noted, however, that the symmetric electrolytic capacitor differs basically from the series combination of two nonelectrolytic capacitors. In the latter case both dielectrics remain fully effective at all times and the electric charges in the two units rise and fall simultaneously.[1]

Tantalum and magnesium are mentioned in literature along with aluminum as suitable *anode materials* for electrolytic capacitors; however, only the last of the three named metals is used extensively in commercial practice. The price of tantalum is prohibitive; more recently, notable progress has been made in reducing the cost of tantalum anodes for wet condensers by making them porous, thus greatly increasing the surface area in contact with the electrolyte and therefore

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[1] C. I. Zimmerman (Transactions of the Amer. Electroch. Soc. Vol. V. 1904) brought out another important difference between nonpolarized (symmetric) electrolytic capacitors and nonelectrolytic capacitors. When operated in alternating current circuits the electrolytic condenser discharges and recharges only one half of the electricity it can store according to its capacitance. The nonelectrolytic condenser discharges completely and then recharges to its full capacitance.

also the capacitance per unit of weight. The results obtained, though encouraging, do not yet permit a commercial competition with aluminum electrodes. Tantalum electrodes can be used with practically any electrolyte, except hydrofluoric acid.

Magnesium is less available than aluminum and would not bring about a reduction in cost if used as a substitute; its fabrication into anodes is not as convenient as that of aluminum. Magnesium presents some interesting possibilities, because electrodes made of it are usable in conjunction with certain electrolytes which would attack aluminum anodes.

The greater the purity of the aluminum used for making capacitor anodes, the better, as apparently none of the usual impurities or additions improve the film-forming properties of the electrode; most of them will rather tend to impair the formation of an effective dielectric film. On the other hand, the price of aluminum rises rapidly with the increase of its purity and it should be determined in every particular case whether the additional cost is justified by the improvement secured. The selection of the grade of aluminum will depend largely upon the type and voltage rating of the capacitor. Wet capacitors are in general more sensitive to impurities; the adverse effects resulting from impurities are more pronounced at higher operating voltages. In cases where the lowest possible leakage current and a minimum of "deforming" are prescribed, aluminum of the highest purity is recommended.

Ordinarily, aluminum used for capacitor anodes is of a purity between 99.6% and 99.8%. It is claimed that aluminum of the highest purity, up to 99.99%, exhibits some unusual properties; for instance, it resists much better the attack of certain corrosive agents (including dilute solutions of hydrochloric acid) as compared with the 99.8% and lower grades of aluminum. The bulk of the impurities in aluminum used for capacitor anodes consists of iron and silicon; when copper electrodes are used in the electrolysis of the aluminum ore, some copper may be present even in the highest grade of aluminum. Other elements, like zinc, magnesium, manganese, titanium, gallium, are usually found only as traces.

It is not definitely known which, if any, of the impurities commonly occurring in aluminum has a specifically detrimental effect upon the dielectric film. Nor has it been established whether the particular state of iron, copper, silicon, and so on, in which they are present (free, in solid solution or as metallic compounds) has a bearing on the dielectric properties of the film. Little is known about the effect of the grain size in the aluminum electrode upon the film. It has been, however, well established that two batches of aluminum, both of the 99.8% grade, may differ widely in film-forming properties. This may be due exclusively to the surface condition[2] of the electrodes—minute quantities of dirt, oil, grease, inclusions or occlusions of foreign matter, or oxides formed spontaneously on exposure to the air. However, the difference may also be caused, at least in part, by traces of certain harmful impurities (present in the metal itself from which the anodes were fabricated) exerting some specific (inhibiting) and potent effect upon the film formation.

In this connection it appears worth mentioning that the author has carried out extensive experiments with nonpolarized capacitors wound with aluminum foils (all from one particular shipment) of 99.3% purity and used on 110 V 60 cycles and in some cases on substantially higher voltages. The various tests, including life tests, gave entirely satisfactory results. The difference in leakage current, capacitance per unit area, power factor and breakdown characteristics between condensers made with 99.3% and those with 99.8% pure foil was slight. These results may indicate that the presence of *certain* impurities[3] in the anode, even in an appreciable proportion, does not necessarily impair markedly the function and life of the capacitor. If the purity of the foil is lowered still more, it may become advisable to cleanse its surface prior to filming and to make adjustments on the operating electrolyte to minimize the possible adverse effects of the impurities. Such adjustments will usually comprise an increase in the resistivity of the electrolyte.

It is generally considered that annealed, "dead soft" aluminum has superior film-forming properties, though no conclusive proof has been established to that effect. In fact, it appears that there is no connection between the tensile strength and elongation of the aluminum on the one hand and the film formation on the other. From the point of view of processing, a moderately hard aluminum is preferable, particularly in dry capacitors comprising very thin foils. The greater tensile strength of the harder foil makes the etching, filming and winding easier. On the other hand, in the course of annealing, oily and greasy substances, left over on the surface of the metal at the mill (in rolling,

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[2] Storing of aluminum foil under ordinary atmospheric conditions, even over periods of years, does not seem to affect its film-forming properties.

[3] Iron and silicon are always present in aluminum and constitute the bulk of the impurities in aluminum both of the 99.3% and of the 99.8% grade. In the former these elements are present, of course, in substantially larger proportions, but since the film-forming properties of the two grades do not necessarily differ very much, it may be assumed that the mentioned impurities are not potent inhibitors of film formation.

and so on), are substantially removed by the high temperature in the oven. Some investigators ascribe additional advantages to the heating of the aluminum anodes prior to or following the film formation.

It is advantageous to supplement the cleansing effect of the annealing with a wash of the anodes before putting them through the etching or filming process. Depending on the nature of the surface impurities, an organic solvent like naphtha or an inorganic, for example, a mild solution of trisodium phosphate, followed by rinsing with distilled water could be used. In a number of cases, erratic characteristics of capacitors, as indicated by an excessive leakage current, high power factor and poor breakdown characteristics, have been traced to some imperfections on the surface of the aluminum foil. It has been found that quite often these troubles can be eliminated by washing the aluminum electrodes, prior to their filming, with a rather strong solution of nitric acid, followed by a thorough rinsing with distilled water. In addition to a general cleansing effect, this acid tends to remove from the surface of the aluminum electrode minute particles of heavy metals (present as constituents of the electrode or as inclusions resulting from rolling and other steps of fabrication) which are apt to impair the formation of a continuous, dense dielectric film. The poor film-forming properties of an inferior anode may be also offset, in some cases and to a limited extent, by raising the formation voltage. However, this is done at the expense of a corresponding reduction in capacitance per square inch of electrode surface.

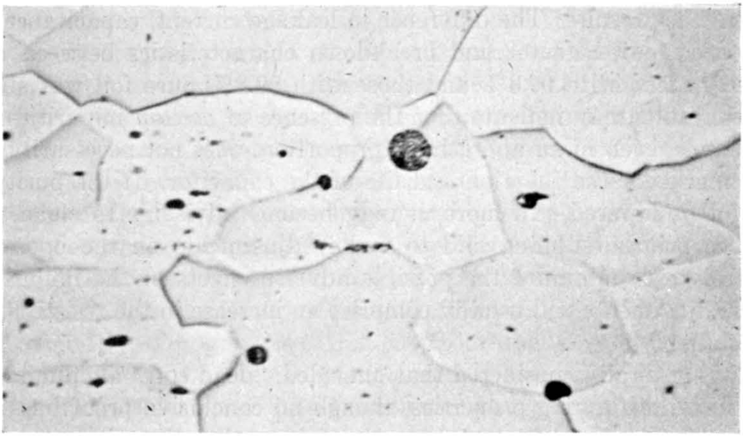

FIG. 9.—Microstructure of 99.8% aluminum foil after an electropolish. The constituents are aluminum-iron and aluminum-iron-silicon compounds. Mag. 500 × (*Aluminum Research Laboratories*).

No connection has been found between the bright or dull surface of the aluminum anode and its film-forming characteristics; nor does the spotty appearance of aluminum necessarily indicate any inferiority in film-forming properties.

Microscopic examinations of properly prepared samples (Figs. 9–10) of the metal give valuable information as to the presence of some of the usual impurities. Apart from the standard methods of chemical analysis, certain short cuts are used to determine quickly, with fair accuracy, the percentage of elements like iron, silicon and copper commonly found in aluminum. In production practice, such quick quantitative determinations are frequently made for iron, on the assumption that the percentage of this element gives an idea as to the purity of the aluminum sample in general. Such analysis, with a proper setup, can often be carried out in about ten minutes.

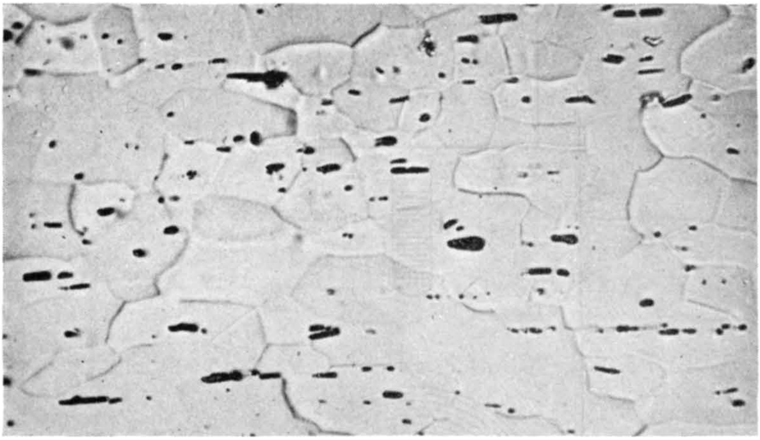

FIG. 10.—Microstructure of 99.2% aluminum foil after an electropolish. The constituents are aluminum-iron and aluminum-iron-silicon compounds. Mag. 500 × (*Aluminum Research Laboratories*).

A spectographic analysis, when available, reveals interesting facts relative to the presence of traces of various impurities. As an example, the results from such an analysis on a sample of aluminum of the 99.8% grade are stated herewith:

Bulk of impurities: iron, silicon and copper.
Traces: magnesium, manganese, titanium and gallium.

The importance of using anodes of a suitable composition and of keeping their surfaces clean cannot be overemphasized. It has been demonstrated that capacitors of the same design and construction, put through identical processing and comprising the same electrolyte, differ greatly in performance solely because of a hardly perceptible difference in their anodes. More investigation is needed to establish definitely the various factors which directly or indirectly affect the properties of the anodic film as used in electrolytic capacitors. By correlating the results from the various tests on the anodes with the behavior of the latter when built into capacitors, valuable information

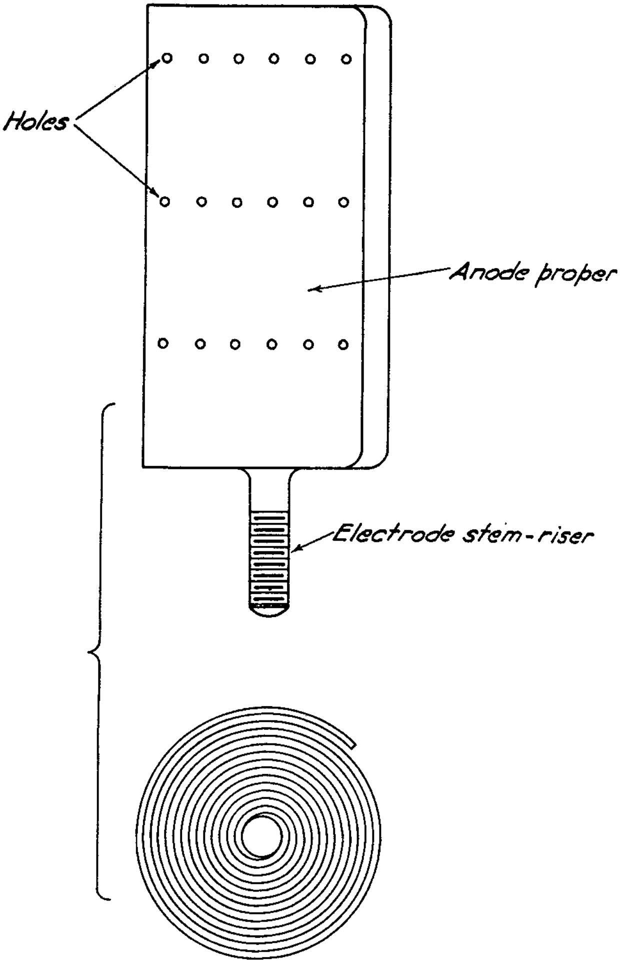

Fig. 11.—Rolled or spirally wound anode for wet polarized capacitor.

may be gained and then utilized in the control of the manufacturing processes.

Figs. 11, 12 and 13 illustrate some of the anode constructions used in wet capacitors. Among the objectives of the design are exposure of a great active surface to the electrolyte; reduction of the resistance to the current flow through the electrolyte, which necessitates keeping the distances between the electrodes as short as practicable; rigidity; light weight; simplicity of construction and ease of fabrication; convenient assembling and low cost. To shorten the path for the current between the electrodes, holes are provided in the anode of Fig. 11 and the plates in Fig. 13 are closely spaced. The latter construction is more efficient because of the intermeshing of the electrode plates of opposite polarity, but it is complicated, costly and therefore less frequently used. Embossments are sometimes made on the rolled anode to prevent contact between the individual turns. Such contact would render inactive portions of the anode and reduce the capacitance of the condenser.

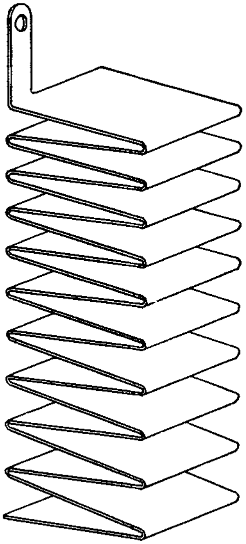

FIG. 12.—Pleated anode for wet polarized capacitor.

It has been observed that the anode (or its riser) in a wet capacitor is particularly vulnerable (subject to corrosion and pitting) within the zone where it emerges from the electrolyte. It is advantageous therefore to bring out the anode stud through the bottom of the container (viewing the unit as it is mounted for operation) and have thus the entire anode structure completely covered with electrolyte while the capacitor is in its operating position.

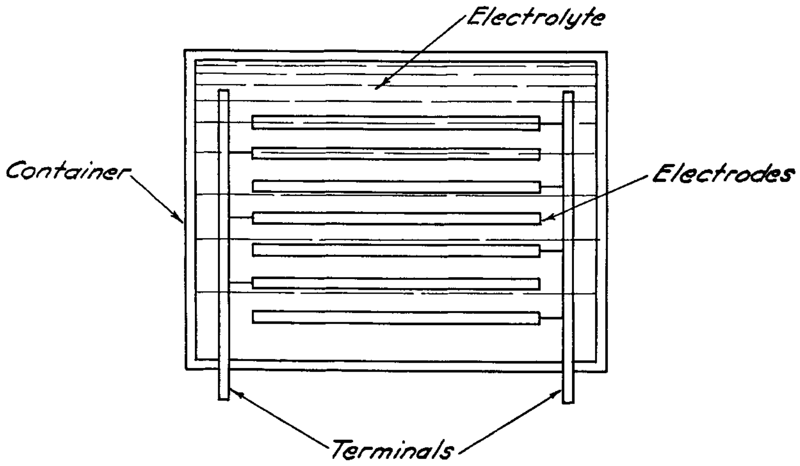

FIG. 13.—Schematic drawing, top view, of wet electrolytic capacitor with intermeshed plate electrodes.

The anode of the dry electrolytic capacitor consists invariably of aluminum foil; its gauge is usually between 0.0005″ and 0.005″, the heavier foils being used if etching is intended prior to filming. It must be realized that an appreciable proportion of the metal is being dissolved by the cleaning and etching solutions and consequently foils subjected to such processing are ordinarily not thinner than 0.003″.

V

The Dielectric Film—Theoretical Considerations

When a piece of aluminum is immersed in a suitable electrolyte—for instance, an aqueous solution of boric acid and sodium borate—and made the anode in a d.c. circuit, as shown in Fig. 14, an oxide film is formed on the surface of the aluminum. Films can also be formed on aluminum by using a.c., but d.c. is ordinarily found more convenient for this purpose. Filming has also been done by superimposing a.c. on d.c. or by forming the anode first with a.c. and then d.c. to obtain

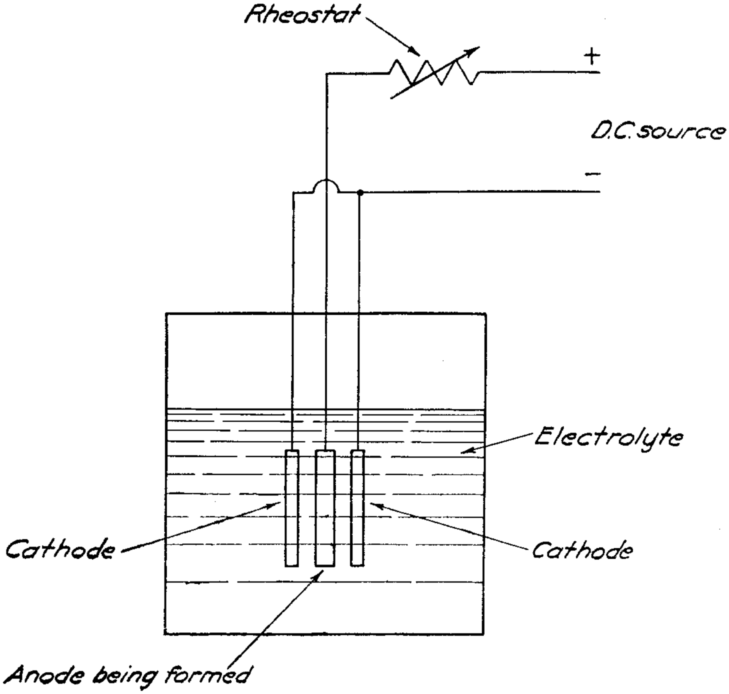

FIG. 14.—Electrolyte bath for the formation of capacitor anodes, batch method.

two oxide coatings of different but complementary properties. At moderate and higher formation voltages, the film is fairly well visible to the unaided eye. Its color is due to light interference effects and depends on the thickness of the film, which in turn is governed by the magnitude of the formation voltage. At very low voltages, 10 V or so, the film may be invisible, particularly so if the forming electrolyte is dissolved in a medium like glycerin instead of in water. The actual presence of a dielectric film on the surface of the aluminum anode is, however, manifested by the capacitance effect at all voltages within the practical range—say from 3 to 800 V or so. Throughout the greater part of this voltage range the inverse proportionality of the capacitance with respect to the formation voltage, as expressed by the equation

$$C \times E = \text{constant} \tag{7}$$

holds quite accurately (C = capacitance; E = forming voltage).

The oldest theory advanced relative to the nature and action of the anodically formed dielectric claims that it simply consists of the visible coating of aluminum oxide or hydroxide. This layer is exceedingly thin and its dielectric constant eventually assumed to be very high, which would account for the great capacitance per unit surface area of the anode. More recent investigations (chemical and X-ray) indicate that the visible anodic coating on capacitor electrodes is an oxide of aluminum, which contains very little physically absorbed water—a few per cent of its weight. However, if the anode is subjected to the action of boiling water (called sometimes the "sealing operation"), as it often happens incident to the film formation, a hydration of the oxide and a change in its structure may possibly take place. The above theory is supported by the fact that the visible oxide film and the dielectric effect ordinarily appear simultaneously during the formation process. It is, however, difficult to account for the great capacitance of the condenser by an unusually high dielectric constant of the coating, as the constant for aluminum oxide is only of the order of 7. On the other hand, if the extreme minuteness of the film thickness, which may be of the order of one millionth of an inch, is to explain the great capacitance effect, a very great dielectric strength must be attributed to the oxide coating as it often has to withstand several hundred volts. It is difficult to assume that the material alumina (aluminum oxide—$Al_2\,O_3$) has the corresponding dielectric strength of tens of thousands of volts per mil (0.001″), the more so as the absorbed water would rather tend to lower the disruptive strength of the insulating coating and also in view of the fact that there are cracks and other imperfections in the latter. The remarkable unilateral or *rectifying* properties of the film make the explanation even more complicated. Furthermore, the surface of the anode may have lost markedly its dielectric properties because of prolonged idling, or because of operation with a reversed polarity, or as a result of excessive heating. The visible condenser film, however, does not seem to change under these influences. This observation would point to the fact that the presence of the visible film is not a complete explanation of the dielectric effect (unless the film is undergoing some changes which are not observable).

Another theory suggests that the true dielectric is constituted by a layer of gas (eventually highly compressed) adsorbed at the surface of the aluminum anode and protected by the oxide coating. A modification of this theory assumes that there are in the coating two or more strata of aluminum oxide of different structures as to density, and so on; the gas (oxygen) is trapped within the pores of the one adjacent to the underlying metal; the outer layer is more porous and the electrolyte penetrates into it. The rectifying effect is explained by the unidirectional conductivity of gases prevailing under certain conditions. The gas theory is supported by the observation that the surface of the anode becomes luminescent when the latter is immersed in a suitable electrolyte and subjected to a voltage approaching the critical value. The luminescence, or glow discharge, is apparently due to the gas which becomes ionized in the strong electric field. It is difficult to explain with this theory the great capacitance of the condenser, as the dielectric constants of gases are low; it is also hard to conceive that an exceedingly thin layer of gas will withstand the rather high potentials which are commonly impressed across electrolytic capacitors. Another question arising in connection with this theory is why anodes made of a number of other metals fail to withstand any appreciable voltage although they too form anodic films and gas is present at their surfaces. It is not clear either why the dielectric properties of the anode (after its formation) should be so strongly and rapidly affected by variations in the composition or concentration of the operating electrolyte, if the gas layer were the only or the major insulating medium.[1]

A third theory assumes that molecular rearrangements and other changes at the metal surface take place during the formation of the anode and are responsible for the dielectric and rectifying effects.

The dielectric formed on the surface of the aluminum electrode has

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[1] Another strong point against the "gas-dielectric theory," hitherto not brought out, is based on the fact that electrolytic capacitors definitely exhibit the absorption effect with its attendant residual charges. Capacitors with gas dielectrics have no absorption or residual charge.

also been viewed as a polarization or as an anodic passivity effect. Other explanations have been advanced as to the peculiar dielectric effects of the anodic capacitor film, some of which will be briefly outlined. The objections mentioned in connection with the preceding theories also apply more or less to the following theories.

The film has a multitude of minute perforations which contract when the electrode is subjected to a positive potential and are enlarged when the polarity is reversed. Accordingly, the movement of anions through the film is greatly impeded, while the cations penetrate freely, which is the cause of rectification.

The film on an aluminum anode is a membrane permeable for certain ions like H^+, but substantially impermeable to others like OH^-, which accounts for the unilateral conductivity. Cl^- (chloride ions) can also penetrate through the membrane, which explains why the rectifying or valve effect is destroyed if the electrolyte comprises chlorides. It must be noted, however, that tantalum anodes are effective in chloride electrolytes.

The film is a coating of gelatinous (colloidal) aluminum hydroxide; the valve action is explained by cataphoresis. While the electrode is subjected to a positive potential it strongly attracts the negatively charged film and the latter tightly covers its surface and insulates it from the electrolyte. When the electrode is at a negative potential it tends to repel the negatively charged film, the contact between the two is loosened, electrolyte penetrates through the gap and comes in contact with the electrode, thus providing a path for the current flow. The deterioration of the valve effect in the presence of chlorides is ascribed to the peptizing or dispersing effect exerted by the latter on the colloidal coating. On the other hand, the introduction of colloids like glue, gums, and so on, is considered to be beneficial as they are apt to strengthen the colloidal aluminum hydroxide film.

The film is permeable to free electrons but substantially impermeable to ions, provided the temperature of the cell is not high. When the metal underlying the film is at a negative potential, free electrons are available in this electrode and the current flows through the film of the cell. With the polarity reversed, the electrolyte is subjected to the negative potential, but as there are only ions and no free electrons in the electrolyte the current is blocked. If the temperature of the electrolyte is raised, the mobility of the ions increases and the leakage current (the current in the blocked direction) progressively rises.

It has also been suggested that the high dielectric constant[2] of the

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[2] Eventually correlated with dipole effects.

usual solvents (water, glycerin, certain glycols, and so on), as employed in the preparation of the condenser electrolyte, may contribute to the great capacitance per unit anode surface area. It is even assumed that some of the solvent alone penetrates into one or more porous strata of the oxide coating and that it may thus contribute also to the dielectric strength of the entire insulator combination on the anode surface.

Apparently, none of the mentioned theories and hypotheses is entirely satisfactory and some of them are distinctly speculative. In attempting to form some idea (based on facts) relative to the dielectric medium in electrolytic capacitors, it may prove helpful to consider, and if possible correlate, certain direct observations, tests and experimental data recorded by a number of investigators. These will be summarized in the following paragraphs.

In practically all cases there is a visible coating on capacitor anodes. This coating consists of alumina, usually with only a few per cent of absorbed water. With certain forming electrolytes traces of the constituents of the latter may be detected in the film. Depending on the film-forming conditions and in general on the treatment of the anode, the film may be brittle or rather flexible, dense or porous, exceedingly thin or of appreciable thickness. Other important modifications in the structure and composition of the film may be effected by varying the forming process in general and the current density and temperature in particular. These modifications may comprise the production of a film which is amorphous or crystalline, anhydrous or hydrated. It appears quite certain that the composition and structure of the anodic oxide film have a pronounced bearing on the electrical characteristics of the capacitor.

It can be demonstrated that one film may be superimposed on another, previously formed on the surface of an aluminum electrode. The two films may have different compositions, structures and properties; the combined film may differ markedly in its appearance and particularly in its electrical characteristics from the individual component films.

There are indications that gas is present in the film or at its surfaces. The liberation of gas from anodes has been observed; the luminescence at the anode at critical voltages also points toward the presence of gas.

The visible film is refractory and not destroyed when the underlying aluminum electrode is fused. The true dielectric is impaired at elevated temperatures but still quite effective, even when a dry electrolytic capacitor is already burning (the temperature recorded at the innermost turns of the winding was around 700°F). After cooling of the unit the dielectric remains markedly impaired but is rapidly and fully restored to its original value when subjected to a re-forming current, if in contact with a suitable electrolyte.

The properties of the dielectric are strongly and adversely affected[3] by the presence of chlorides in the electrolyte or at the anode. Even minute quantities of chlorides—a few parts per million in the electrolyte—markedly weaken the dielectric. This, however, does not apply to tantalum anodes.

While the temperature of the capacitor affects the conductivity of its electrolyte, and this in turn influences the equivalent series resistance and the effective capacitance[4] of the device, the changes in capacitance appear to be too great to be accounted for by conductivity variations only. The correctness of this statement may be checked by varying the conductivity by other means than temperature changes, for example, by using different electrolytes or concentrations. It appears, therefore, that certain properties of the film itself (for instance, its dielectric constant) are influenced by the temperature.

The bulk of the electrical losses[5] in electrolytic capacitors, particularly under normal operating conditions, is to be found in the film or at its interfaces. It is probable that changes in or at the film (including alternating strengthening and weakening of the dielectric) take place periodically as the polarity is being reversed and these changes are accompanied by power dissipation variously termed dielectric hysteresis, electrochemical hysteresis, and so on. The losses due to the leakage current are insignificant except when the capacitor is subjected to excessive voltages or overload in general. The losses in the conducting medium (electrolyte or impregnated spacer) between the metal electrodes are ordinarily of small or moderate proportions, particularly so in the dry type of capacitor. Experiments indicate that hardly perceptible modifications, as traces of foreign matter in the film or at its interfaces, may be responsible for a great variation in the magnitude of the losses and for other changes in the electrical

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[3] In this connection it may be pointed out that aluminum chloride (the formation of which may result from the interaction of the aluminum electrode with the contaminating chloride) is a potent catalyst. The latter may cause the deterioration of the dielectric.

[4] Substantial variations in the dielectric constant of the solvent used in the operating electrolyte do not seem to affect strongly the capacitance per unit anode area.

[5] According to Steinmetz, considerable energy losses are attributable to the continual puncture and repair of the dielectric film. (Charles P. Steinmetz, *Theory and Calculation of Electric Circuits*, p. 10. McGraw-Hill Book Company, New York, 1917.)

characteristics of the capacitor. In particular, the leakage, deforming and breakdown characteristics of the capacitor may be thereby strongly affected.

The capacitance effect of the film is affected by the frequency of the impressed voltage; at very high frequencies the capacitance is drastically reduced (Chapter XVIII).

The capacitance effect of the film is evident even when the contacting medium (the impregnant in spacer-built condensers) exhibits only a very slight conductivity but has a high dielectric constant (Chapter XX).

Depending on the anodizing treatment, the film when dry (out of contact with an electrolyte) may exhibit a moderate or even a very substantial dielectric strength. The dry film, however, has no pronounced unidirectional conducting properties, thus contrasting a film co-operating with a suitable electrolyte. Furthermore, the capacitance effect of the dry film is of a very small order.

VI

The Dielectric Film—Practical Considerations

Though little is known of the true nature of the dielectric film formed anodically on aluminum, considerable progress has been made in controlling the formation process so as to impart to the dielectric and to the coexistent and probably co-operating oxide coating the desired characteristics. For convenience, in the following, the terms *film* and *anodically formed dielectric* will be used interchangeably.

Among the factors which govern the properties of films used in *various applications* are the following:

Purity of the aluminum electrode and the condition of its surface.

Nature and purity of the dissolved filming electrolyte and of the solvent.

Concentration and temperature of the filming electrolyte solution.

Duration of the forming process.

Applied voltage—d.c. or a.c., or the one superimposed on the other; magnitude of the forming voltages and current density.

The properties of the film (respectively of the underlying electrode) affected by these factors include the following:

Insulation resistance.

Dielectric strength and possibly dielectric constant.

Electrical unidirectional conductivity or rectifying effect.

Self-healing.

Ability to withstand the action of corrosive agents in general (protective properties).

Stability and in connection therewith the ability to withstand the action of an operating electrolyte, whether the electrodes are energized or idle.

Thickness of the film, its density, continuity, absorbency, hardness, flexibility, presence of cracks.

Sealing properties upon which depend the retention of the adsorbed substance and the prevention of ingress of extraneous matter.

Intrinsic color and general appearance.
Optical reflectivity.
Heat emissivity.

A number of devices and processes depend on one or more of the mentioned properties. Some of the film characteristics, while useful in one application, may be objectionable in others. Consequently, in each case, the forming or anodizing process must be so arranged as to enhance the properties useful in the given application and to suppress, as far as possible, the undesirable features of the film.

This book is concerned with electrolytic capacitors only and particular attention will be given to such films which are used therein. However, a very brief outline will be made of various anodic films employed in other applications, as their description may indirectly facilitate the understanding of certain peculiarities of the electrolytic capacitor.

For the proper operation of electrolytic capacitors, as most frequently used, it is essential to have a film of as great a dielectric strength and insulating resistance as possible and to make it as stable and durable as feasible. The self-healing properties of the film are also of vital importance, while its valve or rectifying effect may be considered a drawback in many capacitor applications. If the film had equally good insulating properties in both directions, better electrolytic capacitors and of a more general utility could be made. It is probable that the effective sealing of the pores contributes to the stability of the film in the capacitor as it would tend to protect it from contamination; it is also conceivable that the sealed film will resist better the dissolving action (if any) of the operating electrolyte. The thinness of the film, if combined with a sufficient dielectric strength, is desirable in electrolytic condensers, as it tends to impart a great capacitance per unit surface area to the anode.

In the electrolytic rectifier the directional or unilateral conductivity of the film is of paramount importance, as it is responsible for the conversion of alternating into unidirectional pulsating current. The greater the conductance in the "forward" and the less in the "reverse" direction, the more effective the rectification. This involves the insulating resistance in the blocking direction; a sufficient dielectric strength in this direction is also necessary to prevent the breakdown of the device and to permit its operation at comparatively high voltages. The self-healing properties make the recuperation of the rectifier possible in case of a momentary failure due to transient overloads. The capacitance effect is a drawback as it contributes to the flow of some current in the reverse direction. The second electrode of an electrolytic rectifier must be made of a non-film-forming material —for instance, lead—to permit a free flow of current in the forward direction.

The operation of the electrolytic lightning arrester in d.c. circuits has been briefly outlined in Chapter III. In this case the definiteness of the potential at which the dielectric yields, the abruptness of the collapse, the effective and rapid self-healing of the film are of major importance. The high insulating resistance of the film up to the predetermined yielding point is also essential as it reduces to a minimum the electrical losses and heating in the lightning arrester as caused by leakage currents. The rectifying action of the film appears to be of no advantage in most of these applications. Other film characteristics like stability, durability, and so on, are of value in the lightning arrester and rectifier as in the capacitor.

Certain varieties of the filming or anodizing process provide rather heavy coatings on aluminum objects and protect them from corrosion. Such coatings being usually porous may be impregnated with oil or other suitable agents to enhance the corrosion resistance. Coatings of a similar kind make electroplating on aluminum possible as they provide a surface to which the deposited metal adheres firmly. Absorbent oxide coatings serve also as a foundation for the application of suitable dyes, varnishes, light-sensitive substances (for photographic purposes). Heavy and hard films (some of them similar to corundum) greatly increase the abrasion resistance of aluminum. The thickness of such films may be of the order of 0.0001″ and even greater; their dielectric properties are usually poor but this is of little importance for the applications in question. The anodizing process is now used extensively to improve the wearing characteristics of aluminum and to protect from corrosion, staining, smudging, tarnishing, and so on, a great variety of aluminum articles among which are trays and other utensils, ornaments (particularly if installed outdoors), aircraft parts and light- and heat-reflectors. Electropolishing and brightening are also effected by special anodizing processes.

In one particular case the heavy film must exhibit both flexibility and good dielectric properties in the *dry* state (without being in contact with an electrolyte); such anodic films are applied as a substitute for cotton, enamel and similar insulation over aluminum wire used in windings of electrical machines and devices. In this application the oxide coating may be impregnated with a suitable insulating material like wax, synthetic resins, and so on, in order to enhance the dielectric properties (in particular the dielectric strength) of the film.

In most ot the enumerated cases, "sealing" of the film pores is resorted to in order to secure a greater permanency of the effects brought about by anodizing. The sealing may be accomplished by treating the anodized and otherwise processed (dyed or varnished, for example) aluminum object in boiling water or by a subsequent impregnation in oil or with other suitable agents.

VII

The Filming Electrolyte

A great number of electrolytes could be used for the formation of anodic films on aluminum. In fact, most weak electrolytes and many of the strong electrolytes, if sufficiently diluted, will produce anodic films on aluminum if a suitable setup is provided. Among the typical exceptions are strong alkalies like sodium or potassium hydroxide, which vigorously attack aluminum; hydrofluoric acid; hydrochloric acid and the various chlorides as they exert a powerful destructive action upon the film and attack the underlying metal. The properties of the film will vary greatly with the choice of the electrolyte. We shall discuss only a few film-forming electrolytes used extensively in the electrolytic capacitor industry and will mention several electrolytes employed in other branches of the anodizing process.

Among the requirements which must be met by electrolytes intended for the formation of *capacitor anodes* are the following:

1) The electrolyte should not appreciably dissolve the film or attack the aluminum electrode.

2) The formation should be rapid and the film thin, suited to produce the high capacitance effect, withstand the expected voltages in operation and have a high insulating resistance, great stability and other characteristics as outlined in the preceding chapter.

3) The electrolyte must be of high purity, uniform composition and readily available at a moderate price.

4) It should be stable at the temperature used in the film-formation process.

5) The electrolyte must not produce harmful aftereffects if some of it remains on the electrode, or is entrapped within the pores of the film (which may happen in spite of rinsing with water, at the completion of the forming process). Surface deterioration may be such an aftereffect in case some of the corrosive electrolyte gradually seeps out later on. It takes sometimes weeks and even months before the attack on the anode becomes noticeable and its effectiveness is impaired. De-

fects of this kind have been observed, for instance, when sulphuric acid was used in the treatment of capacitor anodes. It is very advantageous if the filming electrolyte is compatible with the operating electrolyte. In such cases, if some of the film-forming substance remains on the electrode, it will not adversely affect the performance of the capacitor, but may even exert beneficial effects. For example, the use of boric acid in the forming electrolyte and phosphates in the operating electrolyte gives entirely satisfactory results in certain types of capacitors.

An aqueous solution of boric acid with the addition of the proper percentage of sodium borate meets the usual requirements for the formation of capacitor anodes and is widely employed. The film formed in a solution of boric acid and some of its salts is dense, impermeable to the solution and practically insoluble in it. As a result, the formation is rapid and stops as soon as an exceedingly thin coating is produced, because the latter, due to its impermeability, prevents any further contact between the underlying anode metal and the ions of the electrolyte. Films of this type, being of such minute thickness, provide poor protection against corrosion and abrasion, have relatively slight adsorbency but excellent dielectric properties; they are well suited for capacitor anodes.

The filming solution may comprise about 10% of boric acid (H_3BO_3) by weight, though substantial variations are tolerable as far as this ingredient is concerned. On the other hand, the addition of sodium borate, usually supplied as $Na_2B_4O_7.10\ H_2O$, must be carefully controlled as it strongly affects the resistivity of the electrolyte solution, upon which depends to a large extent the breakdown voltage of the film. The proportion of sodium borate may be of the order of 1% of the total weight of the solution; for low voltage formation the percentage may be greater to reduce the resistivity of the solution which in turn cuts down the waste of electric power (I^2R). Higher filming voltages call for a solution of greater resistivity and consequently of a smaller percentage of sodium borate. For the highest voltages employed in filming of capacitor electrodes, say above 500 V, a straight boric acid solution, with no sodium borate at all, is often preferred.

The purity of all constituents of the solution, including the water, which should be distilled, is of prime importance. Particular attention must be given to the prevention of contamination with chlorides, as their interfering effect with the film formation is most potent. A few parts per million of chlorides, present in the forming or operating electrolyte, may adversely affect the quality of the film.

Ammonium borate is used sometimes as a substitute for sodium borate in the film-forming solution, particularly when filming at high voltages is required; the former compound is, however, less stable than the latter.

Oxalic, sulphuric and chromic acids and their salts, although not used extensively for the formation of capacitor anodes, have proven to be of great utility in other anodizing processes. Sulphuric acid solutions, for instance, are very effective in forming heavy adsorbent films which will also resist abrasion. The three last-mentioned acids have an appreciable dissolving effect on the film and tend to make its structure porous. Through the multitude of pores or capillaries the contact between the electrolyte and the underlying metal is sustained, and therefore the formation current can continue to flow, resulting in a deeper growth of the oxide into the metal. Films formed in oxalic, chromic and sulphuric acids are consequently rather thick. By properly adjusting the formation process, they can be made comparatively hard and more or less adsorbent to afford protection against abrasion and to facilitate subsequent impregnation with oil, or dyeing, electroplating and the like. The dielectric properties of most of these films are mediocre.

Electrolytes used in electropolishing—for instance, solutions of hydrofluoric acid—attack the film even more vigorously than the three last-mentioned acids. In fact, such solutions dissolve the film as it is formed; to preserve the brightened surface, the aluminum object is subjected to a second anodizing treatment, in a different solution, which forms a permanent, protective oxide coating.

Whatever electrolyte composition is chosen for the formation of the capacitor film, it is essential to observe the rules for the purity of the constituents of the solution and it is equally important to adjust its resistivity to best suit the required filming voltage without causing an undue waste of power. A special cell is used for measuring the conductivity of the solution which is the reciprocal of its resistivity. The optimum resistivity is determined experimentally and should be maintained substantially constant in the course of the filming process, as described in the following chapter.

The acid or alkali content of the filming solution is determined by titration; the active acidity or hydrogen ion concentration, as expressed in pH values, is checked by using the electrometric or colorimetric method. However, investigation based on numerous experiments indicates that these two factors are less important than the resistivity of the solution; substantial variations in acid or alkali content and in hydrogen ion concentration have only a moderate effect on the properties of the dielectric film in capacitors.

A gradual accumulation of aluminum hydroxide in the solution takes place in the course of the anodizing of aluminum. The dissolving of extremely thin strata of aluminum can be observed, for instance, when an aluminum coating on a glass plate is made the anode in the filming bath (such thin coatings may be deposited by heating and volatilizing aluminum under vacuum). The accumulation of aluminum hydroxide in the bath is reflected in the change of the resistivity of the solution, and, if of great proportions, may impair its film-forming properties. Within rather wide limits the increased resistivity is compensated for by raising the filming voltage and thus maintaining the current density constant. When the solution has "aged" to the point that such adjustments become difficult, it is advisable to replace it with a fresh one. The disposal of an old solution is required also because of its progressive contamination with impurities introduced with the anodes and otherwise.

VIII

The Filming Process and Equipment. Re-forming

As already indicated in the foregoing, the film formation on capacitor electrodes represents one of the several varieties of the anodizing process. Upon the formation of a film of the proper type and quality depend to a large measure the life and a number of the operating characteristics of the condenser, as, for instance, the following:

Capacitance per unit surface area.
Breakdown voltage.
Leakage current and deforming properties.
Power factor.

Absence of scintillation or arcing at the electrodes (the scintillation causes pitting of the electrodes and their eventual deterioration).

The uniformity of the electrical characteristics of the capacitors in production depends also largely on the effective control of the film formation.

One of the two methods described in the following is generally adopted for the formation of capacitor anodes, namely the *batch* or the *continuous* method. The first is most frequently used in the manufacture of wet capacitors. It calls for the immersion of a number of aluminum electrodes in the electrolyte bath and their connection in a d.c. circuit of which they form the anode, while the tank, being joined to the negative side of the circuit, serves as a cathode. Separate cathodes, in close proximity to the anodes, may be installed to reduce the length of the path for the current flow and hence the resistance, as shown in Fig. 14. The tank cathode, however, provides a simple and satisfactory setup, as the resistance of the path is of only moderate importance when the batch method (which is usually stationary, i.e., with the anodes at rest) of film formation is used. To avoid an excessive current flow at the start of the forming cycle, either the voltage of the d.c. generator is kept low or, if the source of supply has a constant potential, a rheostat is inserted in series with the circuit to keep the current within the desired limits. As the film formation progresses, the insulation resistance of the dielectric on the anodes rises and the current drops simultaneously. The potential across the cell should then be raised periodically, until the ultimate desired formation voltage is reached and the leakage current has dropped to a predetermined value. The process is then discontinued, the anodes are removed and rinsed with distilled water, after which they are ready to be assembled into capacitors or stored in a clean, well-protected place (the film is particularly apt to adsorb foreign matter right after its formation and may therefore be easily contaminated).

The batch method can be modified in several ways; a.c. can be used in place of d.c., although the process is controlled with greater ease in the latter case. With the a.c. formation half of the anodes may be interconnected and used as one electrode of the cell, while the rest of the anodes are joined in another group and represent the second electrode. When the anodes are formed on a.c., the film is subjected for a longer time to the dissolving action of the electrolyte, and current in the reverse direction is flowing through them during alternate half cycles. It is claimed that the film formed on a.c. is more flexible but of lesser density.

The aluminum electrodes may be energized on d.c. up to the ultimate formation voltage prior to their immersion. Then they are introduced into the solution very slowly, whereby a relatively small electrode area is filmed at a time. With this procedure, the current density is great, without, however, causing an excessive drain on the source of supply. As the gradual immersion continues, larger areas of the electrode surface are in contact with the solution, but the magnitude of the current in the circuit does not change much, since the preceding area has been already substantially filmed because of the prevailing great current density. This modification provides the advantages attributed to the film formation at a great current density; namely, a more permanent dielectric, resisting "deformation." This effect may be explained eventually by the fact that the increased current density entails intensive heating of the area on which the formation of the film is taking place, which in turn tends to cause the "sealing" of its pores. Furthermore, the high temperature, the vigorous gas and steam evolution which also cause agitation of the solution are instrumental in cleaning the surface of the anodes and this is beneficial for the formation of the dielectric coating. Finally, the abundance of nascent oxygen resulting from the vigorous electrolysis of the solution at the anode surface promotes a rapid and effective formation of the oxide coating. It has been already indicated in preceding chapters that the high temperature at the spot of formation, combined with the steam surrounding the anode and eventually the strong electric field set up across the film as it is formed, may have some effect on the composition and constitution (hydration) and on the structure (amorphous or crystalline) of the coating.

The tank is preferably made of aluminum or of some other metal which is not attacked by the electrolyte and which is not apt to contaminate it. The racks, clamps and their extension on which the anodes are suspended and which may be in contact with the solution must be of high purity aluminum; the dielectric film formed automatically on this equipment reduces to a minimum the undesirable stray currents in the bath. But the contact points between the anodes and the supporting members must be kept clean and free from any insulating film, as such would interfere with the free flow of current from the rack into the anodes.

The ultimate formation potential must exceed substantially the working or operating voltage of the capacitor to insure for it a low leakage current, a low power factor and a satisfactory safety margin. The difference between the ultimate forming and the expected peak voltage is chosen with regard to the prevailing operating conditions; the margin may be small—about 10% of the peak voltage—but it also may be much greater.

The forming solution for capacitor anodes may be heated from an external source to enhance the above-mentioned beneficial effects ascribed to the hot electrolyte. On the other hand, some of the corrosion-protective and abrasion-resistant anodic films are better formed at rather low temperatures, and, when such coatings are desired, artificial cooling of the bath may be resorted to.

During the film formation cycle, water is continuously lost from the bath because of evaporation and electrolysis; when the solution is kept hot, sometimes near the boiling point, the losses are very substantial. To maintain the original level and to keep the concentration and resistivity of the solution fairly constant, distilled water and eventually some of the active ingredients must be added from time to time. Stirring of the electrolyte is advisable to keep the solution uniform in its composition and temperature throughout the bath.

Although the "throwing power" of the electrolyte is an important consideration in electroplating, it has a minor effect in the anodizing of capacitor electrodes, particularly so when the batch method of filming is employed. This is explained by the fact that although the portions of the anode nearest to the cathode have at the start a better chance to be coated with a film, because of the dielectric properties of the film, the current flow through them is reduced as the coating is being built up. Meanwhile, the formation on more remote areas of the anode proceeds intensively until they too are well covered with the dielectric; thus, an automatic regulation of the current distribution takes place.

The continuous method of film formation is most extensively used when aluminum foil is employed for the anodes, as is generally the case with dry electrolytic capacitors. The filming in this case is also usually effected with direct current; Fig. 15 illustrates a setup for the continuous process. With the latter, as in the case of batch formation, all precautions must be taken to prevent the attack on the tank and the filming equipment by the solution and also to preclude the contamination of the solution with impurities, in particular with chlorides. For the tank and other metallic parts, aluminum is recommended; if necessary, bearings and other small parts and accessories (not in contact with the anode) may be constructed of stainless steel. Those parts

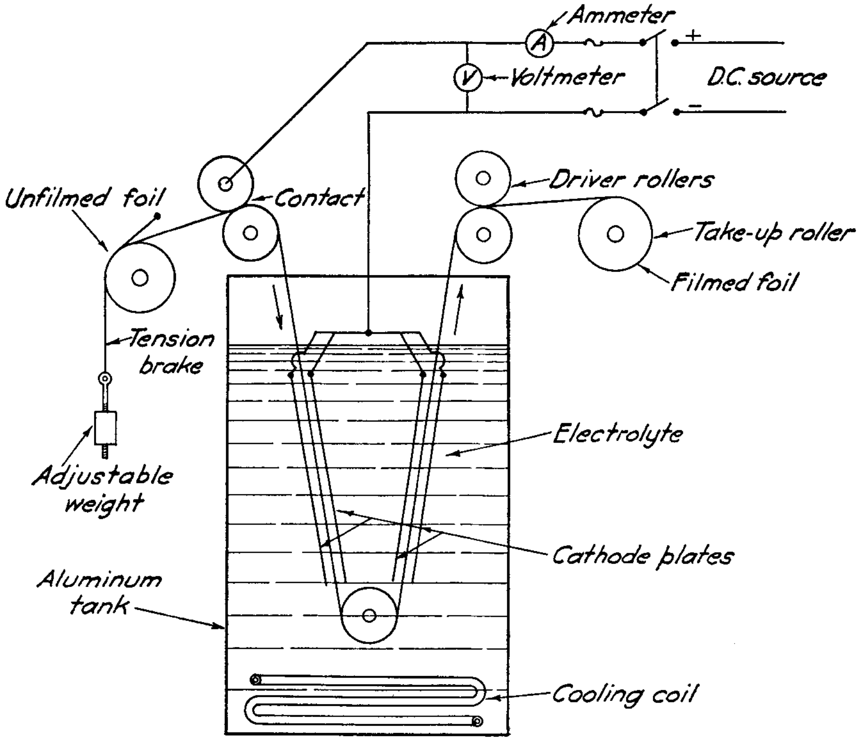

FIG. 15.—Schematic drawing of a machine for the continuous filming of aluminum foil.

like rollers, spacers, and so on, which are touching or may accidentally be in contact with the energized foil, must be of a suitable insulating material—glass, ceramics, hard rubber, Bakelite, and the like.

It is essential to arrange the driving and re-reeling mechanism in such a manner that the foil will travel at a constant speed. To accomplish this a slipping clutch or a re-reeling motor of a special design is used which adjusts automatically the speed of the take-up roll as the diameter of the filmed coil is gradually growing. On the other hand, the speed of the driving rollers must be strictly constant.

To avoid excessive and unnecessary resistance to the flow of the filming current, a firm, clean contact must be provided directly between the exposed foil surface (preferably near to its entrance into the electrolyte solution) and the live roller as indicated in Fig. 15. This contact must be unaffected by the vapors from the solution which may be corrosive to some extent.

The mechanical tension on the foil and the construction and adjustment of the rollers and the accessories must be such that breakage or distortion of the foil or its lateral displacement or injury to its surface is prevented.

As unfilmed portions of foil are continuously entering the solution at a steady rate, the electric current is substantially constant and of a comparatively great magnitude, depending in particular on the forming voltage, width of the foil, and speed at which it is moving and also on the properties of the foil and the electrolyte. The current may be, for example, of the order of 100 amps. and the potential a few hundred volts. Consequently, large amounts of energy are dissipated within the filming bath. This electrical energy is partly converted into heat and partly used up in the electrolysis of the solution, with the evolution of hydrogen and oxygen. The current density and the heat given off in this process are of the greatest magnitude at that small region of the foil which just enters the solution. As the unfilmed foil hits the latter, a large proportion of the total current flows from that small foil surface into the bath and the enormous current density in this region effects an almost instantaneous film formation. Thus, the areas of foil a little farther down in the bath are already coated with a dielectric and they permit the passage of only a small proportion of current into the electrolyte. Hence, the major portion of the film is formed right at the entrance of the foil into the bath, where the temperature of the metal is very high—far above the boiling point of the solution and under certain conditions approaching the fusion temperature of aluminum. Film-forming conditions set up in this case are therefore analogous to those described in connection with the batch forming of fully energized and gradually immersed anodes. With the continuous foil formation, however, the heating and other effects are usually greatly intensified. As the heating produced by the current is concentrated where it is actually needed, i.e., in the region of film formation, an external preheating of the entire solution of the bath is unnecessary. In fact, experiments have indicated that no appreciable difference in the characteristics of the capacitor is observed whether, in the formation of its foils, preheating was used or omitted. On the other hand, moderate cooling of the solution is frequently resorted to, so as to keep its temperature below the boiling point and thus prevent excessive evaporation. As in the case of batch formation, additions of distilled water and ingredients are made when necessary and the solution is preferably stirred.

Extensive experiments have been carried out to determine the minimum of time of immersion required for the satisfactory formation of the film. While the major portion of the dielectric is formed almost immediately, as the foil enters the solution, some continuation of the process takes place afterward, until the foil leaves the bath. The time of immersion is, of course, determined by the length of the strip in contact with the electrolyte and the speed at which the foil travels. These two factors must be so adjusted as to permit the completion of the film formation; foils rated for higher voltages require a longer period of immersion. It has been found, for example, that with a forming voltage of about 200 V and the foil traveling at a high speed—30 and even 40 feet per minute—only 2 or 3 feet of foil have to be immersed to obtain complete film formation. A substantial reduction below this minimum length at the stated speed may, however, adversely affect the properties of capacitors wound with such foil. On the other hand, even a much greater length than the required minimum will not bring about any appreciable improvement. It appears, therefore, that there is no advantage in increasing excessively the size and cost of the filming equipment to provide an extra length for the immersed foil. Nor will there be an improvement in the quality of the capacitors if the speed and hence the output of the filming machine are unnecessarily cut down.

The capacitance per unit surface area of the anode and the other important properties of the capacitor as listed at the beginning of this chapter depend on the forming voltage *actually impressed across the film* during its formation. In other words, the important voltage is the one between the foil and the adjacent electrolyte in contact with the film. This voltage is substantially equal to the voltage applied to the filming cell, at the time the formation cycle is completed, in the case of *stationary* batch formation. The reason for this is that at the end of the formation cycle the current flowing through the cell is exceedingly small and consequently the voltage drop (*IR*) in the solution and in the various parts of the circuit (whose resistance is small) is negligible. Practically the entire voltage drop (i.e., the full voltage applied to the cell) is across the film as its resistance is very high at the completion of the forming. The situation is entirely different when continuous film formation is employed, as the current for a given setup is under such conditions steady and of a great magnitude. When a filming current of the order of 100 amps., for example, is flowing, even slight changes of resistance (a rather small fraction of an ohm) in any part of the circuit result in appreciable variations of the *IR* drop therein, which will markedly affect the voltage at the film and consequently the properties of the formed anode. Such changes in resistance may be due to a slight loosening of the connections of the conductors in the circuit, to corrosion or tarnishing of contacts, to the surface condition of the cathode plates (corrosion or deposits from the solution) and most frequently to variations in the resistivity of the electrolyte solution. The resistance of the circuit may be also affected by variations in the cross section of the foil, by impurities in the foil and by the surface condition of the latter—traces of oil, dirt or its natural oxidation (while the foil was exposed to the air) prior to formation.

It is obvious from the above discussion that with the complex and rather unsteady conditions of continuous film formation a mere reading on the voltmeter, indicating the voltage applied across the cell, will not give the true information as to the all-important potential impressed across the dielectric film being formed. To control satisfactorily the filming under these conditions, both the applied voltage and the current flowing through the foil must be checked. It appears advisable to keep the current constant by adjusting the voltage, thus compensating for the usual variations in the resistance of the electrolyte and other parts of the circuit. The constant current at a steady speed of the foil and a well-controlled solution will ordinarily insure uniform formation of the dielectric film. On the other hand, should a voltage adjustment out of the normal range become necessary to maintain the current constant, something has gone wrong with the filming setup. The trouble may be either with the electrolyte solution (excessive accumulation of aluminum hydroxide, contamination with conducting and interfering substances, a considerable change in the level or in the concentration due to the evaporation of water or loss of active ingredients, and so on), or with some contact, connection and the like; or it may be that the foil itself has abnormal film-forming properties, or has some poorly conducting substance on its surface (oil, grease, oxides, for example). The various items should then be immediately checked and the cause of the interference eliminated.

As the magnitude of the current with continuous film formation is great, the waste of electric power (I^2R) in the electrolyte bath is substantial. To reduce it, the path between the foil and the cathode must be shortened; this is accomplished by providing cathode plates, closely spaced from the foil and protected from contact with it by the interposition of perforated or otherwise suitably arranged insulators. These plates are positioned on both sides of the foil; in addition to improving the filming process, they quite effectively protect the walls of the tank from anodic corrosion caused by stray currents.

No appreciable difference has been noticed in the properties of the dielectric film whether the foil is running slowly, say at 10 feet per minute, or fast, at 40 feet per minute, if the forming current increases in direct proportion to the speed, and sufficient foil is immersed in the solution to provide the required filming time, as explained in the foregoing. However, small deviations from the expected capacitance per unit surface area may be eventually observed and can be attributed to a slight etching effect, because of the very high current density at the greatest speeds of the foil.

In the continuous film formation a peculiar effect near the edges of the foil is sometimes noticeable. The color of the film in that region appears to be different from that near the center line of the strip. Variations in temperature of the electrolyte, time of immersion, formation voltage and current density may be eventually correlated with this effect. This edge effect may perhaps indicate that under certain forming conditions the current density is substantially greater near the edges, where the filming is impeded because of the sharpness of the edge. If this is the case, the dielectric is not uniform over the entire anode surface, which would be undesirable, on general grounds. However, no definite experimental data are available to indicate the inferiority of a foil exhibiting the edge effect.

When films are formed at high voltages—300 V and higher—the formation may be improved and accelerated by passing the foil through two or more filming machines in succession. These are lined up in tandem so that the foil is threaded through the tanks in one cycle. The electrolytes in the tanks usually differ from each other, as they are prepared to suit the voltages of the corresponding machines. Thus, the voltage impressed across the first unit is the lowest, say 200 V, and the solution in it has the lowest resistivity; the voltage at the second unit may be 400 or 500 V and the resistivity of its solution substantially higher; the third unit may be operated at 600 or 700 V and the resistivity of its solution is highest. The first two aqueous solutions may comprise different proportions of sodium borate in addition to boric acid, while the last one may consist of boric acid only dissolved in water. To supply the filming current at different voltages, three d.c. generators of the required capacity and voltage rating may be connected in series. The positive terminals of the filming machines are connected to the respective generators, and the negative terminals are joined to a common return conductor.

It will be mentioned at the conclusion of this chapter that capacitors can be wound with unfilmed foils and impregnated in the operating nonaqueous electrolyte. The dielectric film can then be formed in *this same electrolyte* by passing direct current through the capacitor section, prior to its assembly into the container. Overheating and thus damaging of the section is avoided by immersing it in a vessel filled with some of the operating electrolyte and by inserting a resistance of a suitable value in series with the section as shown in Fig. 16. The time of formation depends primarily on the kind of electrolyte used, the purity of the foil, the use of artificial cooling, if any, the length of the foil, and in general the size of the section, the value of the series resistance and the formation voltage. It may take an hour or a day to complete the filming, depending on the above conditions. At the start of the cycle, as the foil is entirely unfilmed, practically the total voltage drop is across the resistor; as the building up of the dielectric on the foil progresses, the drop across the capacitor gradually increases and that across the resistor correspondingly decreases. At the end of the cycle the insulation resistance of the film is so great that almost the total voltage is impressed across the capacitor section.

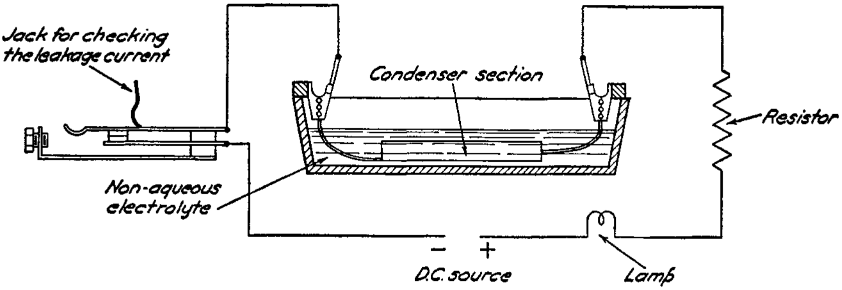

FIG. 16.—Illustration of the formation of a pre-wound capacitor section; the section is immersed in the operating electrolyte.

This filming process is less suitable for mass production than those which call for the formation of the dielectric on the foil in an aqueous solution, prior to its winding into a section. Probably because of the slowness of the forming at a low current density in a nonaqueous solution of high resistivity, the film exhibits subsequently an appreciable tendency to deform. The power factors of capacitors comprising anodes filmed in this manner are higher, possibly because their dielectric is somehow different and also because of the resistance to the current flow resulting from trapped gas and vapor bubbles produced during the formation cycle at the surface of the foils.

On the other hand, the fact that the film was formed to the desired voltage in its operating electrolyte indicates that the latter should be satisfactory to maintain the film in the normal use of the capacitor, at potentials not exceeding the forming voltage. With foils preformed in an aqueous solution and operated with a different, nonaqueous electrolyte, a special check is required to ascertain that the latter is satisfactory to *maintain* the film at the rated capacitor voltage. In other words, the mere fact that a dielectric film has been produced at a given voltage in one particular electrolyte *does not mean at all* that it will be sustained at the same voltage (or even at a much lower potential) when operated with a different electrolyte! The main good point of the method of film formation last described consists in the simplicity of the setup, as no filming machine is required for it.[1] This method lends itself for production on a small scale and particularly so when the deforming characteristics of the capacitor are of minor importance or not objectionable at all. Such is the case, for instance, with the regulating type of capacitor, frequently installed in filter circuits next to the rectifier tube, as described in Chapter III. Fluid electrolytes, promoting diffusion and cooling of hot spots, are more suited than very viscous or substantially solid electrolytes in conjunction with capacitors in which the anodes are formed according to the method last described.

Re-forming

After the capacitor is assembled (and filled with the operating electrolyte if it is of the wet type) and sealed, it is subjected to reforming. This operation is also known as "aging" and comprises the impression of a continuous potential (of the proper polarity) across

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[1] It is also possible to use in conjunction with this method the thinnest available foil (down to 0.00025"), as the latter is not subjected to mechanical strains in the course of the filming operation. When filming is done prior to winding, foil of such an extremely thin gauge cannot be used, because of mechanical considerations.

the capacitor terminals until the leakage current is reduced to a very small value, as called for in the manufacturing specifications. The purpose of the re-forming is to iron out the slight imperfections in the film as caused by handling, hot impregnation, storing, and so on. The re-forming voltage is usually of the order of the peak voltage to be expected in the operation of the capacitor. To restrict the re-forming current to a rather small value, irrespective of the condition of the capacitor (normal deforming, scratches on the film, and so on) and thus to limit its warming up, a suitable resistor is connected in series with the unit (see Fig. 48). It may also be found advantageous to provide intermissions during the process of aging which will facilitate the cooling of the capacitor.

In a.c. capacitors the one electrode is first re-formed in a manner similar to that just described relative to the polarized type. Then the polarity of the applied voltage is reversed and the second electrode is re-formed. Sometimes quicker aging is accomplished and the warming up of the capacitor practically eliminated if the polarity is reversed a number of times at short intervals, for instance every five minutes or so.

The re-forming is followed by the final test on the capacitors as described in Chapter XV. Wet capacitors are re-formed and tested in substantially the same manner as dry capacitors of the corresponding type (polarized or nonpolarized) and rating.

IX

The Etching of Aluminum Electrodes

The capacitance of a condenser with an anode of given physical dimensions can be increased if its total surface in contact with the electrolyte is augmented. Roughening the surface by sandblasting, scratching and similar mechanical expedients usually does not effect a sufficient gain in capacitance to make such processing worth while. Furthermore, it is difficult to control such processes accurately and to avoid contamination of the aluminum surface with the abrasive medium. A comparatively simple chemical or electrochemical etching, however, may attack and modify the electrode surface in a controllable manner and to the extent of rendering its capacitance several times greater compared to its value prior to the processing (Fig. 17–B).

Etching with a fairly strong alkaline solution of sodium or potassium hydroxide will clean the aluminum and may thus improve its film-forming properties, but the capacitance of the electrode after this treatment will be only slightly greater. The reason for this is that the alkaline solution attacks the entire surface quite uniformly and simply dissolves some of the aluminum, leaving exposed a new stratum of about the same total surface area as the original one.

Capacitor electrodes are most effectively and conveniently etched with chloride solutions, though fair results are obtainable with nitric acid in electrochemical etching. Hydrofluoric acid (HF) and various fluorides are also used in certain etching processes. The usual etching solutions, however, comprise hydrochloric acid (HCl). Eventually, one or more of the chlorides of copper, iron and nickel are added, the chloride ion remaining the main active agent. The metals mentioned have a lower electrolytic solution pressure than aluminum (are below it in the electrochemical series) and have therefore the tendency to precipitate, while the attack on the aluminum electrode is enhanced.

Microscopic examinations indicate that the chloride solution produces minute cavities and capillaries (Figs. 17–A and B) exposed to the electrolyte, the total surface of which may greatly exceed the original surface of the electrode. The number, depth and configuration

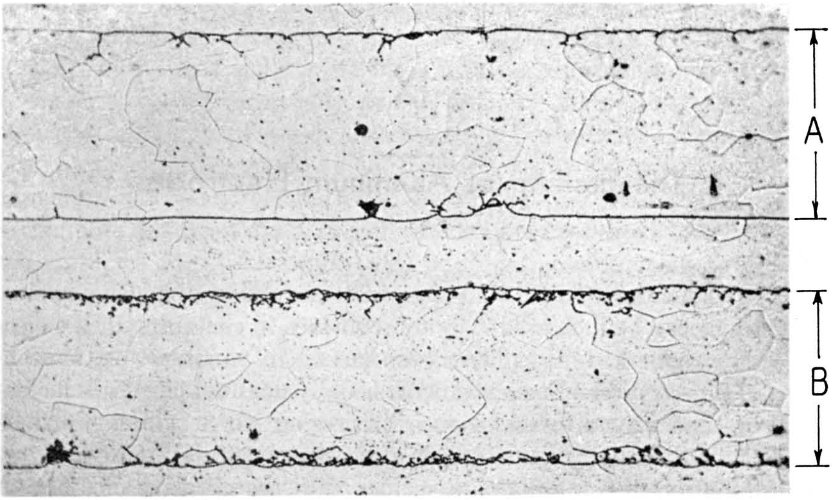


FIG. 17–A.—Cross section of two samples of 99.8% aluminum foil. Sample A was etched lightly; sample B, deeply. The microconstituents are aluminum-iron and aluminum-iron-silicon compounds. Mag. 250 × (*Aluminum Research Laboratories*).

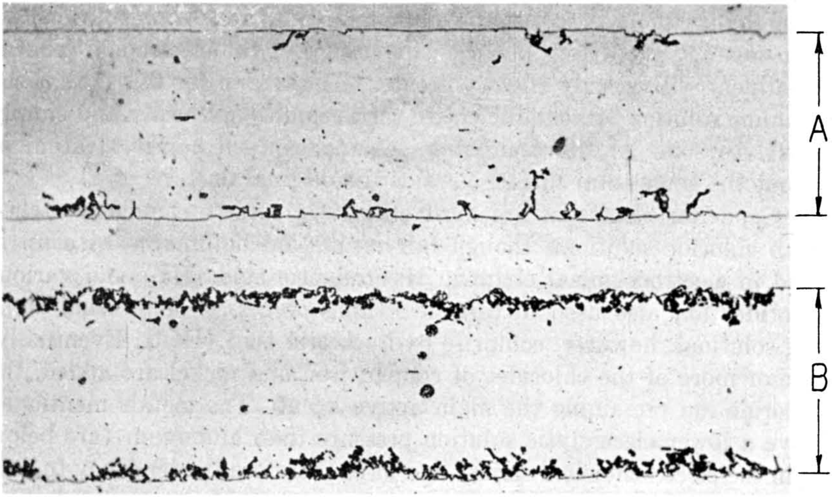


FIG. 17–B.—Cross section of a lightly etched (A) and a deeply etched (B) sample of 99.8% aluminum foil after formation as electrolytic condenser anode. The capacitance after forming was increased 200% by the light etching and 540% by the deep etching. Mag. 250 × (*Aluminum Research Laboratories*).

of these cavities and channels determine the gain in capacitance. A ratio of 12:1 and even greater can be obtained when etching with chloride solutions. In practice, however, smaller ratios are advisable, particularly for heavy duty and a.c. capacitors. A ratio of 4:1 is seldom exceeded for the latter type, as deep etching and very great capacitance per unit of "projected" foil area is accompanied by serious drawbacks, some of which will be mentioned here.

It is increasingly difficult to rinse out thoroughly traces of the etching substance from the deep capillaries. If such substances remain there, they are apt to cause a delayed corrosive action on the electrode.

Excessive capacitance per unit electrode plate results in a great current density between the electrodes, a rise in temperature and a tendency for the operating electrolyte to evaporate or dry out and deteriorate.

The high temperature at the electrodes weakens the film; this in turn may cause arcing and pitting of the metal.

If etching is carried too far, it may bring about the dissolution of an appreciable layer of aluminum in the course of the processing, thus necessitating the use of extra-heavy electrodes. The usual gauges for etched aluminum foils are between 0.003″ and 0.005″.

The effectiveness of the etching and consequently the gain in capacitance depend primarily on the attacking solution and to some extent on the composition of the electrode and the pretreatment of its surface. The etching is ordinarily intensified with the increase of the concentration of the chloride solution and of its temperature; a more prolonged contact between the electrolyte and the electrode also enhances the attack on the aluminum. Many variations of the last three factors are possible and are actually used by capacitor manufacturers. Substantially the same result can be obtained by using a strong solution at a lower temperature or a weak solution at a higher temperature. Similarly, the weakness and low temperature of the solution usually can be compensated for by keeping the electrode in contact with it for a longer period of time. The essential thing in practice is to establish the correlation among these three factors required to produce the desired etch and after that to maintain them as constant as practicable.

Concentrations of C.P. (chemically pure) hydrochloric acid as low as a few per cent and up to 20% at temperatures from 100°F to 150°F have been successfully used. Too great a concentration combined with a high temperature produces a violent action and makes the control of the process difficult. Moreover, such extremely active solutions may damage the foil, particularly if it is of a thinner gauge. On the other hand, very weak solutions at a low temperature require a prolonged contact with the solution and thus reduce the output capacity of the etching equipment.

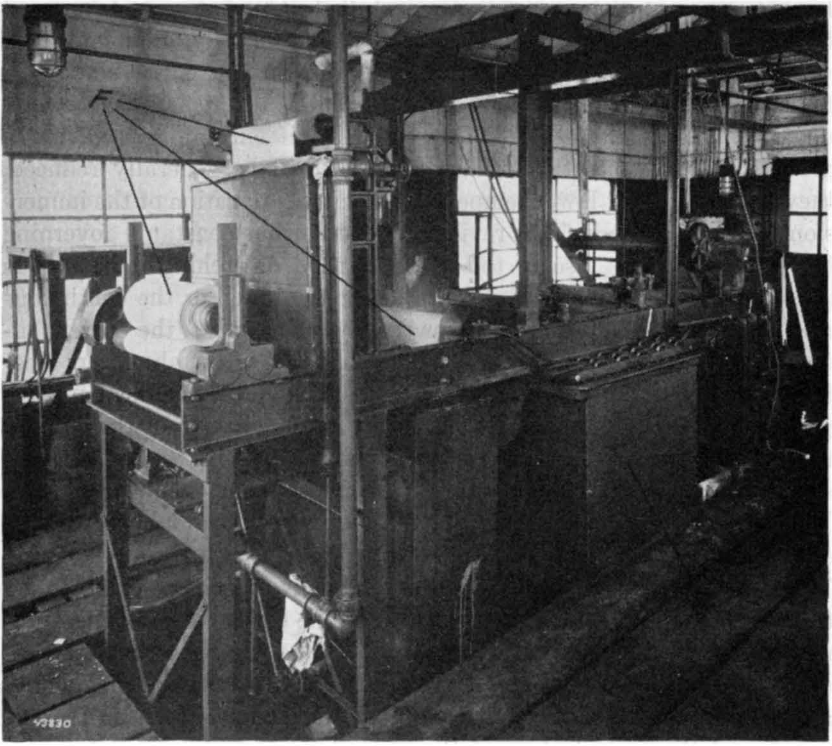
As in the case with filming, etching may be done with a batch setup or continuously, the latter method being generally adopted for the processing of foil electrodes. With continuous etching, immersion periods of a minute or so have given good results when the concentration and temperature of the solution were adequately adjusted.

In designing the etching equipment due consideration must be given to the selection of the material for the various component parts and eventually to their protection (by coating, plating, and the like) from the strong corrosive action of the solution, its fumes and the spray. Effective ventilation and other precautions common in electroplating plants are required to protect the operator from the corrosive agents.

To facilitate the etching and make it more uniform, the aluminum electrode is preferably first treated with an alkaline solution. Usually an aqueous solution of a few per cent of sodium hydroxide is employed, the concentration being lower if the bath is heated. This solution effectively attacks the electrode and removes from its surface the impurities and also the undesirable natural oxide which is always formed spontaneously when aluminum is exposed to the air. After being rinsed with water, the electrode is immediately treated in the chloride bath, which produces its full effect on the clean, freshly exposed surface of the electrode. This treatment is also followed by rinsing first with tap and then with distilled water.

It has been established that a subsequent wash in a nitric acid solution at room or elevated temperature markedly improves the electrical characteristics of the capacitor electrode, as the etched surface is thereby effectively cleaned without, however, dissolving the aluminum. In particular, the leakage current and power factor of the capacitor are lowered because of the thorough removal of impurities, including particles of heavy metals present in the electrode or deposited onto it in the course of the etching process. While concentrations of about 25% of nitric acid give good results, considerably stronger solutions have been used successfully. This treatment must be followed by several washes and rinses with *distilled* water.

Figs. 18–A and B illustrate the continuous etching process. Provisions must be made, as in continuous filming, for the constant speed at which the foil is traveling, for the automatic adjustment of the rereeling roll and for the drying of the foil. When the *electrolytic method of etching* is used, the foil is made the anode and special cathodes (omitted when straight chemical etching is adopted) resisting the cor-



(*Courtesy P. R. Mallory & Co., Inc.*)

FIG. 18–A.—Machine for etching of aluminum foil for electrolytic capacitors.
F—foil in the process of etching, washing and re-reeling.
T—etching tank.

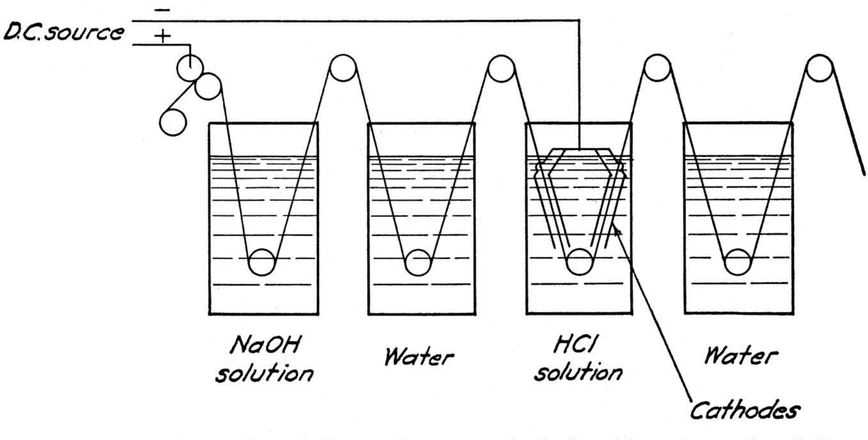


FIG. 18–B.—Illustration of the continuous method of etching of capacitor foil. Only four of the several tanks used in the process are shown in the picture.

rosive action of the solutions are installed. Current may be passed through the bath containing the chloride solution only, or it may flow also through the sodium hydroxide and even through nitric acid solutions. In all cases the effect from the current is to intensify the attack upon the aluminum surface. Consequently, if current is used in the process, the concentration of the solutions will be generally reduced, they may be kept at lower temperatures, and the duration of the immersion will be shortened. This revision of the various constants governing the process applies also to the batch method of etching if current is passed through the electrodes. With either the batch or the continuous method, the applied potential is low (a few volts only), the current increases with the voltage, and the anodic corrosion of the aluminum electrode is correspondingly intensified. Thus, the electrochemical process provides a simple and effective means for the regulation of the etch. It furthermore permits the use of rather weak solutions (such as NaCl alone) which would be ineffective with the straight chemical process. The control of the etch, when such weak solutions are employed, is considerably facilitated.

The success of the etching process depends to a large extent upon the care taken in the thorough removal of the corrosive substances immediately after the aluminum electrodes leave the bath so as to preclude any harmful aftereffects. Neglect of this precaution may badly affect the operating characteristics of the electrode and cause its corrosion and the early failure of the capacitor.

The accurate control of all factors governing the extent and quality of the etch—pretreatment and cleaning, concentration and temperature of the solutions, duration of immersion and magnitude of the current (if such is applied)—is of vital importance, as upon it depend both the quality and the uniformity of the manufactured capacitors. Variations in any of these factors are likely to be reflected in one or several of the characteristics of the condenser—capacitance per unit area, leakage current, power factor, breakdown voltage, tendency to arc and corrode, and the like. Great deviations from the expected capacitance of the condenser may upset production schedules and be responsible for a high percentage of rejects.

The various solutions used in the etching process should be periodically tested for acid and for alkali content; the pH should be also determined frequently and the purity of the water used for washing and rinsing checked. As the solutions are used up or grow weaker, because of their interaction with the aluminum and because a certain quantity of the chemicals is lost by the spray and removed with the anodes, the tanks must be replenished from time to time. When the products of reaction and the impurities in general have accumulated to the point that the effectiveness and uniformity of the etch may be adversely affected, it is advisable to change the solutions.

In closing this chapter it will be mentioned that etching of the cathode has also been suggested in the past. The purpose of such etching is the increase of the cathode surface in contact with the electrolyte, resulting in the reduction of the resistance to the current flow in the cell and the prevention of an attack on the cathode.

X

The Electrode Spacer

The use and construction of spacers or separators in wet capacitors have been discussed in Chapter III. The material (celluloid, hard rubber, and so on) of which the separator is made must be carefully selected to preclude any contamination of the electrolyte. The absence of chlorides is in this case, too, of foremost importance; sulphur and its compounds are also considered undesirable.

In the early dry electrolytic capacitor, the usual spacer consisted of one or two layers of cotton gauze, or one of gauze and one of paper. Its function was, as it also is of the modified spacer used at present, to keep the electrode foils sufficiently apart to prevent short circuits and, at the same time, to serve as a carrier for the operating electrolyte. The thickness of the gauze was of the order of 0.005″– 0.008″. For several years the use of gauze for capacitor spacers has been substantially discontinued, as paper of great absorbency, high purity and sufficient tensile strength has been developed and made available to manufacturers. Paper is preferred to gauze because it is much cheaper and can be made thinner, thus permitting a reduction in the cost and bulk of electrolytic capacitors. Moreover, with the proper selection of the grade of paper, the operating characteristics of the capacitor are at least as good as they were with the gauze spacer.

The absorbent paper used most frequently in electrolytic capacitors comprises cotton rag and wood pulp, to which hemp fiber and the like are sometimes added. The absorbency, density, mechanical strength and other properties of the paper are controlled to a large measure by processes of hydration, beating and calendering. The paper should not be bleached and must be free from sizing substances to prevent its contamination with chemicals harmful to the capacitor and to insure the greatest possible absorbency. Particular care must be taken to eliminate even the most minute quantities of chlorides. To secure a maximum of absorbency, the density and uniformity of the texture are substantially sacrificed and the tensile strength is low, usually just sufficient to permit the winding of the section without breakage. Even the

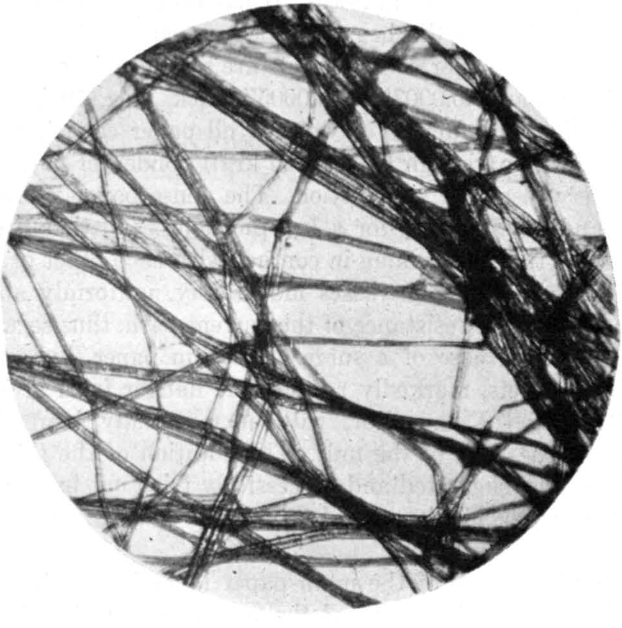


FIG. 19–A.—Photomicrograph of a sample of .0012″ absorbent condenser paper. Mag. 100 diam.

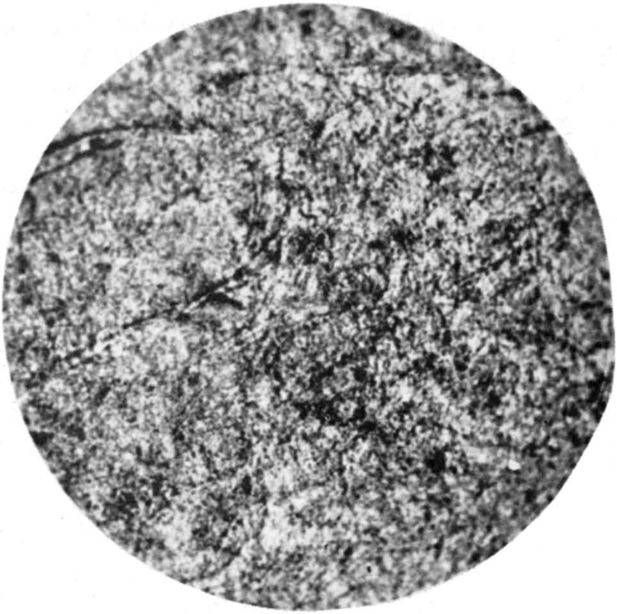


FIG. 19–B.—Photomicrograph of a sample of .0005″ uncalendered condenser linen paper. Mag. 100 diam.

naked eye can easily discover that this kind of paper has in some regions rather heavy clusters of fibers, while in others there is a deficiency in fibers to the extent that almost open spaces (Fig. 19–A) are visible. All over the paper small holes are noticeable. Such paper would be useless in the manufacture of wax- or oil-paper capacitors, where the true dielectric is the impregnated paper. In the dry electrolytic capacitor, however, the actual dielectric is the electrolytically formed film, while the paper, as already mentioned, serves primarily as an electrode spacer and electrolyte carrier. This fact explains why the apparent defects of the absorbent paper are tolerable in this application. There is, nevertheless, a limit to this tolerance, for reasons outlined below.

The absorbent condenser paper is ordinarily 0.001″ to 0.003″ thick and although usually two or three layers are placed between the foils, their spacing is close, seldom exceeding a total of 0.006″ and often as low as 0.003″; in some special cases the spacing of the electrodes is only 0.001″. It has been observed that when the foils are so close to each other and there are substantially open spaces in some regions of the paper (because of the discontinuity of its texture—see Fig. 19–A) minute sparks may jump between the foils in such regions and cause pitting; voltage surges are apt to cause arcing-over, resulting in healed and sometimes permanent breakdowns. It has been furthermore established that by adding to the heavy absorbent paper a layer of very thin, uniformly dense paper, these defects are minimized or eliminated. A layer of linen paper 0.0003″ to 0.0005″ thick (Fig. 19–B), of the grade used in the manufacture of wax- or oil-paper capacitors, lends itself for this purpose, though high-grade kraft condenser paper of the same gauge may also give satisfaction. .The dense paper is free from open spaces and holes, except for a few pin holes, and thus precludes the possibility of the foils coming in contact with each other or getting dangerously close. It also increases moderately, uniformly and in a controllable manner the resistance of the current path, thus securing an attenuating action in case of a surge. The thin paper, by providing these beneficial effects, markedly reduces the danger from arcing and short-circuiting of the capacitor, without materially increasing its power factor or the bulk of the unit. The addition of the thin, dense paper has been first suggested and successfully tried out by the author in conjunction with highly absorbent gauze spacers (U.S. patent 2,098,745).

The great absorbency of the main paper layer is of prime importance for the good performance of the capacitor. If the electrolyte penetrates into every particle of the paper, a thorough wetting of the foil surface is thereby promoted and an unobstructed path of uniform and moderate resistance for the current between the entire electrode surfaces established, upon which depend the effective capacitance, the power factor and the over-all efficiency of the condenser. Furthermore, a thorough penetration of the electrolyte eliminates dry spots and air bubbles, the harmful effects from which will be discussed in Chapter XIII. Finally, the great absorbency insures a sufficient supply of the vital electrolyte for the duration of the normal life of the capacitor and enables the latter to withstand occasional short-lasting overloads. It must be realized that the overloading is accompanied by heating, by evaporation and by an appreciable electrolysis of the electrolyte within the capacitor. There is also a tendency on the part of the evolved vapors and gases to force the electrolyte out of the interstices of the winding. Thus, some of the electrolyte, in particular the volatile constituents like ammonia and water, is likely to be lost when overloads occur.

It is difficult to use dense papers as the sole spacer in an electrolytic capacitor because of their low absorbency. When they are combined with one or two layers of highly absorbent paper, however, the latter acts as a wick, and because of its intimate contact with the former brings about a satisfactory impregnation of the entire spacer. When extreme compactness of the capacitor is of foremost value, and the operating conditions are not severe, thin dense paper alone can be eventually used but it then requires special provisions for a satisfactory impregnation. Good results have been obtained with straight dense paper spacers in certain types of capacitors by employing a suitable vacuum impregnating process in conjunction with a very fluid operatating electrolyte.

The acceptance tests on electrolytic condenser paper ordinarily cover the following:

Tensile strength.
Check for large holes.
Absorbency.
Freedom from chlorides and sometimes from sulphur compounds.
Absence of bleaching and sizing substances.
Acidity as indicated by the pH value of an extract made with distilled water; the indication should be close to the neutral point (7.).
Eventually, a check for metal specks, the presence of which is, of course, undesirable, though not as dangerous as in wax- or oil-paper capacitors.

XI

The Operating Electrolyte

The main functions of the operating electrolyte are to provide a path for the current flow between the capacitor electrodes and to maintain an efficient dielectric film on the anode. The electrolyte has to meet a number of requirements, the more important of which are discussed here.

It must not attack any part of the device with which it is in contact.

It must be physically and chemically stable to insure to the capacitor long life and uniform and good performance.

Its electrical resistivity must be of such magnitude that, while the power factor of the capacitor remains sufficiently low, the breakdown voltage of the latter is well above the rated value.

Its penetrating and wetting properties must be adequate to insure an uninterrupted conducting path throughout the space between the electrodes.

The choice, purity and proportions of the ingredients used for the preparation of the electrolyte must be such as to maintain the good original characteristics of the dielectric film. The electrolyte should even tend to improve these characteristics in the course of the operation of the capacitor. In case of a momentary breakdown of the dielectric, due to surges or short-lasting overloads, the electrolyte should be effective in the automatic healing or rebuilding of the film.

It is desirable that in case of a prolonged overload, the electrolyte diffuse sufficiently to bring about a uniform temperature within the unit and thus prevent the formation of hot spots. The diffusion will also facilitate the conduction of the heat from the interior toward the container, thus effecting a better cooling of the unit.

Its physical, chemical and electrochemical properties should be affected as little as possible by changes in temperature, within the normal operating range.

Its flammability should be as low as possible, to prevent fire hazards in case of a short circuit or violent sparking.

The ingredients must be readily available at a moderate price.

Many chemical compounds meet more or less the above requirements; some of these compounds are weak bases, but most are weak acids or their salts, used separately or in combination. Unless there are some special advantages in mixing a considerable number of electrolytes, it appears advisable to reduce their number to a minimum, whereby the control of the properties of the composition is simplified.

Only a few of the known capacitor electrolytes will be mentioned; they have been tried not only experimentally but, at least to some extent, in production.

The acids
boric
phosphoric
acetic
chromic
oxalic
lactic
citric
tartaric
and their ammonium
and sodium salts (less
frequently potassium
salts are used).

Ammonium carbonate, sodium carbonate and sodium bicarbonate.

A few investigators are of the opinion that ammonium salts are less conducive to the corrosion of aluminum electrodes than the corresponding sodium or potassium salts. The use of ammonium salts appears to be also particularly advantageous where the operation of the capacitor at very high voltages is of major importance. On the other hand, the sodium and potassium salts are more stable.

Wet capacitors are usually filled with an aqueous solution of boric acid and sodium borate or ammonium borate. Water is chosen as a solvent because of its good ionizing properties and in conjunction with this the comparatively high conductivity it imparts to the solution; the latter feature is necessary in wet capacitors because of the considerable distance between their electrodes. As in the case of the film-forming solution, the operating electrolyte may have a lower resistivity for low-voltage capacitors; the alternating current per unit electrode surface area may be in these units of a considerable magnitude, and to reduce the electrical losses a more conducting solution is preferred. Capacitors operated at high voltages are supplied with an electrolyte solution of greater resistivity to improve their breakdown characteristics. The resistivity of the solution is adjusted by controlling the percentage of the sodium (or ammonium) borate, its effect on the resistivity being much greater than that of the boric acid. The latter, however, has outstanding film-forming and -maintaining properties and may be present in sufficient quantities to render the solution saturated at operating temperatures. The alkali or alkaline salt added constitutes a small percentage of the dissolved boric acid and the reaction of the solution is usually kept on the acid side. The specific resistivity of such electrolytes may be of the order of a few hundred ohms (per cubic centimeter) at room temperature, though substantially lower resistivities may be chosen depending on the construction and rating of the capacitor and also on the operating conditions.

As the freezing point of straight aqueous electrolytes used in capacitors is not much below 32°F, they cannot be employed when the ambient temperature is low. The addition of a sufficient quantity of a compatible "antifreeze," like glycerin or ethylene glycol, will ordinarily remedy this condition by lowering the freezing point of the solution to the required degree. In selecting the antifreeze and deciding upon the percentage to be added, consideration should be given to the following factors: the added substance must not interfere with the film-forming properties of the electrolyte; it should not unduly affect its resistivity; it should not gum up or form interfering deposits on the electrodes (within the operating temperature range).

The operation of wet capacitors at elevated temperatures also presents difficulties on account of the weakening of the film and the substantial increase of the vapor pressure of the electrolyte. Heating may cause appreciable losses of electrolyte because of evaporation and also because it tends to increase the leakage current and thereby electrolysis. These electrolyte losses in turn may result in a drop of capacitance.

The curves in Figs. 20–24 indicate that the capacitance, the power factor and the leakage current of both wet and dry electrolytic condensers are strongly affected by temperature variations. The shape of these curves may vary markedly depending on the type of electrolyte solution used, on the film characteristics and eventually on the constructional features of the device. As already pointed out in Chapter V, the temperature has a bearing on the effective capacitance not only because of its influence upon the resistivity of the electrolyte but also because it produces direct effects in or at the film. The power factor improves, i.e., falls with rising temperature up to a certain point (depending on the type of film, impressed voltage, electrode spacing, kind of electrolyte, and so on), because of the decreased resistivity of the electrolyte. Above this point the effect is reversed, since the heat weakens the dielectric and consequently the leakage current and the electrical losses at the film in general increase. The latter effect more than offsets the benefit from the decreased resistivity of the electrolyte

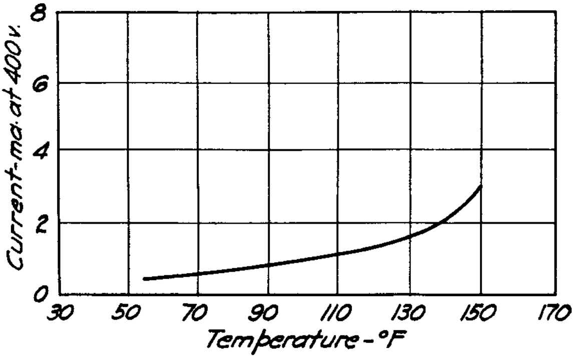


FIG. 20-A.—Leakage current vs. temperature.
8 MF—450 V polarized wet capacitor.

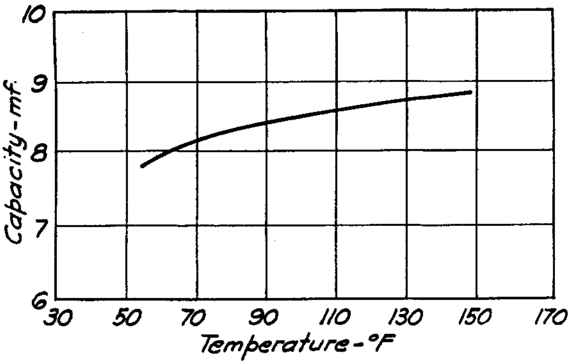


FIG. 20-B.—Capacitance vs. temperature.
8 MF—450 V polarized wet capacitor.

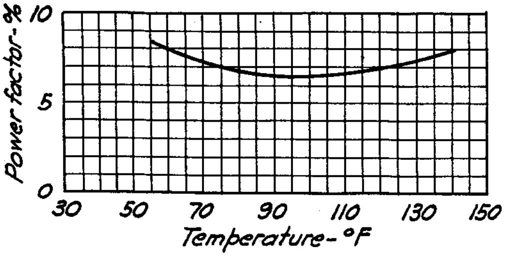


FIG. 21.—Power factor vs. temperature.
8 MF—450 V polarized wet capacitor.

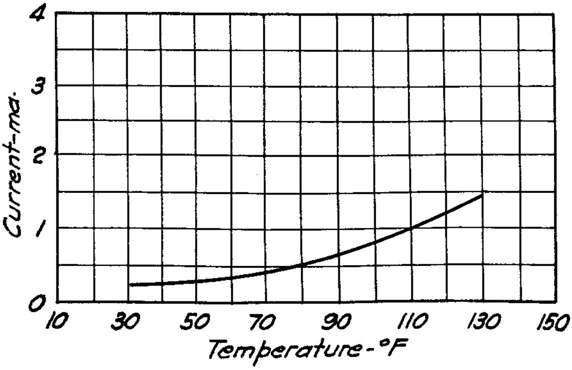


FIG. 22.—Leakage current vs. temperature.
8 MF—500 V polarized dry capacitor.

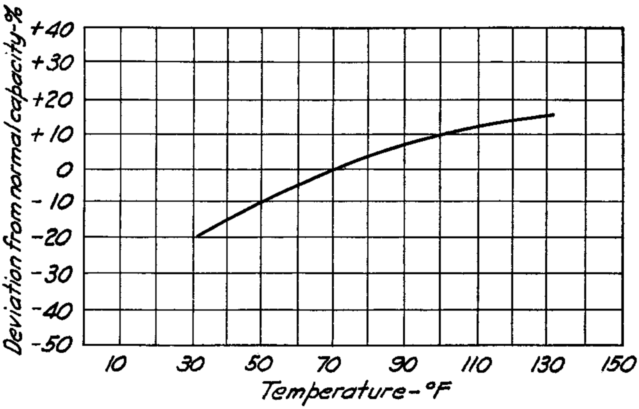


FIG. 23.—Capacitance vs. temperature.
8 MF—500 V polarized dry capacitor.

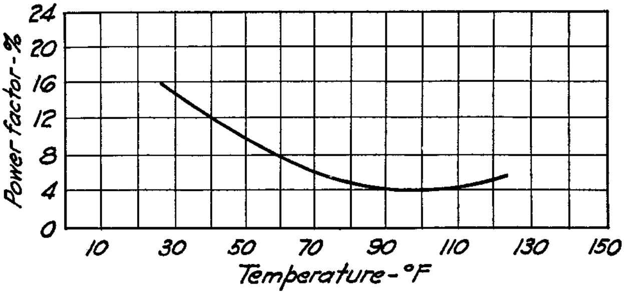


FIG. 24.—Power factor vs. temperature.
8 MF—500 V polarized dry capacitor.

Finally, it must be pointed out, heating of the condenser always adversely affects its breakdown characteristics.

The electrolyte of dry capacitors usually comprises an organic solvent, like glycerin (glycerol) or a glycol (ethylene or diethylene) which plays a *very important* part in the performance of the device. The power factor, the breakdown voltage and in particular the temperature characteristics of the capacitor are considerably affected by the solvent and its selection will depend on the expected operating conditions.

With the solutes most commonly used—boric acid and ammonium borate—the glycerin $C_3H_5\ (OH)_3$ or ethylene glycol $C_2H_4\ (OH)_2$ reacts chemically, forming glyceril-borate and ammonium-glyceril-borate, respectively glycol-borate and ammonium-glycol-borate. Corresponding esterification products are formed when sodium borate is used in place of ammonium borate. One of the reaction products in all these cases is water. Thus to the water of crystallization of the borate salt (as for instance in the case of sodium borate $Na_2B_4O_7.10\ H_2O$) and to the water contained as an impurity in the glycerin or glycol a substantial quantity of water of reaction is added.

As already previously indicated, the extremely close spacing of the electrode foils in dry capacitors and the resulting danger from sparking and arcing-over make it imperative to provide an electrolyte which will most effectively maintain the film even under adverse service conditions and at the highest operating voltages likely to be encountered. Such electrolytes must have a fairly high resistivity, which in turn calls for the restriction of their total water content. Moreover, in case of an excessive transient resulting in a momentary breakdown on some spot of the film, the main limiting factor for the current surging through the break is the resistance of the spacer impregnated with the electrolyte. This resistance protects the foil, the paper and consequently the entire section from violent and destructive discharges. It follows from the above considerations that the safe operation of the dry capacitor depends in a large measure on the restriction of the *water content* of the electrolyte composition. On the other hand, as pure glycerin and the glycols have only moderate ionizing properties, the resistivity of the electrolyte would be excessive and therefore the efficiency of the condenser low (reduced effective capacitance and increased power factor) were it not for the little water present, which markedly increases the ionization of the composition. Consequently, either too great or too low resistivity (as brought about by a deficiency or, in the latter case, by excess of water) of the electrolyte is undesirable.

These facts have been investigated by the author and his findings stated in U.S. patent 1,815,768. The discovery and control of the various factors upon which the properties of the electrolytes for dry capacitors depend, and particularly the understanding of the important role played by the water content of the electrolyte, made it possible to produce efficient and compact dry electrolytic capacitors which will withstand safely peak voltages of the order of 600 V. With this improvement, the field for the use of dry electrolytic capacitors, particularly in radio receivers, was greatly expanded. The effective control of the breakdown voltage and of the power factor made the dry capacitor also more adaptable and suitable for use in a.c. circuits.

The usual preparation of the electrolyte for dry capacitors begins with the mixing of the ingredients; as the boric acid and its salts are dissolved in glycerin or glycol, they react with these solvents and the products mentioned above are formed. At this stage, the electrolyte contains an excess of water and is not well suited even for low-voltage units, not to speak of the usual moderate and high-voltage capacitors. The resistivity of this electrolyte is low and its film-forming properties are poor. One simple and generally adopted method of conditioning the electrolyte so that it will be suitable for capacitors of the desired voltage rating consists of driving off the excess of water by heating, preferably at the boiling point of the solution. As the water is being evaporated, the boiling point rises and the resistivity and viscosity of the electrolyte increase. If the proportions and purity of the mixed ingredients are always the same and in general the conditions under which the evaporation is carried out are unchanged, the checking of one of the three correlated factors—boiling point, resistivity and viscosity—should be sufficient for the control of the electrolyte solution. However, small variations in the proportions of the mixed substances and even minute quantities of conducting impurities may upset this correlation, and it is advisable to check at least two of these factors to secure a better control of the film-forming properties of the electrolyte. It is easier to measure the resistivity and the boiling point; however, a check on the viscosity gives the additional information on the penetrating properties of the solution and this is important with regard to the impregnation of the spacer. The extent to which water must be driven off is determined experimentally for each type of capacitors, since the water content of the solution strongly affects the various characteristics of the capacitors, in particular their breakdown voltage. For instance, appreciably more water is driven off when the electrolyte solution is intended for 500 V capacitors than is the case when an electrolyte for 200 V capacitors is prepared. Once the optimum water content is established, as reflected in the mentioned properties of the solution, it should be a rather simple matter to reproduce the desired results in the preparation of production batches of electrolyte. It may happen that accidentally, or otherwise, too much water is removed from the solution; the boiling point, resistivity and viscosity will then be too high. This condition can be remedied, however, by a simple addition of distilled water to the electrolyte—just enough to bring the mentioned properties to their optimum values.

The water content of the electrolyte used in dry capacitors is small, usually within a few per cent of the total weight of the composition. The resistivity per cubic centimeter at a given temperature may vary within wide limits; the value to which it is adjusted will depend on the ingredients used, the type of capacitor, its voltage rating and the operating conditions for which it is intended. For instance, a few thousand ohms per cc at room temperature may be satisfactory for an a.c. capacitor rated for 110 V and comprising an electrolyte made of ammonium phosphate and glycerin. Resistivities of greatly different magnitudes may be required if the capacitor is rated for 500 V d.c., if borates, citrates, and so on, are used in place of phosphates or if different solvents are employed.

Similarly, the boiling points of the various electrolyte solutions used for the impregnation of dry capacitors may vary considerably. Many of the glycerol-borate and glycol-borate solutions have boiling points between 260° and 300°F.

The viscosity varies to a still greater extent; some of the capacitor electrolyte solutions in actual use are as fluid as ordinary C.P. glycerin, while others resemble molasses; electrolytes substantially solid at room temperature are also extensively used. These extreme variations in the physical state of the composition are due, however, not only to the choice and processing of the ingredients, but also to the difference in proportions of solute and solvent. For example, a rather solid electrolyte composition (at room temperature) may be obtained by using approximately equal quantities, by weight, of a suitable solute (a mixture of ammonium borate and boric acid) and a solvent (ethylene glycol). On the other hand, a mixture of about 5% of ammonium phosphate and 95% of glycerin results in a very fluid electrolyte. Sometimes more or less inert fillers, like starch, silica, carbon powder, for example, are added to the electrolyte composition and render it very viscous or solid. The presence of such fillers is considered by some manufacturers beneficial for the capacitor in improving its electrical characteristics and preventing electrolyte leaks.

It must be borne in mind that while the electrolyte solution is being heated in an open vessel, along with water some ammonia, glycerin and other admixed ingredients do escape. If the heating of a batch of electrolyte is carried out repeatedly, as happens with some methods of impregnation, the original proportions of the ingredients may be appreciably upset. A check on two or on all three of the above-mentioned controlling factors will facilitate the recognition of this state, and it can be remedied by the addition of the ingredients which are deficient. This procedure is particularly important when ethylene glycol is used as a solvent since the derived compounds exhibit a tendency to "cake" or solidify (possibly because of polymerization), even at elevated temperatures, after they have undergone several cycles of heating. The caking is more likely to occur if the proportions of the ingredients are disturbed, and it may interfere with the impregnation of the sections.

It is advantageous to supplement the determination of the boiling point, resistivity and viscosity by a test of acidity, as the pH index gives valuable information on the general condition of the solution and on eventual changes in it. With some of the electrolytes a neutral reaction is considered to be most desirable, while with others an appreciable acid reaction is preferred.

In some cases it is more convenient or economical to mix glycerin (or glycol), boric acid and strong ammonia water, instead of glycerin and ammonium borate; the first combination, however, may contain more water than the second and will require then a more prolonged heating to reduce the water content to the proper value.

Another scheme calls for dissolving only boric acid in glycerin and then bubbling ammonia gas through the solution. In this case there will be less of an excess of water.

It should be mentioned at this time that in certain electrolyte compositions used for the impregnation of dry capacitors the control of the water content is effected solely by properly selecting and combining suitable ingredients. For instance, in the glycerin-ammonium acetate electrolyte the water content can be reduced to the desired proportions by using glacial acetic acid or even acetic anhydride in place of ordinary acetic acid.

The use of substantially solid electrolytes makes the housing of capacitors easier, as the possibility of leaking is thereby minimized; thus, wax-impregnated paper containers are frequently used in place of cans when solid electrolytes are adopted. On the other hand, such electrolytes when overheated or exposed to the atmosphere are usually more subject to drying out, causing a drop in effective capacitance and increase of power factor in the condenser. Although these electrolytes become fluid when heated during the impregnation cycle, they are ordinarily not as penetrating as the typical fluid compositions and therefore make the impregnation of the spacer more difficult.

Some of the fluid electrolytes, particularly those of the ammonium acetate variety, are almost immune to the adverse heat and evaporation conditions as encountered sometimes in actual operation. Repeated heating of the capacitor, combined with exposure of its electrolyte to the atmosphere, fails to affect markedly and permanently the operating characteristics of the unit. Moreover, fluid electrolytes facilitate the uniform cooling throughout the section as already mentioned in this chapter. This effect is of particular importance in a.c. capacitors (and in such polarized units in which the a.c. component is large), because of the considerable amount of heat generated therein. Fluid electrolytes have such great penetrating properties that under certain circumstances they may permit the use of very dense, thin and mechanically strong spacers, like calendered and even supercalendered linen paper, which offer advantages in the construction of very compact and high-voltage capacitors. The fluid electrolyte, however, calls for greater care in housing the capacitor to prevent leaks; in fact, it requires a hermetically sealed container. Another important consideration is that the fluidity must be adapted to the ability of the particular spacer to *retain* the liquid in its pores and interstices.

The viscous electrolyte occupies a middle position between the solid and fluid electrolytes and its advantages and disadvantages are accordingly restricted.

While most of the electrolytes for dry capacitors are prepared by dissolving boric acid in an organic solvent of a substantially neutral reaction, like glycerin or ethylene glycol, and then adding ammonium hydroxide or bubbling through ammonia gas, in a few cases ethanolamines (mono-, di-, or tri-ethanol-amine), which have a basic reaction, serve as a substitute for both the solvent and the ammonia. With this combination the solution of the boric acid in, and the reaction with, the ethanol-amine result in an electrolyte having properties similar to those of the ammonium-glycerol-borate variety.

In some cases the use of the organic solvent has been dispensed with altogether by using certain solid compounds (for instance ammonium acetate) which when properly heated—singly or several in combination—become fluid and remain in this state after cooling (U.S. patent 2,235,067).

Mention should be made also of some attempts to do away with the absorbent separator in dry electrolytic capacitors by using a layer of a substantially solid electrolyte as a spacer between the foils or the plates. Such electrolytes may comprise fillers for the purpose of imparting to the composition the necessary mechanical strength and toughness. The difficulties in winding or otherwise assembling a compact unit without the use of the conventional spacer are obvious.

In the preparation of the electrolyte much attention is given to the purity and uniformity of the various ingredients used; a number of tests are carried out to make sure that the requirements of the material specifications are met. All ingredients are tested most carefully (with silver nitrate) for chlorides, which are tolerated only as traces—not more than a few parts per million. In some cases limits are also set for sulphates and nitrates. One of the routine tests is the determination of the pH value of the substance or of its solution or extract in distilled water. Titration and other tests may also be found useful.

XII

The Winding of Capacitor Sections and Their Connections

Dry electrolytic capacitors could be made by assembling into a stack a plurality of properly interconnected aluminum plates with interposed spacers impregnated with electrolyte; or foils and spacers properly lined up could be pleated or arranged in some other convenient way. In practice, however, dry electrolytic capacitors are always made by winding sections with foils separated by papers. The section is built up in this manner rapidly, and the method is simple and most economical with respect to both labor involved and the utilization of practically the total surface of the foils for the capacitance effect.

There are, however, several precautions and considerations which must be kept in mind, as upon them depend to a large extent the quality of the winding and the performance of the capacitor. To prevent wrinkling and lateral shifting of the foil and paper layers, sufficient tension must be provided for them; too much tension, however, may cause tearing of the layers, in particular of the mechanically weak absorbent papers. Excessive tension may also result in a very tight winding, which in turn will make difficult a thorough penetration of the electrolyte during the impregnation cycle. The required tension is secured by using friction straps, applying brakes to the shafts or spindles, and so on (Figs. 25–A and B). The important point in this setup is to regulate the tension according to the continuously changing winding conditions, preferably by providing automatic adjustments for this purpose. As the winding is progressing, the diameter of the rolls from which the foils and papers are taken is decreasing and the tension will change unless adjustments are made on the friction straps or brakes.[1]

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[1] Recently, extensive improvements have been made in condenser winding machines. Automatic stopping, electronic control of the alignment of the paper- and foil-strips, automatic regulation of the tension on the strips and the like are some of the features which contribute to the increase in the output of the winding machine and to the improvement of the quality of the capacitor section. See also article "Winding Industrial Capacitors" in *Electronic Industries,* Feb., 1944, p. 113.

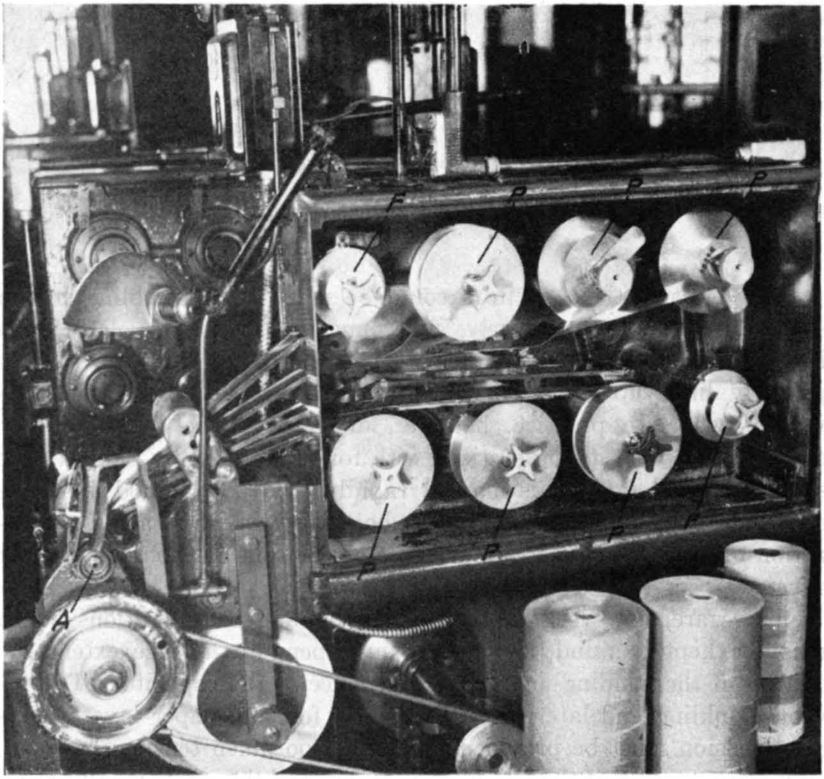

FIG. 25–A.—Capacitor winding machine.

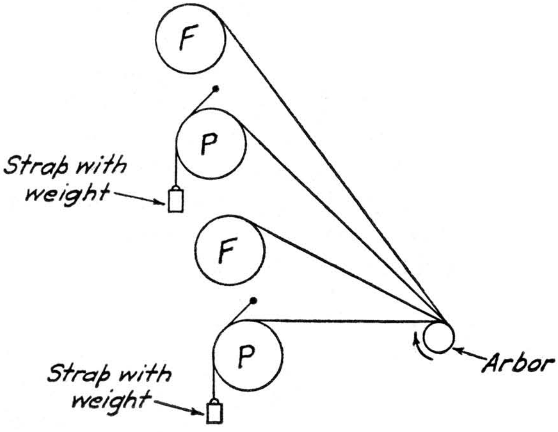

FIG. 25–B.—Schematic presentation of the winding of capacitor sections.
F—coils of aluminum foil.
P—rolls of paper.

When long sections are wound, the innermost turns have a tendency to be excessively tight because their diameter is considerably smaller than the diameter of the outer turns. This effect is accentuated when arbors of a small diameter are used. To prevent the excessive tightness in the central portion of the section, which may interfere with its impregnation, larger arbors are preferable if the length of the foils and papers is great. To adapt sections wound on large arbors for mounting in containers of a given form and to make the assembly compact, the section may be flattened, folded or otherwise shaped as shown in Fig. 26.

In the conventional winding the paper spacers are wider than the foils; the margin left between the edges of the foils and those of the papers is necessary to prevent contact between the foils of opposite polarity even if they are slightly misaligned. A good winding setup and particularly an accurate and steady alignment of the various layers permit the adoption of smaller margins, thus reducing the total quantity of paper used and the size of the section.

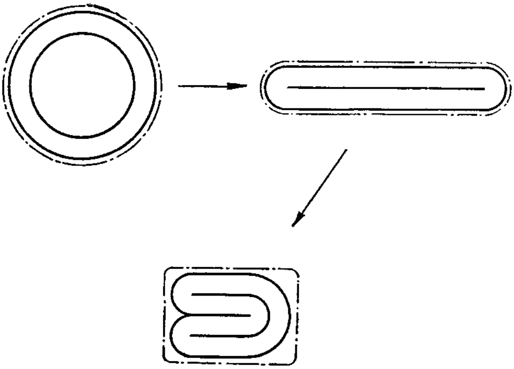

Fig. 26.—Section wound on a large arbor and subsequently flattened out and shaped to fit into containers of various physical proportions.

On account of possible flaws in the paper, two or three layers are ordinarily interposed between the foils. As already mentioned in the chapter on spacers, these layers may be of different thicknesses and of paper of different grades—one very porous, absorbent and of low tensile strength, with others dense, of lower absorbency but strong mechanically. Thus, the two or three layers may supplement each other and provide the most desirable combination of properties. Double and triple layer papers, calendered together into a single sheet, have been used to some extent in dry electrolytic capacitors; they are ordinarily built up of layers of different textures and characteristics. The winding of sections with such combination-paper is simplified as fewer rolls are to be handled.

Particular care is required in securing reliable terminal connections on the section. Soldering of a tab, as it is done in some wax-paper capacitors, is unsatisfactory, except perhaps when the unit is rated at a few volts only. Apart from the fact that soldering on aluminum is difficult, the aluminum solder has poor film-forming properties and may give rise to excessive leakage currents and electrolysis at the joint.

The welding of a tab to the foil, eventually combined with riveting, may give satisfaction if a clean, firm and permanent contact is established. As in the wet capacitor, any loosening of the joint or its contamination with extraneous substances may result in corrosion, pitting and electrolysis and may ultimately set up a high resistance at the tab connection or even cause an open circuit.

Whenever practicable, the terminal tab should be integral with the foil; this arrangement is usually brought about by slitting and bending over a strip of foil as indicated in Fig. 27. If the foil is thin, it becomes necessary to reinforce the tab by folding the foil and thus providing a plurality of layers at the joint to the external terminal; however, this construction, shown in Fig. 28, involves extra labor and material.

Figs. 29–A and B illustrate a winding (U.S. patent 2,232,320) which exhibits the following advantages. The offsetting or telescoping of the two foils at the start of the winding provides an extension at each end, suitable for the terminal connection.[2] Thus, no extra operations for slitting, bending or folding of the tabs are required. The offsetting involves only a few turns, while in the rest of the winding the two foils are lined up in the conventional manner; consequently, practically no waste of foil for establishing the terminal connections results from the telescoping. The fact that the terminal joint provides contact with several turns of the foil minimizes the danger from an open circuit in case the foil at one of the turns is corroded or otherwise severed. By joining several turns of foil, the inductive effect of the roll is minimized and the path for the current flow shortened, which tends to reduce the electrical losses and may be of particular value when the capacitor is used in high-frequency circuits.

When large capacities are provided by a single section, its bulk may be excessive and its thorough impregnation uncertain; furthermore, in operation the cooling of the innermost turns of large sections

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[2] This method of winding permits the use of exceedingly thin foils, as the formation of terminal tabs is in this case obviated. With the conventional method of winding, tabs are required, and they necessitate the use of a sufficiently heavy foil to provide mechanical strength.

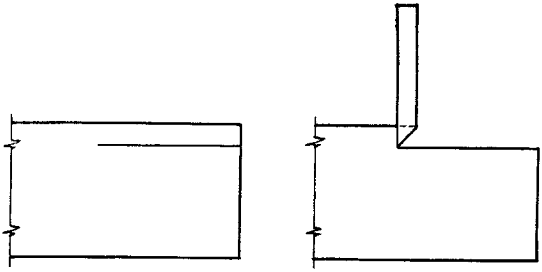


FIG. 27.—Integral tab for a heavy foil electrode.

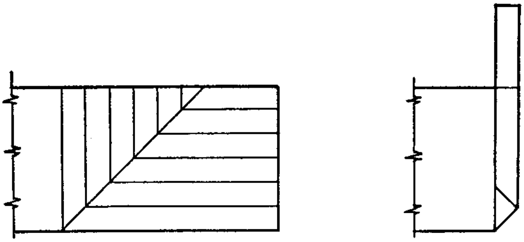


FIG. 28.—Integral tab for a thin foil electrode.

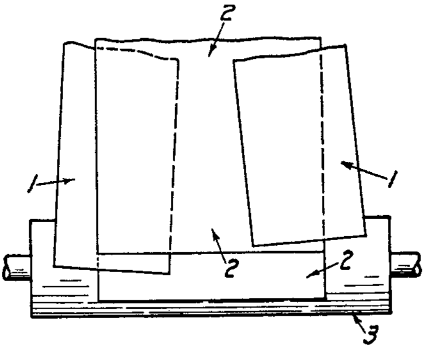


FIG. 29-A.—Telescoped section; the beginning of the winding.

1—foils.
2—paper spacers.
3—arbor.

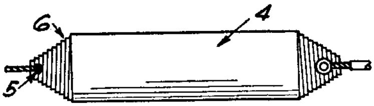


FIG. 29-B.—Telescoped section; the completed section.

4—capacitor section.
5—connection to terminal or to lead.
6—telescoped portion of foil.

is difficult. In such cases a subdivision of the capacitor into two or more sections, with their tabs connected in parallel, may prove advantageous.

Fig. 30 presents a combination of two (or several) polarized capacitors wound into one section, wherein one foil serves as the common cathode for two or more units. This construction is more economical and compact than the equivalent winding of several separate sections with the subsequent interconnection of their negative tabs or terminals.

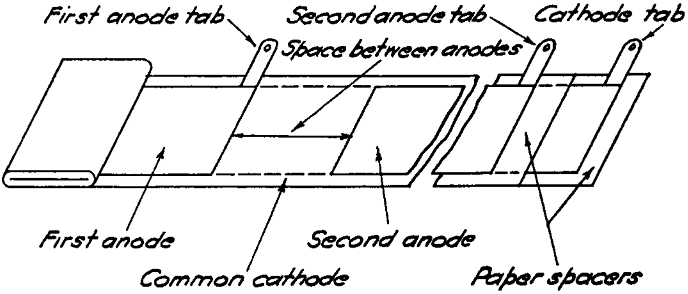


FIG. 30.—Two capacitors wound into one section. Two anodes and one common cathode foil.

When the operating voltage in the circuit is of such magnitude that a single capacitor may not withstand it safely, two or more units are joined in series. Sometimes it is desirable to save space and reduce the cost of the series combination by housing the units in one container and properly interconnecting their terminal tabs. A further improvement in this direction is obtainable by winding certain types of series-connected capacitors in one section.

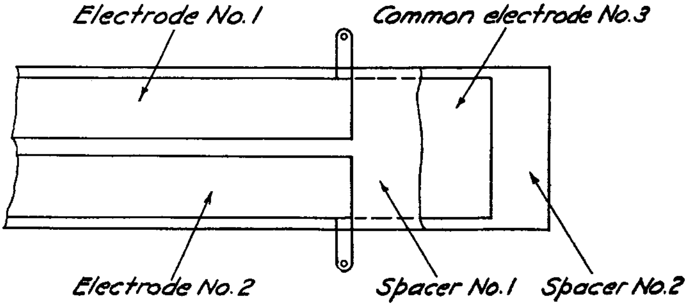


FIG. 31.—Series combination of two a.c. capacitors having a wide common foil and wound into one section.

Fig. 31 illustrates a symmetric or nonpolarized capacitor assembly with two units having a wide common foil and operating in series. It should be noted that in this combination the common foil is "floating," that is to say, it has no terminal connection. Instead of having one common foil of more than double width and two spaced, narrow foils, all three strips can be of substantially the same width, but the length of the common strip must be then somewhat greater than the combined lengths of the two separate electrode strips. This layout would resemble that of Fig. 30, though in the present case no tab would be provided for the common strip. To eliminate a direct leakage path between the edges (at the top and at the bottom of the section) of the two short foils, the width of the common foil is preferably made a little greater (about ¼″ on each side) as indicated in Fig. 32–A. This extra

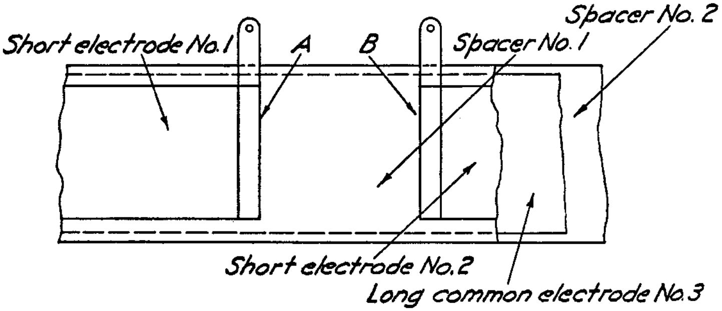


FIG. 32–A.—Series combination of two a.c. capacitors having a long common foil and wound into one section.

width establishes barriers between the short electrodes, the potential between them being twice as great as the potential between either of them and the common.

The potential difference among the various electrodes rolled into the same section must be carefully considered in all dual and multiple capacitors. Thus, in Fig. 31 the potential between the narrow strips is also twice as great as that between either of them and the common foil; this fact is of particular significance because ordinarily the film on all these foils is formed to stand the single potential only. However, in the latter case, by properly spacing the narrow foils from each other and because of the usually high resistance of the electrolyte in dry capacitors, excessive leakage currents and deterioration of the electrodes can be effectively prevented, at least when intermittent service only is considered, which is generally the case with a.c. electrolytic capacitors.

Similarly in the capacitor shown in Fig. 32–A, enough space must be left between the ends *A* and *B* of the short foils to suppress excessive leakage currents; a piece of varnished paper or cloth inserted in that region will substantially insulate the two capacitors, reduce still more the leakage and minimize the danger from breakdown around that area. The insertion of such insulating strips between the sections is recommended even when the latter are separately wound, connected in series and mounted in the same container.

In polarized capacitors with several sections having a common negative, the positive foils are usually at different potentials; depending on the magnitude of these differences and the resistivity of the electrolyte, insulating strips between the ends of the anodes may or may not be necessary. When a *common positive* foil is used and the two (or more) negatives are at different potentials, very elaborate insulation between the negatives is required, since they are unfilmed and consequently apt to permit the flow of excessive leakage currents between them. Beside the fact that such currents may interfere with the operation of the apparatus to which the capacitors are connected, there will be a gradual formation of a dielectric film on the aluminum cathode, the potential of which is less negative; this filming will result in a drop of capacitance in the corresponding condenser unit.

XIII

The Impregnation of Dry Electrolytic Capacitors

The objective of the impregnation is to remove any air and moisture from the section and then to saturate thoroughly its spacer with the operating electrolyte. The life and operating characteristics of dry electrolytic capacitors depend to a great extent upon their proper impregnation. First will be considered the factors governing the effectiveness of the impregnation and the precautions necessary to obtain the desired results. Then will be described the methods of impregnation adopted by manufacturers of dry capacitors, and their respective advantages and drawbacks.

Thorough impregnation of the paper spacer is not necessarily effected by merely putting its surface in contact with the electrolyte. Air present in the pores of the paper may be trapped while the latter is coated with electrolyte and the air is apt later on, when the unit is in service, to interfere with the free flow of electric current between the foils and therefore impair the operating characteristics of the device. Dry spots resulting from the trapped air and from imperfect wetting of the paper and foil may be responsible for the formation of weak regions where a breakdown is more likely to occur or around which minute sparks may cause pitting. For the uniform production of high-grade capacitors the elimination of air bubbles or pockets is imperative. This problem calls for particular attention when paper layers of moderate or low absorbency are used and when prewound sections are impregnated.

Normally, the paper spacer, prior to its impregnation, contains several per cent of moisture; if this is not removed, it will enrich the water content of the electrolyte during the impregnation cycle and tend to upset the proportions of its various constituents. For a strict control of the water content of the operating electrolyte it is desirable to dry the sections prior to their impregnation. Then the original characteristics of the electrolyte, imparted to it at the time of its preparation, will remain unchanged after it has penetrated into the paper spacer.

In the course of the impregnating cycle the electrolyte, especially when hot, should not be exposed to the surrounding atmosphere as it may lose by evaporation some of its important constituents—water, ammonia, and so on.

The contamination of the sections and of the electrolyte (with moisture, chlorides and other impurities) while they are in storage or during impregnation should be carefully prevented.

The optimum temperature of the electrolyte in the course of the impregnation cycle is usually below 300°F and should be determined experimentally. At high temperatures the electrolyte is more fluid and penetrates readily into the voids of the section and pores of the spacer. Excessively high temperatures, however, may be injurious to the paper and cause decomposition of the electrolyte or some other undesirable changes in it.

Due consideration must be given to the wetting properties of the electrolyte and the ease or difficulty with which the foil and paper are being wetted. Oily spots on the metal, sizing substances in the paper and similar agents may interfere with the intimate contact between the electrolyte on the one hand and the foil and paper on the other; such effects will tend to raise the power factor and lower the efficiency of the capacitor.

Although the penetration of the electrolyte solution into the paper pores must be thorough and the impregnation must insure a sufficient supply of it, an excess of the solution is rather undesirable as it increases the cost of the section and may contribute to electrolyte leakage after the capacitor is assembled in its container. In this connection it is noteworthy that only a minute proportion of the electrolyte in the section is electrolyzed and thus used up throughout the life of the dry capacitor, under *normal operating conditions*. Electrolysis is effected by the leakage current only; as the leakage is normally exceedingly minute, the quantity of decomposed electrolyte is usually negligible.

One of the first methods of impregnation called for smearing the electrolyte onto the spacer, or foil or both, followed by the winding of the section. The good point of this procedure is the positive application of the electrolyte, irrespective of its fluidity, over the entire area of the electrodes and their spacers; very little equipment was required in this operation. The drawbacks are outlined in the following:

The process is slow, involves much labor and is therefore costly. The electrolyte, electrodes and spacers are exposed to contamination by moisture, dust, and so on while the coating is carried out. Since the electrolyte is usually applied hot and exposed to the atmosphere as it is smeared on, it is apt to lose some of its constituents because of evaporation.

In spite of the positive application of the electrolyte, air may be trapped within the spacer and interfere with its thorough soaking; the penetration of the electrolyte is particularly difficult when dense paper is used.

The moisture originally present in the paper is not driven off but tends to diffuse into the electrolyte and render the water content of the latter uncertain and uncontrollable.

It is difficult to wind compact sections when using foils and spacers coated with electrolyte.

A modification of the above procedure calls for the application of the electrolyte to the various layers while running the section through the winding machine. This method is better than the preceding one inasmuch as there is less chance for the materials to be contaminated; the operation is also faster and more uniform. The other drawbacks, as mentioned above, are present, and on the whole the process is slow and costly.

The third method comprises the immersion of the prewound sections in a tank filled with hot, fluid electrolyte; the vessel may then be closed or kept open. The pros and cons in this case are as follows:

The winding of the dry section is convenient, rapid and economical.

There is little danger from contamination while winding and impregnating.

The impregnation process and equipment are simple and relatively inexpensive.

If the vessel is closed, the moisture present in the paper spacer is added to the water of the electrolyte and the total water content may become excessive.

If the vessel remains open, the evaporation of water and glycerin, loss of ammonia, and so on, are uncontrollable and the proportions of the constituents are likely to be upset; ingredients are also wasted. Although it is feasible to add ingredients to compensate for the losses, it is difficult to determine quickly the required quantity for each substance.

The air trapped within the voids of the section and in the pores of the spacer impedes the penetration of the electrolyte.

In the early days of manufacture of dry electrolytic capacitors, attempts were made to impregnate the sections in the same manner as wax- or oil-paper capacitors were impregnated. No satisfactory results were obtained because at that time the fundamental difference in the operation of the dry electrolytic and the nonelectrolytic capacitor was not well understood. In the manufacture of the latter it is highly desirable to remove all traces of moisture not only from the section but also from the impregnating medium (oil, wax, and so on). This removal is required since any ionization of (caused by the presence of water), and the resulting conductivity exhibited by, this medium greatly lowers the quality and shortens the life of nonelectrolytic capacitors. For this reason, heating and evacuation are carried on throughout a considerable portion of the impregnating cycle to secure as complete a dehydration as possible of both the sections and the impregnant. On the other hand, in the case of the dry electrolytic capacitor, the presence of *just the right proportion of water* in the impregnating electrolyte is of vital importance as it brings about the limited but *necessary* ionization of this medium. Either excess or deficiency of water in the electrolyte is objectionable as explained in Chapter XI. When the process of unlimited dehydration was applied to electrolytic capacitors, moisture and along with it ammonia and other volatile constituents were removed from the electrolyte in a haphazard manner during the impregnation cycle. Depleted to various degrees of these essential substances, the capacitors proved to be very nonuniform and mostly inefficient.

The author modified this method of vacuum impregnation as outlined in the following and obtained excellent results. The dry, prewound sections were placed in an empty tank, preferably of aluminum, to prevent its attack by the electrolyte introduced later on. The lid might be left open to allow the driving off of moisture while preheating was going on. Then the lid was closed hermetically and, while the heat was maintained, as thorough evacuation as practicable was applied so as to remove both air and moisture from the sections. The next step was the introduction of the properly conditioned (as to content of water and other constituents) and preferably preheated (in a separate closed vessel) electrolyte into the evacuated tank. As soon as the sections were covered by the solution, the *evacuation was stopped* but the lid remained sealed. The electrolyte was maintained hot for several hours, then allowed to cool to a predetermined temperature. When this was reached the sections were removed from the tank, the excess of electrolyte was allowed to drip off and they were then stored in a clean, dry, closed vessel. After cooling to a temperature convenient for handling, the sections should be promptly assembled into containers and sealed. Exposure of the unmounted sections to the air should be avoided as far as possible because it is conducive to their contamination with moisture and other impurities.

The optimum values for the impregnation temperature, the duration of the cycle and the temperature at which the sections are removed from the electrolyte are determined experimentally. These factors are correlated with the nature of the electrolyte, in particular its penetrating properties; with the absorbency of the spacers and the tightness of the winding; with the quantity of electrolyte it is desired to retain within the sections. The removal of the sections from the tank while the electrolyte is at about the impregnating temperature, i.e., very hot and usually very fluid, causes the draining of a greater proportion of the solution than is the case when they are taken out at room temperature. Ordinarily, the removal is carried out at an intermediate temperature.

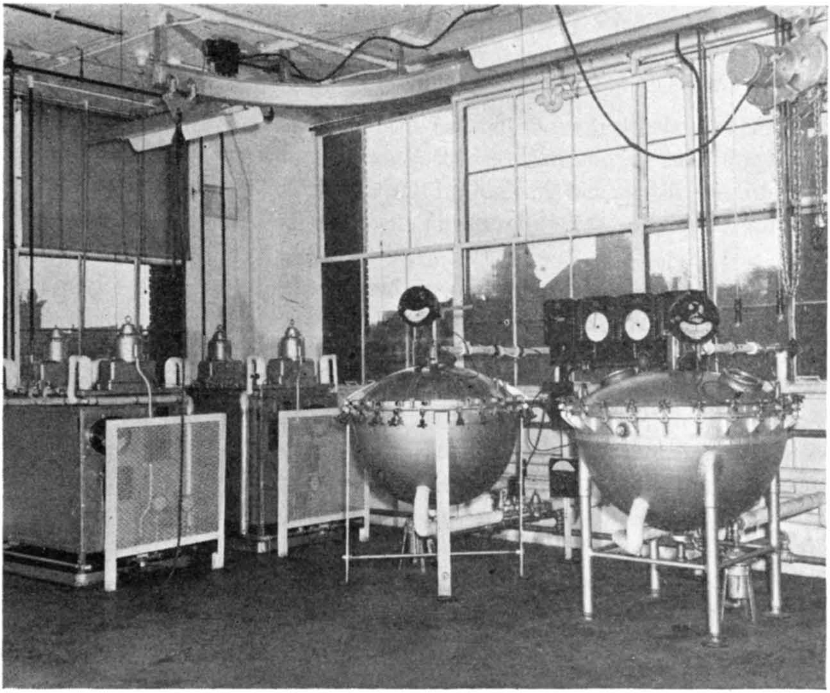


FIG. 32-B.—Equipment for the impregnation of electrolytic capacitors.

Another method of impregnation depends on the penetration of the electrolyte into the prewound sections when a great centrifugal force is applied to the fluid or liquefied impregnant. For this purpose the capacitor sections are properly positioned in a revolving tank containing the fluid electrolyte. The good points ascribed to this method are the rapid completion of the cycle and good penetration. Whether the elimination of the air pockets, particularly from dense paper spacers, is as good as is obtainable with the vacuum process is uncertain. Furthermore, the problem of removing the moisture, always found in paper spacers, presents additional complications.

XIV

The Capacitor Container and Its Vent. Assembling the Capacitor

The container has to protect the capacitor from mechanical injury, prevent the ingress of moisture and other contaminating substances and preclude the egress of the electrolyte by leaking out, or the loss of some of its constituents by evaporation. These requisites call for an airtight enclosure.

On the other hand, the operation of electrolytic capacitors entails some electrolysis which, however, is slight under normal conditions. If overload occurs, the electrolysis may be intensified to the point where appreciable quantities of oxygen and hydrogen are given off and set up an internal pressure. Overloading is also accompanied by heating of the unit which in turn increases the vapor pressure of the electrolyte. While the total internal pressure in the capacitor is moderate under ordinary service conditions and not disturbing at all, it may become excessive and objectionable when the device is subjected, for any length of time, to abnormally high voltages and overloads in general. In such cases internal pressures of the order of 100 lbs. per square inch and greater may be set up and, if no adequate provisions are made, the container may be ruptured or blown up.

To cope with this situation requirements must be met, some of which are conflicting. It appears desirable, from what has been said, that until the safe maximum pressure has been reached there should be no opening whatsoever in the container. Beyond that maximum the pressure should be released without losing electrolyte; this precaution is particularly important for wet condensers as in their case a loss of electrolyte is frequently coupled with a drop in capacitance. These requisites suggest the use of a vent, which must be, however, of a very simple construction and inexpensive to be in line with the general design of electrolytic capacitors and their low price. A permanent opening, like a pinhole in the can, will not do, because the internal pressure would force out through it vapors and some electrolyte and thus impair the efficiency and life of the device. Furthermore, electrolyte leaks may be responsible for setting up paths for disturbing stray currents in the equipment in conjunction with which the capacitor is used. Even pinholes in a rubber membrane may eventually allow enough leakage to cause trouble. On the other hand, if the vent is not sufficiently responsive, it may not open in time to give the desired protection and the unit may be blown up under severe overload conditions.

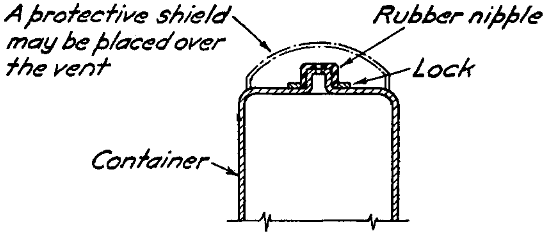


FIG. 33.—Vent for wet capacitor.

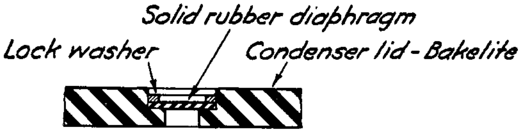


FIG. 34.—Venting arrangement (protective plug) for dry capacitor.

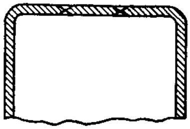


FIG. 35.—Weak-spot vent for dry capacitor.

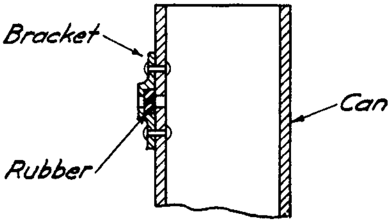


FIG. 36.—Vent for dry capacitor with a pierced rubber membrane.

Figs. 33–36 illustrate a few vents for wet and dry capacitors. It has been found that on accelerated tests most of the vents often act in an erratic manner and either open too soon or do not respond before the blow up. Such tests should be considered as inconclusive, since they bring about a very rapid increase in pressure which may interfere with the normal operation of the vent. In the field, the pressure is built up rather slowly and experience has shown that under such circumstances certain types of vents and protective plugs operate quite satisfactorily.

A "weak spot vent," like that shown in Fig. 35, may keep the capacitor hermetically sealed to about 80 or 100 lbs. per square inch and open above that pressure, which may be entirely satisfactory. Such safety vents, plugs, and the like, are used in certain dry capacitors, where the loss of some electrolyte, incident to the opening of the vent, is not necessarily of vital importance for the device.

Wet capacitors are more frequently protected by rubber membranes or nipples pierced by a needle, as shown in Fig. 33. This member is usually shielded or located in an indentation on the container to prevent its injury or accidental removal. The excessive internal pressure opens the minute hole in the rubber fitting to permit the escape of accumulated vapors and gases; but it should close automatically as soon as normal pressure is re-established, thus preventing the evaporation and leakage or creepage of electrolyte. To function properly the rubber or similar material of which the fitting is made must not lose its resilience over long periods of storage or use or when exposed to elevated temperatures as ordinarily encountered in the operation of capacitors.

Other requisites for a satisfactory container for electrolytic capacitors are immunity from attack by the electrolyte; mechanical strength, preferably combined with light weight; convenience of assembling and sealing; compactness and ease of installation in the chassis, on the frame, and so on; heat emissivity and reflectivity; ease of manufacture and low cost.

Practically all these requirements are met by extruded or drawn aluminum and copper cans. By employing the can of the wet capacitor as the negative terminal, the construction of the device and its connection to the external circuit is simplified. This connection is ordinarily established by using a clamp or screw type of arrangement which can be easily combined with or incorporated into the capacitor structure. In case it is desired to insulate the can from the metallic frame, wrappers, sleeves or washers made of paper or fiber are interposed between the frame and the can, as in Figs. 37–38.

Dry electrolytic capacitors are frequently housed in similar cans, usually made of aluminum or zinc. Tin cans are sometimes used as a substitute; care must be taken in this case to remove any soldering flux remaining in the can to prevent the contamination of the section. With aluminum cans the contact between the container and the electrolyte is ordinarily not objectionable and, if desired, one of the tab terminals may be grounded to the can by riveting or clamping, Fig. 39. This arrangement is simple and reduces the cost of the device; it is extensively used in the manufacture of dry polarized capacitors in which case the grounded foil is usually the negative. It should be pointed out in this connection that the electrolyte is substantially at the potential of the negative foil and that if the latter is grounded no stray currents will result from the contact between the can and the electrolyte. If the can is to be insulated from the chassis, paper or fiber members are employed as in the case of wet capacitors. Motor-starting capacitors assembled in cans are placed as a rule in specially treated paper boxes prior to their mounting on the frame to preclude any contact between the latter and the can, and thus prevent the flow of disturbing stray currents.

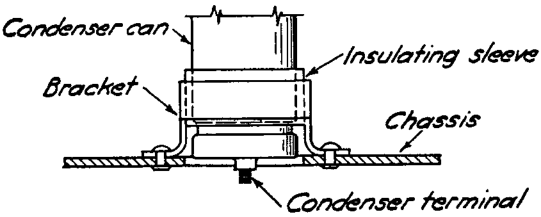


FIG. 37.—Inverted mounting of a capacitor. The can is insulated from the chassis.

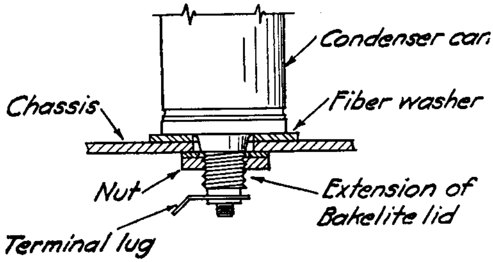
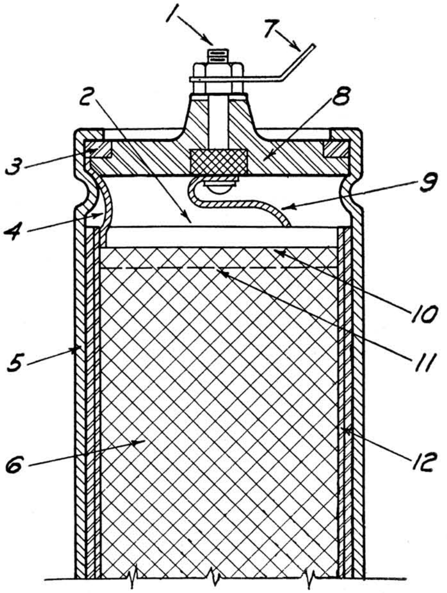


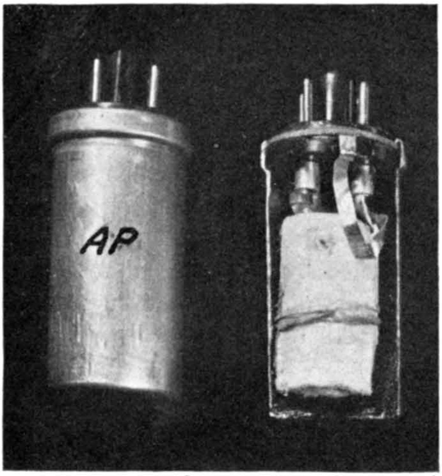
FIG. 38.—Inverted mounting of a capacitor. The can may be grounded to the chassis if the fiber washer is removed.

If the can is made of zinc or some other nonfilming metal, the grounding of the cathode tab is not recommended, while the grounding of the anode is not permissible at all with such cans, as its joint would be destroyed by electrolysis. Cans made of metals other than aluminum are frequently coated on the inside with an acid-proof paint or varnish or some other material which resists the action of the electrolyte and is free from chlorides. Although this coating will prevent satisfactorily a chemical interaction between the electrolyte and the can, it should not be depended on entirely for the electrical insulation of the section from the frame, as there may be pinholes and other imperfections in



1—terminal.
2—varnished paper wrapper.
3—rubber gasket.
4—grounded tab.
5—can.
6—condenser section.
7—soldering lug.
8—Bakelite lid.
9—insulated tab.
10—edge of paper spacer.
11—edge of foil.
12—varnished paper insulator-wrapper.

FIG. 39.—Cross-sectional view of a dry electrolytic filter capacitor; the negative tab is grounded to the can.



(Courtesy Aerovox Corporation.)

FIG. 40.—Aerovox filter capacitor and cutaway picture.

FIG. 41.—Motor-starting capacitor mounted in a Bakelite container.

the coating through which the electrolyte may conduct current to the can. The paper or fiber which envelops the can should provide this insulation; however, when capacitors are operated in a humid atmosphere, at high temperatures, the ordinary wax-impregnated paper box may prove to be inadequate and the flow of disturbing stray currents may take place. Impregnation of the paper with Bakelite varnish makes the insulation more reliable. If the service conditions are extremely severe for the insulator, as for instance when motor-starting capacitors are used in tropical countries, the substitution of Bakelite or hard-rubber containers for the can (though more costly) may be sometimes advisable (Fig. 41).

In assembling the dry capacitor, precautions must be taken to prevent an inadvertent grounding of the tabs or edges of the foil-winding to the can; similarly, a short circuit between the tabs must be precluded. For this reason the section is ordinarily wrapped in a strip of varnished paper or cloth and, if necessary, an insulating spacer is placed between the tabs; sometimes, a partition fin is molded on the bottom of the lid to keep the tabs apart. An insulating washer is also placed at the bottom of the can.

With hermetically sealed cans, the dipping of the section in wax or pitch prior to its assembly or the pouring of such sealing compounds over the top of the section appears to be unnecessary. The use of such compounds may even interfere with the free conduction of the heat (generated within the section) toward the can and thus impede the cooling of the capacitor.

The terminal board which serves also as a lid for the capacitor is preferably made of hard rubber or Bakelite as these materials are strong mechanically, do not warp readily and provide a good insulation for the terminals. Furthermore, by molding the latter into the lid, danger from the electrolyte's leaking out is minimized. It is essential to have those parts of the terminals (particularly the anode terminal) that are exposed to the electrolyte made of aluminum, lest they be attacked by electrolysis. The use of non-film-forming metals for anode terminal tips (inside the unit), protected by a coating of some insulating compound, may not be always entirely safe, as even a minute fissure in the coating may provide a path for the electrolyte to reach the tip or joint and cause electrolysis.

The use of inexpensive paper boxes or tubes, properly treated, in place of cans, Bakelite and similar containers for the housing of dry electrolytic capacitors is in many instances practicable. Such substitution reduces the cost, eliminates the necessity of providing an external insulating envelope or internal wrapper and may contribute to

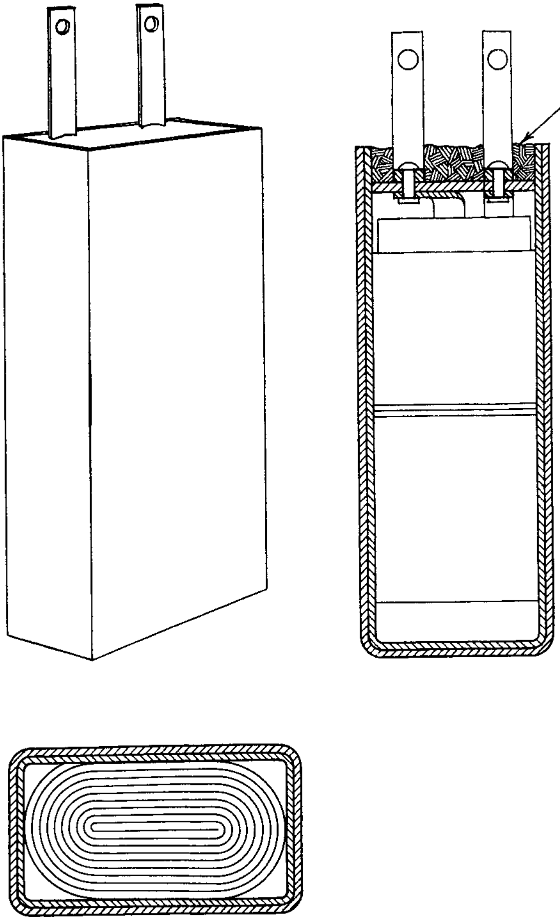


FIG. 42.—Dry electrolytic capacitor section assembled in a wax-impregnated paper box; sealed with an asphalt compound.

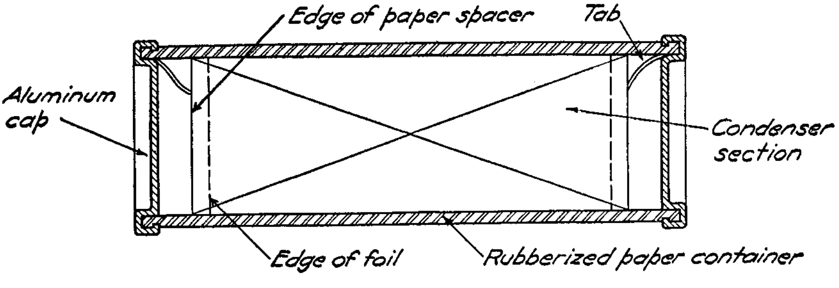
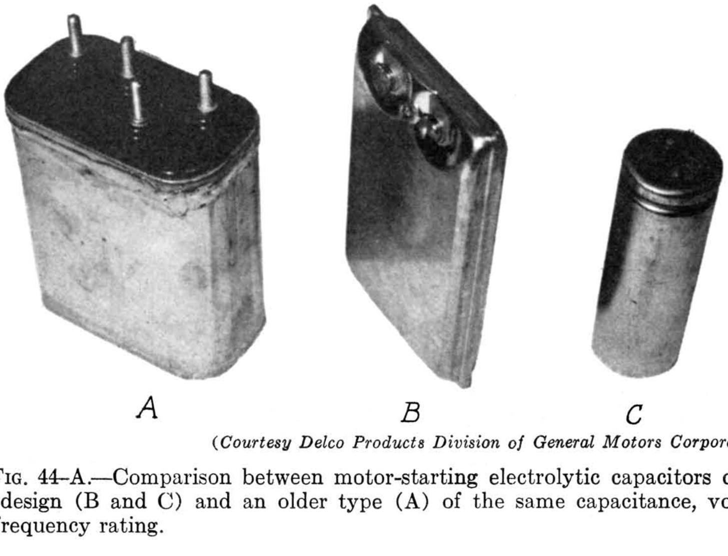


FIG. 43.—Fuse type of dry electrolytic capacitor assembled in a rubber-coated paper tube. Aluminum lids serve as terminals.

the compactness of the unit. Ordinarily, the paper container is impregnated with a high melting point wax and sealed with pitch (asphalt base compound). The problem is to prevent the leakage of electrolyte, its evaporation and the drying out of the section; the ingress of moisture is another consideration. By-pass capacitors, filter capacitors and the like housed in such paper containers have given satisfaction when operated under normal conditions. The sealing with pitch must be done very carefully to avoid the formation of fissures and imperfections in general, as such may be easily caused by bubbles given off by the electrolyte when it is in contact with the hot pitch. Substantially solid electrolytes lend themselves better for this type of construction than the viscous or fluid electrolytes as illustrated in Fig. 42.

Under severe conditions, however, in storage, transportation and use, the paper container may prove to be inferior to the can or Bakelite housing. At elevated ambient temperatures, in particular, the sealing compound may exhibit the so-called "cold flow" and the enclosure may become imperfect. Moreover, at high temperatures even the solid electrolytes turn more or less fluid and tend to soak into the container.

A modification of the paper container (Fig. 43) has been tried out with notable success. It consists of a paper tube coated preferably inside and outside with rubber, thus combining the impermeability of the hard-rubber housing with the economy, light weight and compactness of the paper container. The crimped-on aluminum caps make an airtight seal, doing away with the use of pitch and thus insuring satis-



(*Courtesy Delco Products Division of General Motors Corporation.*)

FIG. 44–A.—Comparison between motor-starting electrolytic capacitors of recent design (B and C) and an older type (A) of the same capacitance, voltage and frequency rating.

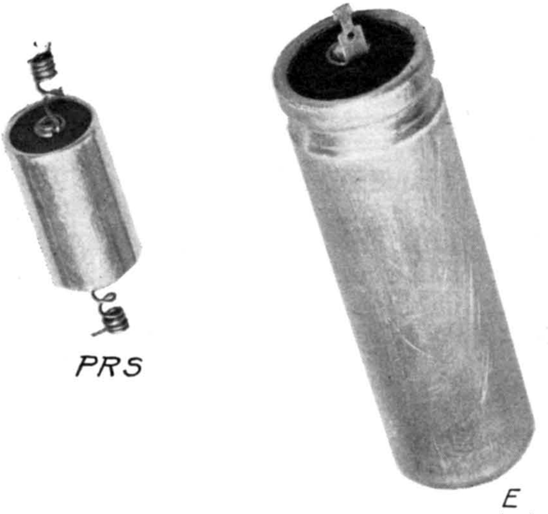
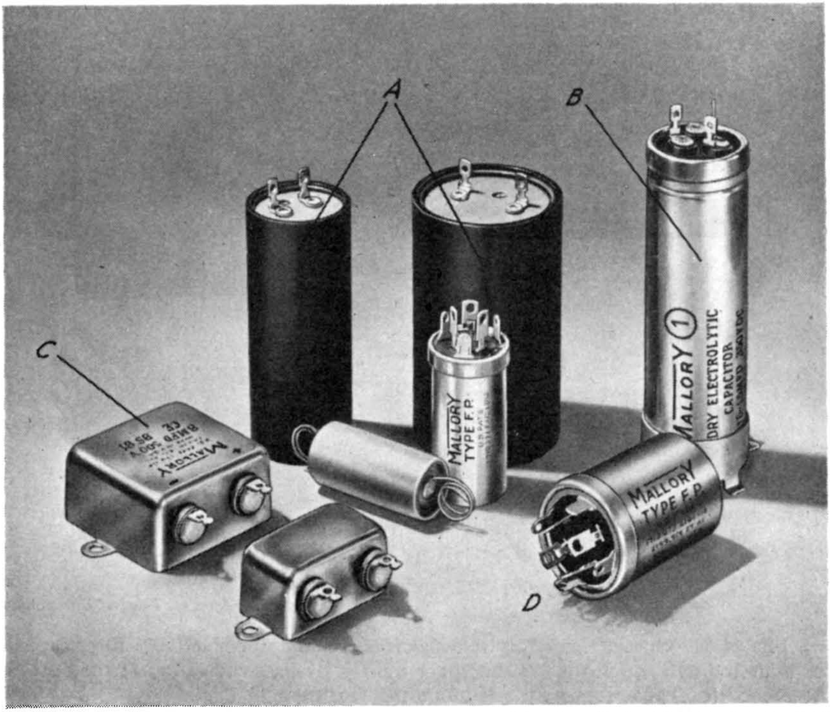


FIG. 44–B.—Dry electrolytic filter capacitors; both rated at 8 MF—450 V.

PRS—etched Aerovox capacitor, 1½″ long, ⅞″ OD.

E—plain foil Aerovox capacitor, 4⅜″ long, 1⅜″ OD.

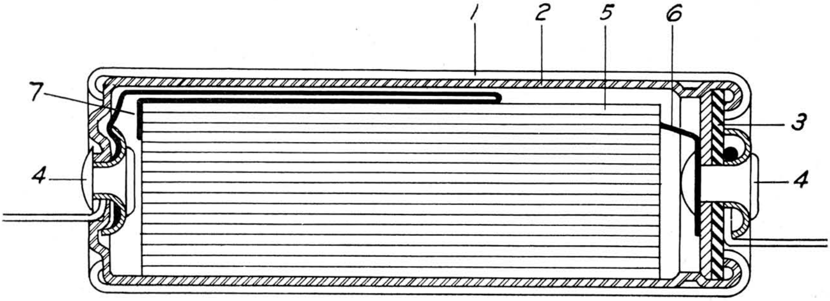
(*Courtesy the Aerovox Corporation.*)



(*Courtesy P. R. Mallory & Co., Inc.*)

FIG. 44–C.—Mallory electrolytic capacitors.

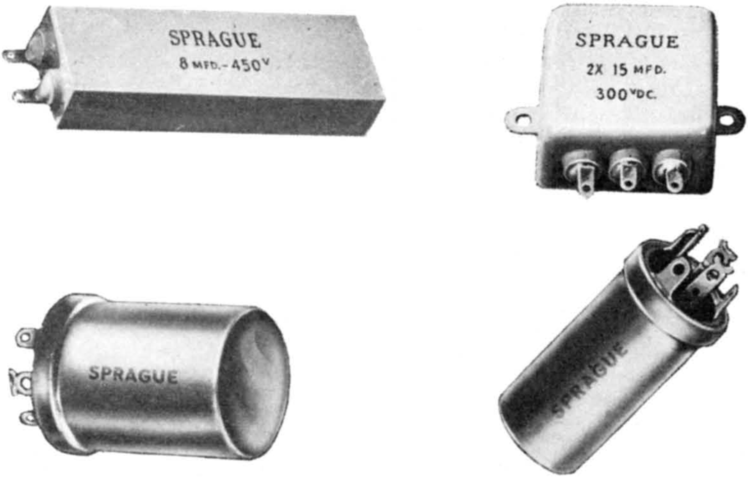
A—mounted in plastic containers.
B—mounted in round cans.
C—capacitors in rectangular cases.
D—capacitor with self-mounting prongs.



(*Courtesy Solar Manufacturing Corp.*)

FIG. 44–D.—Minicap tubular capacitor.

1—cardboard tube.
2—metal can.
3—composite rubber-Bakelite washer.
4—riveted leads.
5—condenser winding.
6—anode tab.
7—cathode tab.

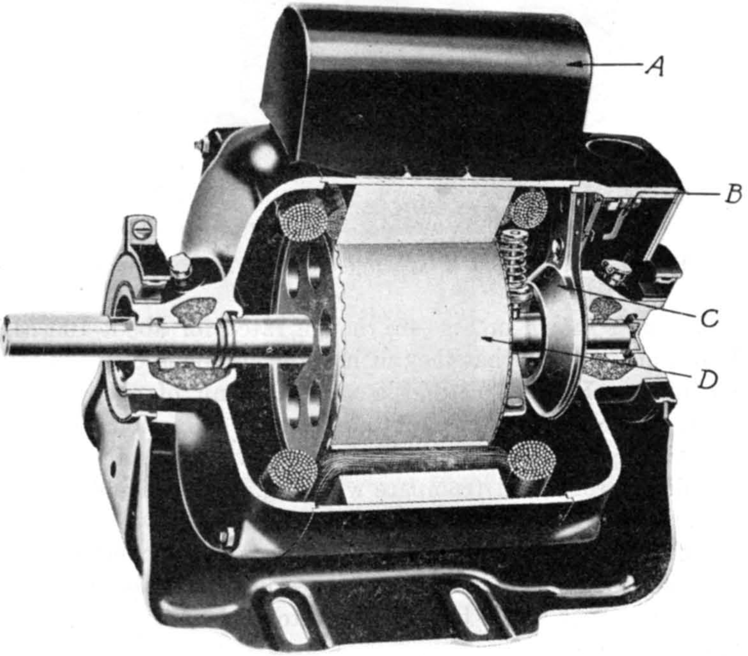


(*Courtesy Sprague Electric Company.*)

FIG. 44–E.—Sprague electrolytic capacitors. At the upper left is a filter capacitor mounted in a paper box; at the upper right, a by-pass capacitor; at the bottom are etched foil capacitors with self-mounting features.

factory operation at elevated temperatures. The tabs are clamped by the aluminum caps at the opposite ends of the capacitor, greatly simplifying the entire assembly; external paper envelopes, internal section wrappers and tab separators thus become unnecessary. Such units have the appearance of a fuse and like the latter are conveniently installed; the end caps serve as terminals and incidentally also as safety plugs, since they are loosened by excessive internal pressure, thus precluding a blowout (U.S. patent 2,264,900).

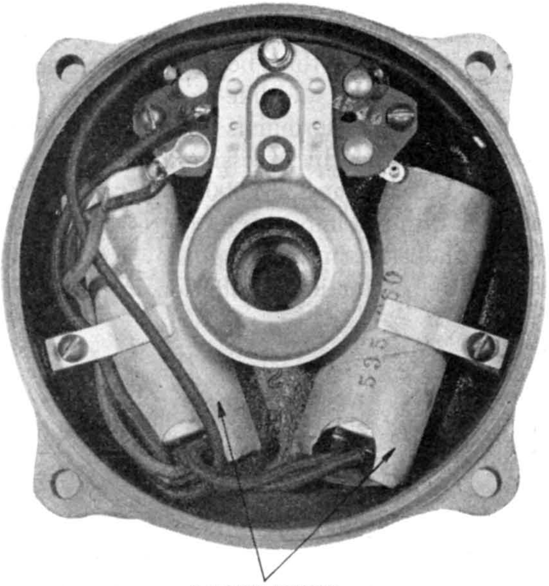
Figs. 44–47 illustrate the impressive progress made in recent years by the condenser industry in reducing the size of the electrolytic capacitor and adapting it for its installation in places of varied out-



(Courtesy Delco Products Division of General Motors Corporation.)

FIG. 45.—Capacitor-start motor.

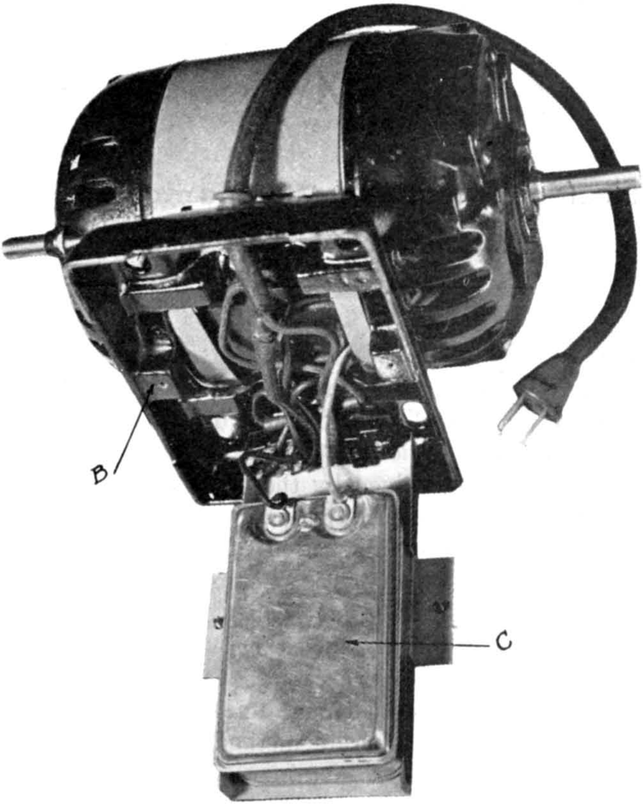
A—capacitor.
B—thermotron for protection.
C—centrifugal switch.
D—rotor.



(*Courtesy Delco Products Division of General Motors Corporation.*)

FIG. 46.—Motor-starting capacitors mounted in the end-frame.

line. The units shown in Fig. 46, though rated for about 100 MF at 110 V a.c., are so small that they fit into the end plate of a 1/5 HP induction motor. Fig. 47 pictures a very flat unit of about 200 MF, 110 V a.c. suitable for mounting into the base of a fractional HP motor. In both cases protrusions on the motor are avoided as the capacitors are completely concealed (compare with Fig. 45). It should be noted, however, that the mounting into the end plate is not always practicable. When the capacitor is apt to be subjected to frequent overloads and in general operated under adverse conditions, it is advisable to mount it in a place where it has a better chance to cool off, unless provisions are made for a forced air draft.



(Courtesy of Sunlight Electric Division of General Motors Corporation.)

FIG. 47.—Flat motor-starting capacitor mounted in the motor base.
B—motor base.
C—capacitor.

XV

Electrical Measurements and Routine Tests on Electrolytic Capacitors

Compared to wax- or oil-paper capacitors, the electrolytic type has a much greater (tens of times) leakage current per microfarad and a much higher power factor. Both of these quantities undergo substantial variations in electrolytic capacitors, especially with the change in temperature. The heat evolved by the test current is often sufficient to affect appreciably the capacitance and power factor of electrolytic condensers, but the re-forming action of the test current upon the dielectric film may have an even greater influence. To these considerations must be added the fact that the applications for electrolytic condensers are ordinarily such that wide tolerances are acceptable (particularly capacities in excess of the rated value).

The electrical measurements on mica, wax-paper and similar capacitors often involve elaborate methods and equipment of great precision, the purpose being to obtain very accurate results. For instance, measurements of power factors expressed by hundredths of 1% are common with nonelectrolytic units. Such precision would hardly be of practical advantage when testing electrolytic capacitors because, as already mentioned, the magnitude of the power factor, leakage current, and so on, are in this case of a very different order and subject to considerable changes.

The above statements will be illustrated by a few examples. The power factors of electrolytic capacitors measure mostly between 5 and 10%, but 13 and even 15% are often tolerated; the power factors of wax-paper capacitors, on the other hand, are ordinarily less than 1%. When checking an a.c. electrolytic capacitor it may be observed, not infrequently, that its power factor is dropping during the test, within a few seconds, from a value of 10% or more to 5% or less, primarily because of the re-forming of the film. No comparable changes occur with mica or wax-paper units. The leakage current of the electrolytic capacitor is not only many times greater but is also quite unsteady and strongly affected by the magnitude of the applied voltage, the temperature and the period of idleness for the unit prior to the test. Finally, when dealing with nonelectrolytic condensers we are usually concerned with capacities of a small or moderate value per unit; on the other hand, in the case of electrolytic condensers we come across units rated several hundreds or even thousands of microfarads each (though smaller values, but rarely below 1 MF, are manufactured in greater quantities). When acceptance specifications for electrolytic condensers are made, wide tolerances for the capacitance, up to 25%, are usual; for filter circuits +100% or even more is not uncommon.

We will therefore be concerned in the following with the description of only such methods of measuring and testing of electrolytic capacitors as are in line with their general characteristics and meet the ordinary practical requirements of the user. It is desirable to start the measurements with the determination of the leakage current, as such procedure will usually eliminate at this stage defective units which, when tested for capacitance and power factor, may result in the damage of the test equipment. Furthermore, while the leakage is checked, the dielectric film of the condenser is being re-formed and stabilized, which makes the subsequent measurements of the capacitance and power factors more definite and accurate, as an excessive leakage current renders the readings erratic. This sequence in testing is particularly desirable when capacitors are checked after long or unknown periods of idleness in the course of which their films may have been markedly deformed.

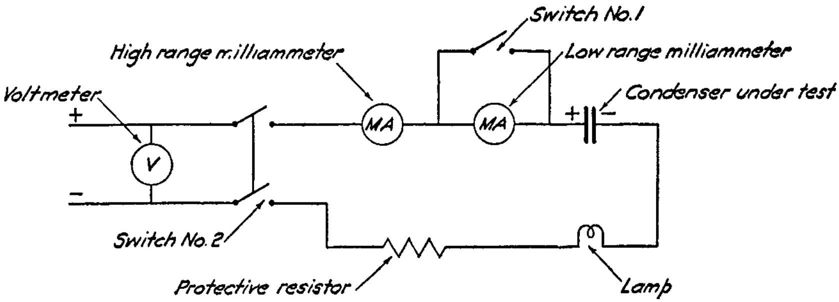


FIG. 48.—Test-circuit for measuring the leakage current of electrolytic capacitors.

Fig. 48 presents a simple circuit for measuring the *leakage current*. For comparative tests the impressed d.c. voltage is arbitrarily chosen but ordinarily does not exceed the rated working potential of the capacitor. Before the voltage is applied to the unit, switch 1 is closed to protect the milliammeter from damage in case its range is low and the capacitor happens to be very leaky or short-circuited. In the latter case the steady and intense light of the bulb indicates the defect after the main switch 2 is closed. If the capacitor is open-circuited there will be no light, and no current will be indicated on the milliammeter during the following steps of the test. If there is no short and the unit is in fair condition, the light will very soon be dimmed and then go out, indicating the normal re-forming of the film. Then the shunting switch 1 can be opened and readings on the milliammeter taken after the elapse of a predetermined time, usually a few minutes from the closing of switch 2. Modifications of this circuit can be made by using a low- and a high-range milliammeter connected in series and shunting the first meter only; this arrangement permits following the changes in the leakage continuously, from the moment the voltage is impressed across the capacitor. If the bulb is rated for a voltage lower than that of the test circuit, a protective resistance of the proper value must be inserted in series with it. The final reading of the leakage is only slightly affected by the resistance of the bulb (and the protective resistor) as the latter usually amounts to only a small fraction of the insulation resistance of the re-formed capacitor. To obtain useful and comparable information from this test, the applied voltage must be maintained constant by making the necessary adjustments. If the capacitor is polarized, care must be taken to connect the anode to the positive terminal of the fixture. If a nonpolarized unit is under test, the leakage is measured as before and the polarity is then reversed and the test repeated.

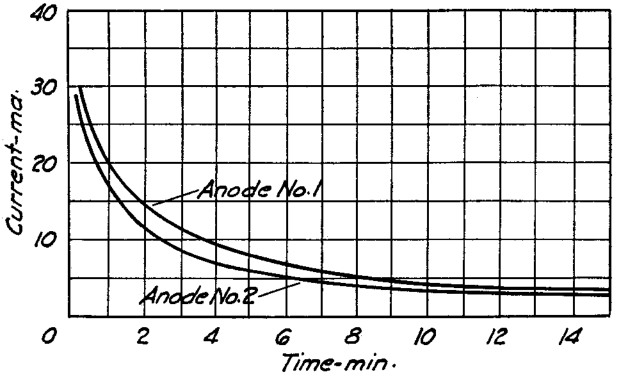


FIG. 49.—Re-forming curves of a dry a.c. electrolytic capacitor section rated for 100 MF, 110 V, 60~. This is the first re-forming after the section was taken out of the impregnating tank and allowed to cool to room temperature.

It will sometimes be observed, as in Fig. 49, that the leakage current curves of the two electrodes in a nonpolarized capacitor differ markedly; this may be due to the nonuniformity of the two dielectric films. However, some allowance should be made for this difference in connection with the deforming action of the current upon the electrode which happens to be used temporarily as a cathode. Finally, the re-

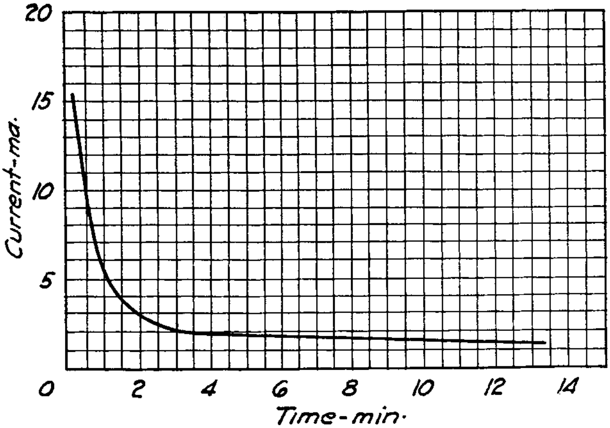


FIG. 50.—Leakage current after several days of idling. 100 MF, 110 V, 60~, dry a.c. electrolytic capacitor.

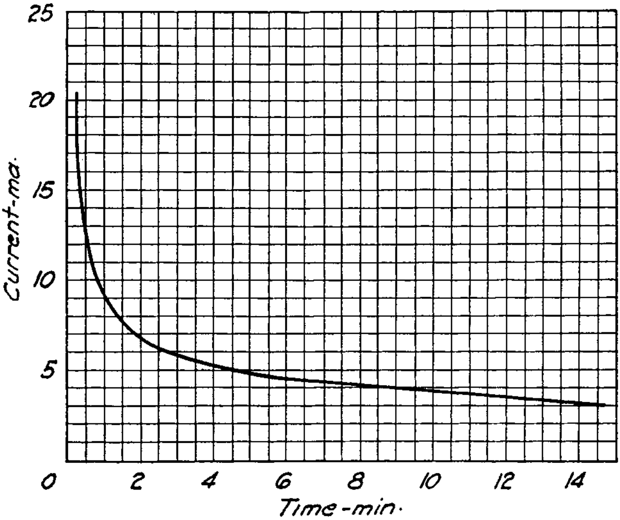


FIG. 51.—Leakage current after several months of idling. 100 MF, 110 V, 60~, dry a.c. electrolytic capacitor.

forming current causes some electrolysis of the electrolyte resulting in the release of gas, at the foils, which contributes to the total resistance of the circuit; its effect may be more noticeable when the re-forming of the second foil is started.

Graphs 49–51 indicate the re-forming of several capacitors rated for 110 V 60 ~, each of about 100 MF's. Curve 49 refers to a section taken out of the impregnating tank and subjected to re-forming immediately after it had cooled to room temperature. Fig. 50 pertains to a capacitor which has been re-formed, then left idle for several days when its leakage current was checked. Fig. 51 is the leakage curve of a capacitor which has been idle for several months (after its initial re-forming). Two leakage curves are also shown in Chapter II.

In testing various capacitors very substantial differences in their leakage characteristics may be eventually noticed; they are mostly due to the following factors:

Difference in test (and rated) voltage and to a smaller measure difference in the value of the inserted series resistances.

Type of capacitor; wet units exhibit usually a greater leakage and more pronounced deforming.

Purity of the aluminum anode and its surface condition. The etching may also have some influence on the leakage.

Filming voltage and current density; the method of anode formation; the properties of the filming solution.

Type of operating electrolyte and thoroughness of impregnation.

Temperature of the capacitor during the test.

Period of idleness prior to the test.

The curve in Fig. 52 indicates a somewhat erratic behavior of a capacitor tested for leakage; the drop of leakage followed by its temporary increase is not unusual and does not necessarily mean that the unit is not serviceable. If, however, the fluctuation is great, it is indicative of the sluggishness in the rebuilding of the film and of its pronounced tendency to deform while the device is idle. This behavior is mostly due to some weakness in the film brought about by one of the factors discussed in Chapters V and VI. Imperfect impregnation, contamination and improperly compounded operating electrolyte may also be responsible for this effect.

For the production *capacitance test* of filter and similar electrolytic condensers of small and moderate capacitance, an ordinary direct-reading microfarad meter as used for the checking of nonelectrolytic condensers will be often found satisfactory, even if the electrolytic condensers are polarized, provided the impressed voltage is very low. If

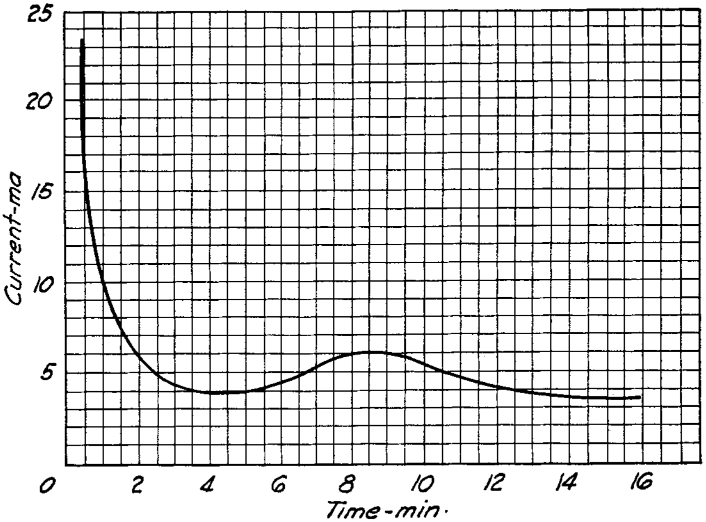


FIG. 52.—Graph showing the sluggish re-forming of a dry a.c. electrolytic capacitor rated for 100 MF, 110 V, 60~.

the capacitance exceeds the range of the meter, a wax- or oil-paper condenser of known value (of the same order as the unknown) should be connected in series with the unit under test. The following formulae are used for the computation of the capacitance when two condensers are connected in series:

$$Cs = \frac{Ca \times Cx}{Ca + Cx} \tag{8}$$

and

$$Cx = \frac{Ca \times Cs}{Ca - Cs} \tag{9}$$

where Cx = the capacitance of the electrolytic condenser,
Ca = the capacitance of the standard condenser connected in series,
Cs = the capacitance of the two units in series.

To eliminate the necessity of computations when many tests are carried out in production with the same standard capacitor in series, a special calibration can be made on the meter to permit the taking of direct readings.

The impedance method illustrated by the circuit in Fig. 53 is sufficiently accurate for ordinary purposes and it indicates the actual effectiveness of the capacitor in most of its applications—filter circuits, and the like. This method is usable for checking capacitors of all values, provided meters of the proper range and type are available;

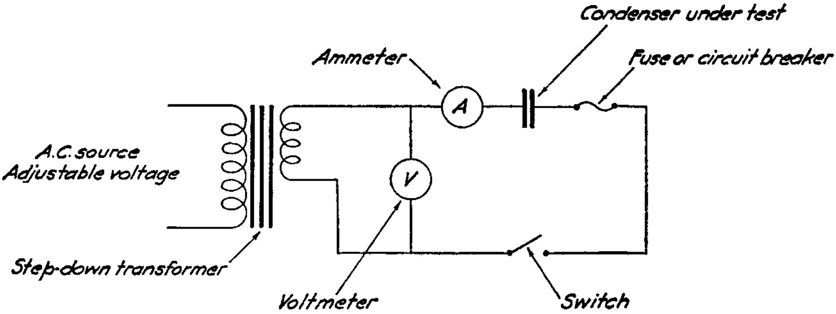


FIG. 53.—Circuit for measuring the capacitance of condensers. Impedance method.

the applied voltage must be low (a few volts) and held constant. To compute the capacitance in this case the following formula is used:

$$C = \frac{I \times 10^6}{E \times 2\pi f} \tag{10}$$

where C = capacitance in MF's,
I = current in amps.,
E = impressed volts across the condenser,
f = frequency of current (cycles per second).

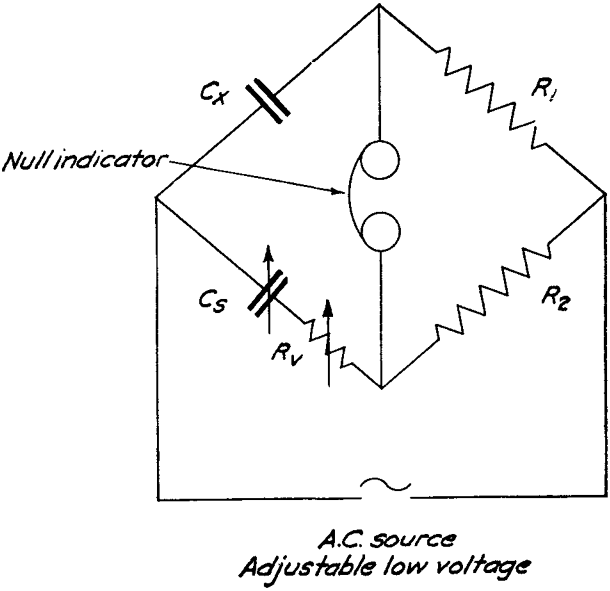


FIG. 54–A.—Bridge circuit for measuring the capacitance and equivalent series resistance of condensers.

For more precise measurements of the capacitance and the determination of the power factor of the condenser, a bridge circuit, similar to the one shown in Fig. 54–A is commonly used. The component parts of the bridge must be selected with regard to the range of the capacities to be measured. The standard capacitor included in this setup does not have to be very costly or of the highest precision for reasons mentioned at the beginning of this chapter. The null indicator may be a pair of head-phones, a suitable galvanometer or the "magic eye." The formulae stated below permit computations (sufficiently accurate for most practical purposes) of the capacitance, equivalent series resistance and power factor.

$$Cx = \frac{R_2}{R_1} \times Cs \tag{11}$$

$$Rx = \frac{R_1}{R_2} \times Rv \tag{12}$$

$$PF\% = \frac{2\pi f \times Cs \times Rv}{10^4} \tag{13}$$

Where Cx = capacitance of the condenser under test in MF's,
Rx = equivalent series resistance of the condenser in ohms,
Cs = capacitance of the variable standard condenser in MF's at the time the bridge is balanced,
$\left.\begin{matrix} R_1 \\ R_2 \end{matrix}\right\}$ = resistances of the respective arms of the bridge (ohms),
Rv = the value of the variable resistor in ohms at the time the bridge is balanced,
$PF\%$ = power factor in per cent,
f = frequency of the test current.

In testing polarized capacitors a still greater accuracy can be obtained if a polarizing voltage—a constant d.c. voltage of the proper polarity and magnitude—is applied across the unit to insure that its anode remains at all times at a positive potential as shown in Fig. 54–B. The a.c. used in the bridge circuit is then superimposed upon the d.c. This circuit can be easily modified, by adding a few switches and meters, to serve also for the leakage test of the capacitor; while the leakage reading is taken, the a.c. remains off. A polarizing voltage can be used also in connection with the above-described impedance method of testing as in Fig. 53. Whenever polarizing voltages are provided in test circuits, *precautions must be taken* to limit the flow of d.c. and a.c. to those respective branches only where they are required, lest they cause disturbances in the various component parts of the circuit and inaccuracy in the readings. This requisite involves complications, for with the addition of a battery (or other suitable source of d.c. supply), a choke coil and a blocking condenser of the proper value, as indicated in Fig. 54–B, must be used. The presence of the blocking condenser, connected in series with the unit under test, must also be taken into consideration when computing the capacitance of the latter. It should also be noted that the application of a polarizing voltage may affect the capacitance and power factor of the condenser under test.

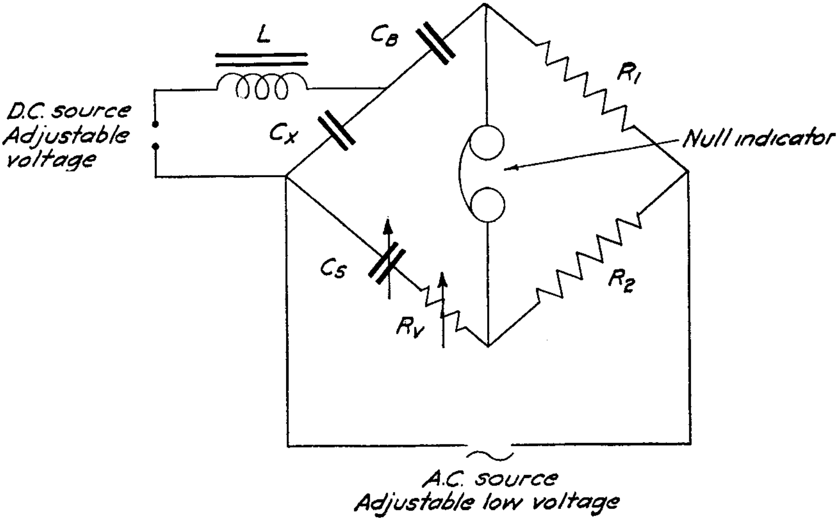


FIG. 54–B.—Bridge circuit with polarizing voltage applied across the capacitors under test.

C_X—capacitor under test.
C_S—standard capacitor (variable).
C_B—blocking capacitor (nonelectrolytic); its capacity must be of the order of the capacitance measured.
L —choke coil.

In the above tests the a.c. voltage is usually kept very low to reduce the heating caused by the test current and (when no polarizing voltage is used) to minimize the deforming action of the a.c. on the anode and also the tendency of film to form on the aluminum cathode. In fact, when asymmetric capacitors are checked without the application of a polarizing potential, the a.c. should not exceed a few volts as the unfilmed electrode may otherwise tend to cause a breakdown of the unit during the half cycles when it is subjected to a positive potential; the indications of the meters under these circumstances would be also very unsteady and unreliable.

When nonpolarized capacitors are tested, the use of the circuit shown in Fig. 55 offers several advantages. This test is simple and sufficiently accurate, makes the determination of both effective capacitance and power factor convenient and in addition permits testing at or near the operating voltage of the condenser. The last point is of special value when units are checked which will be normally operated on straight a.c. (without any polarizing d.c.), like the motor-starting capacitor. In such cases it is very desirable to get a general idea during the test as to how the capacitor will behave under actual operating conditions. For example, certain condensers show on this test substantial steadiness in capacitance and power factor during the several seconds of alternating voltage application, while others may indicate violent changes, particularly in power factor, revealing excessive deforming during the period of idleness prior to the test. Incidentally, very weak capacitors may exhibit momentary breakdowns, followed by self-healing; some of them may be shorted permanently. Thus, along with the check on capacitance and power factor, valuable information may be obtained on the general condition of the a.c. condenser. It should be noted, however, that to derive most dependable information from this test, the applied a.c. should be of the same frequency as that for which the capacitor is rated. The higher the frequency, the more severe the test.

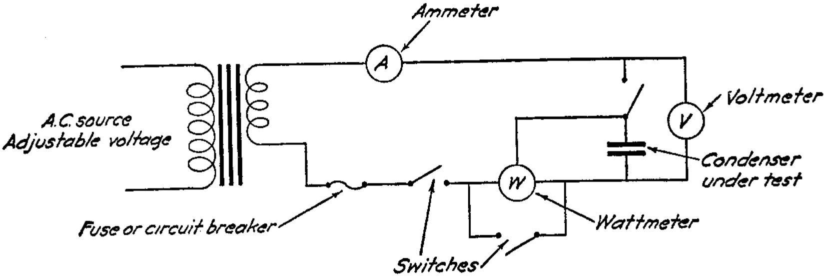


FIG. 55.—Voltmeter-ammeter-wattmeter test-circuit for the determination of the capacitance and power factor of a.c. capacitors.

Depending on the type and rating of the capacitors under test, the test voltage and the meters used, the voltage coil of the wattmeter (and the voltmeter) may be connected across the capacitor only (as shown in the above figure), or across both the capacitor and the current coil of the wattmeter (and the ammeter).

The formula for the computation of the capacitance is the same

(10) as stated in connection with the previously described impedance test; the power factor is calculated from the equation

$$PF\% = \frac{W \times 100}{I \times E} \qquad (14)$$

where $PF\%$ = power factor in %,
I = current in amps.,
E = voltage impressed across the capacitor,
W = watts.

In selecting and using the wattmeter, care must be taken to avoid the excessive overloading of its current coil. Such overloads can easily occur even if the readings on the wattmeter are low, because of the high wattless current (out-of-phase current) in the test circuit. Both the ammeter and wattmeter must be protected by sufficiently responsive circuit breakers or fuses as a capacitor may be short-circuited while under test.

It must also be realized that, depending on the voltage and frequency used in the last test described, the capacitors will more or less warm up and their films may be temporarily weakened to different degrees while the test is going on. For this reason, tests which are otherwise identical and performed on the same capacitor but at different voltages and frequencies may give markedly different results. The use of a higher voltage and frequency will cause more heating and deforming, will increase the leakage current and will be responsible for higher capacitance and also usually for higher power factor readings.

Whenever electrolytic capacitors are tested on a comparatively high alternating voltage, as is the case with some of the nonpolarized capacitors, the duration of the test period must be as short as practicable to avoid overheating and possible damage to the unit.

Users of electrolytic capacitors must be *cautioned against the application of the so-called flash test.* The latter is widely used in the checking of wax- or oil-paper capacitors and consists of impressing across the unit, for a very short period of time, voltages which are often two or three times greater than its rated value. Such tests are entirely incompatible with the peculiar dielectric properties of electrolytic capacitors and will result in the damage and possible blow up of the unit. As previously pointed out, the film is formed at a voltage only moderately greater than the rated voltage (the difference is frequently of the order of 10%). Consequently, the dielectric film will invariably break down *immediately* upon the application of much higher potentials, like those used in the flash test, as can be readily concluded from the examination of the leakage-voltage curve in Fig. 3.

XVI

Special Tests for Electrolytic Capacitors

The leakage and power factor determinations give information on the dielectric properties of the film and on the electrical losses and the efficiency of the capacitor itself. While on general grounds the losses, as reflected in the power factor, should be kept as low as possible, it would be futile to attempt a prediction as to the life of the electrolytic capacitor in the field on the basis of this factor alone. In fact, there have been many cases when, under the same operating conditions, electrolytic capacitors of high power factor outlived those of low power factor. The point is that in this class of capacitors a high power factor may be due to a number of causes of an entirely different nature, such as the following:

Weakness of the dielectric film,
Excessive resistance at the film boundaries (gas bubbles, greasy substances on the electrode, and so on),
Great resistivity of the electrolyte itself,
High density of the paper spacer or imperfect impregnation,
Great distance between the electrodes, and the like.

Depending on the particular cause, a moderately high power factor may or may not indicate faulty design, inferiority of material or poor processing in the manufacture of the capacitor.

Again, the importance of the power factor depends to a large extent on the expected use of the device; in continuous duty operation on straight a.c. (electrolytic capacitors have been rarely used, so far, in this application) a low power factor is strongly reflected in the reduced energy dissipation and low operating temperature and is therefore of paramount importance. For intermittent service in a.c. circuits, as in the starting of single-phase induction motors, the power factor is of appreciable though not of major importance, for the effect of a rather high PF on the starting torque of the motor can be substantially offset by a correspondingly greater capacitance. In filter and similar circuits, where a comparatively small a.c. voltage is usually superimposed on a rather high d.c. voltage, the power factor of the capacitor becomes of real consequence for the performance of the associated apparatus only when it exceeds, say, 20%. It may be said in conclusion that, while the PF is a definite indication as to the quality and merits of a non-electrolytic capacitor, its significance in the case of an electrolytic capacitor is rather limited.

To gain more information as to the over-all quality of a given electrolytic capacitor and its ability to withstand temporary overloads (because of excessive voltages or other factors), and also to form an idea of its probable life under normal service conditions, a variety of tests have been devised by manufacturers and users of such capacitors. These special tests are frequently carried out in addition to the routine tests described in the preceding chapter. When all the data derived from such investigations are examined, a fair idea of the quality of the capacitor can be formed, though even then the forecast as to its life is not too sure. Reports from the field on the actual performance of the devices (provided the operating conditions are normal) are very helpful in establishing some guidance on their life expectancy.

The most dependable information on the performance of capacitors, outside of field data, is obtained from life tests carried out over long periods of time, under carefully controlled conditions, simulating the service in the field. Frequent checks are made on the leakage current, capacitance and power factor to detect the gradual or sudden deterioration of the unit. These checks are supplemented by visual inspection and general observations to establish whether the capacitor tends to overheat, leaks electrolyte, vents, and so on. At the end of the test the unit is torn up and the component parts are examined for corrosion, pitting, drying out, carbonized areas on the spacer, dents on the foil, punctured spots, and similar defects. Such tests involve a considerable amount of equipment, require much work and usually take months to complete.

To accelerate the life tests, certain modifications of the setup are made. For instance, the intermissions or rest periods for the capacitor under test are cut short or eliminated. This, however, means a deviation from the operating conditions in the field and often introduces factors which are seldom, if at all, encountered in the ordinary use of the device and which may drastically affect its characteristics and life. For example, motor-starting capacitors installed in refrigerators may be operated about one hundred times a day and energized during each start for one second or so. To obtain quick information on their expected life they are often tested at 3,000 starts a day; in some cases as many as 30,000 starts were performed in one day, which corresponds to about one year of normal operation in the field. Such accelerations result in the heating of the unit to a temperature not normally experienced in the field. The excessive temperature in turn tends to dry out the capacitor, weakens the film, enhances pitting and corrosion of the electrodes and causes an abnormally great internal gas and vapor pressure. These effects may contribute to the increase in power factor and the drop in capacitance; they are also apt to cause venting of the condenser and to shorten its life (as evaluated from the total number of starts).

Other test modifications may comprise prolonged voltage applications (several seconds) during each start on an a.c. capacitor; higher than normal voltages impressed on the unit; inverted, inclined or some other position of the capacitor; its operation in an atmosphere of excessive humidity, sometimes combined with the presence of corrosive vapors, fumes, salt spray, and so on; its operation at a very low or at an elevated temperature—the latter may be combined with a very dry atmosphere to determine the tendency of the capacitor to dry out; and variation of the magnitudes of the a.c. and d.c. components as applied to polarized capacitors.

The effect of the temperature on the capacitance, power factor and leakage current may be of considerable importance in some applications of electrolytic condensers. While curves indicating these correlations are plotted special care must be taken to insure a uniform temperature throughout the mass of the unit before readings on the meters are taken, as in Figs. 20–24.

Breakdown tests are carried out by gradually increasing the impressed voltage (d.c. or a.c., depending on the type of capacitor) to determine the maximum potential a unit can withstand and also (in the case of d.c.) to find the critical voltage, i.e., the voltage at which the leakage current suddenly and greatly increases as shown in Fig. 3. The latter test reveals, incidentally, the approximate forming voltage of the film. Relative to a.c. motor-starting capacitors, breakdown tests at the rated or some other voltage and frequency are of considerable interest; the capacitor is left in the a.c. circuit continuously until it fails; curves are plotted indicating the changes during that time in capacitance, power factor and eventually temperature, Figs. 56–57. Observations are also made during this test on the response of the vent and the effect from its opening on the capacitance and power factor. The latter information may give an idea as to whether the condenser will lose capacitance and efficiency at elevated temperatures in case its seal or enclosure is imperfect. The ability of a motor-starting capacitor to withstand prolonged voltage applications is of practical

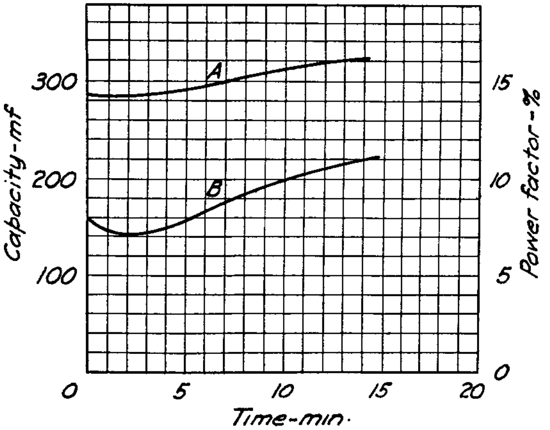


FIG. 56.—Breakdown test on a standard dry motor-starting (nonpolarized) electrolytic capacitor subjected to 110 V 60~ continuously. The capacitor failed in fifteen minutes.

A—capacitance vs. time.
B—power factor vs. time.

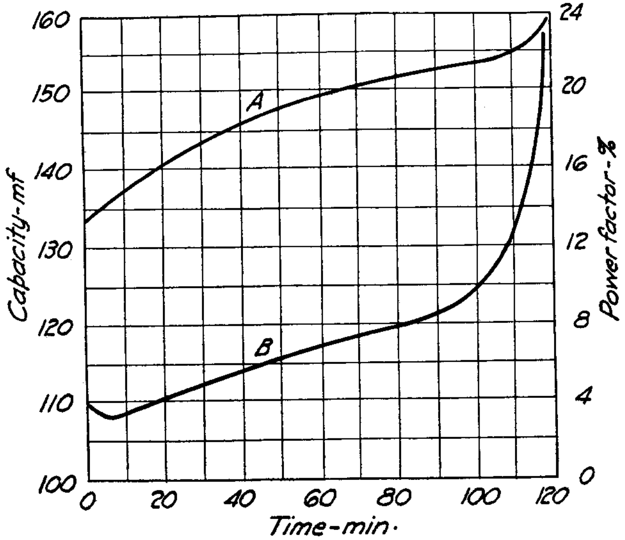


FIG. 57.—Breakdown test on a reinforced dry (nonpolarized) electrolytic capacitor subjected to 110 V 60~ continuously. The capacitor failed after two hours.

A—capacitance vs. time.
B—power factor vs. time.

value when, for instance, the coming up to speed of the motor is frequently retarded because the latter is overloaded or the line voltage is low; in either case the capacitor will be energized for abnormally long periods of time.

A heat test without energizing the capacitor at all may be illuminating as to the leakproof seal, durability and, in general, suitability of the container at some particular temperatures. Checking the leakage current, capacitance and power factor prior to the heating, and again after the condenser has cooled to room temperature, reveals the extent to which the unit is affected by prolonged heating. For instance, the leakage current may be and usually is substantially higher after this treatment, but drops to its normal value after re-forming. Such heat treatment is sometimes used to effect a permanent improvement in the power factor of the capacitor, as it tends to establish a more intimate contact between the electrolyte and the film.

Shelf tests over short and long periods of time are informative, particularly relative to the deforming tendency of the film, the spontaneous changes in the electrolyte and the attack by the latter (if any) on the electrodes, container and other component parts of the device.

In concluding this chapter it will be emphasized again that each of the tests named may indicate only the comparative merits of the various capacitors under test in some particular respect. Although the information obtained from these tests is interesting and valuable, no single test is sufficient to permit a broad evaluation of the quality of a unit. As to the longevity of electrolytic capacitors, it may be stated in a general way that it is entirely satisfactory in their usual applications. However, in order to perform well in every respect and during the entire period of its useful life, the capacitor not only must be properly designed and manufactured but should also be selected (as to its rating) to meet the prevailing service conditions. The latter comprise the line voltage, its fluctuations and surges in the circuit; the frequency of the current; the required capacitance; intermissions and rest periods; humidity and ambient temperature. Under the proper operating conditions the useful life of the capacitor may compare favorably with the life of the apparatus or machine in conjunction with which it is used.

XVII

Troubles in Electrolytic Capacitors, Their Causes and Detection. Emergency Repairs. Replacements

We will consider now the various troubles which may occur in electrolytic capacitors for one or another reason.

Short circuits.
Open circuits.
Loss of capacitance, frequently accompanied by an increase of the power factor.
High leakage current.
Corrosion; pitting.
Stray currents from the capacitor to the chassis or frame.
Leaking electrolyte.
Blowing up of the container.

Short circuits, as previously mentioned, seldom happen in wet capacitors, because of the comparatively great distance between the metallic electrodes of opposite polarity. In dry capacitors "shorts" may occur either because of abnormally severe operating conditions, or because of weaknesses and defects in the unit itself, or because of a combination of both factors. High ambient temperature is one of the adverse conditions likely to induce deterioration in the device and favor its breakdown. When a unit is operating under overload, usually resulting from an excessive voltage (or because of prolonged and frequent voltage applications to an a.c. capacitor), it may warm up considerably. Because of the combined effect from the heat and the high potential, the dielectric film may weaken to the point where an internal discharge of the stored electricity takes place at some particularly vulnerable spot of the electrode film. Such discharge may take the form of an intense spark between the foils and is accompanied by the release of heat. As the discharge is instantaneous and localized at a small spot, the action is eventually so violent that it may cause not only the puncture and burning up (in that area) of the spacer but the melting of the metal in the region of the breakdown. A healing effect is not unusual if the metal is simply removed from the affected zone by the action of the spark; the carbonization of a small area of the spacer by the spark will not interfere very markedly with the performance of an electrolytic capacitor. If the discharge is substantially attenuated by the resistance of the path between the electrodes, the melting of the aluminum and carbonization of the paper spacer may not occur. In this case the only visible effects may be dents on the foils at the point of discharge; the spacer may or may not be punctured. If the dents on the opposed foils are not in contact, the unit may continue to operate indefinitely. When momentary voltage surges of a moderate magnitude occur in the circuit, the electrolytic capacitor will usually act as a lightning arrester, permitting a more or less restricted discharge at one or several weak spots of its film, thus providing a by-pass for the surges and protecting the various associated apparatus from damage. It is typical of electrolytic capacitors that up to a certain point the intensified leakage current, resulting from an overload or an internal discharge, tends to re-form and strengthen rapidly the film within the weak region and exerts therefore a beneficial effect. If the re-forming action of this current is more effective than the damaging influence from the heat generated by the *same current*, automatic healing takes place and, as the surge is over, the device is eventually completely restored to its original condition. The self-healing or re-forming action of the restricted current may be so rapid and thorough that no visible sign, not even a dent on the foils, is detectable. On the other hand, if the discharge is so violent that the destructive effect of the localized heat outweighs the re-forming action of the discharge current, a breakdown will result. If the latter causes a permanent contact between the two foils, the unit is short-circuited and hence rendered inoperative.

There have been explanations advanced as to the formation of the above-mentioned dents, based on the assumption that the spark from the discharge ignites and causes a minute explosion of the mixture of hydrogen and oxygen (produced by electrolysis of the operating electrolyte) accumulated in pockets between the foils. However, there appears to be no evidence as to the occurrence of such explosions. Measurements and observations have shown that in the course of normal operation of dry electrolytic capacitors, particularly those of the a.c. type, electrolysis is hardly detectable. Many dry units have been opened and carefully examined after the completion of their life tests; some of them were tightly wound with thin, dense paper, affording no opportunity to speak of for the formation of gas pockets. In a number of cases dents were present which established contact between the foils and effected a short; in other sections the dents remained spaced; however, in both groups a considerable number of units showed no evidence of burning or explosion and in no case was there a visible indication as to the formation of a gas pocket.

The appearance of the dents could be explained by the fact that during the instantaneous discharge of a relatively large quantity of electricity at a single point the current flowing through it is of a large magnitude. Though lasting for only a small fraction of a second it raises the temperature at this spot so much that intensive evaporation of the electrolyte takes place. The localized vapor pressure may be eventually great enough to produce an indentation in the foil (the attraction between the electrodes of opposite polarity may contribute to this effect). The denting may or may not be accompanied by a violent spark; if it is, the impact of the spark may accentuate the deformation of the foil and eventually cause charring of the spacer.

Under normal operating conditions, with no overload or voltage surges, breakdowns may occur either because the wrong type of capacitor was chosen for the given application or because of faulty design, inferior materials used in the construction, poor processing or improper assembling.

Some of the specific weaknesses and faults causing *short circuits* in dry electrolytic capacitors include the following:

Inferior grade of aluminum electrodes, as, for instance, characterized by the presence of specks of impurities in the metal.

Impurities on the electrode surface—oil, grease, dirt, and so on.

The filming process itself may be at fault, in particular the formation of the film at a voltage below the required minimum.

Improper compounding and preparation of the operating electrolyte, in particular its contamination with chlorides or an excessive water content.

Contaminated paper separators. Open spaces in the paper; extremely close spacing of the foils by thin paper. It should be noted that the type and thickness of the spacer affect to a considerable measure the breakdown characteristics of the capacitor.

Open circuits, drop in capacitance, increase of power factor.—An open circuit in the condenser is indicated by its apparent complete loss of capacitance; it may occur in both wet and dry electrolytic condensers and is usually due to a severe attack upon one of the electrodes (usually the anode in the polarized type) or its terminal connector. On visual inspection the region where the "open" took place looks as if it were corroded, but it may be and usually is pitted by minute sparks jumping between the metal and the electrolyte. Over a more or less long period of time, depending on the intensity of the sparking, the small perforations may sever the electrode or its connector and the capacitor then becomes inoperative. As in the case of "shorts," open circuits are often induced by a high ambient temperature, excessive voltages, unsatisfactory filming, low-grade aluminum, contamination, in particular with chlorides (in the case of dry capacitors, also with moisture)—factors that weaken the dielectric film and thus permit the sparking and pitting just mentioned. On the other hand, a voltage surge or severe but temporary overload of a dry unit is more likely to result in a "short," while prolonged though not very severe overloads will more frequently lead to an open circuit.

Poor spacer impregnation may cause a similar trouble, as the dielectric cannot be maintained satisfactorily around the dry spots for lack of film-forming electrolyte. As a result, minute sparks may make their appearance and perforate the electrode. With prewound sections impregnated by immersion but without vacuum application the electrolyte penetrates to the center line of the roll with considerable difficulty, and it is along this line that pitting may often be observed, though in this case it may not impair the efficiency of the capacitor noticeably.

If a wet capacitor is so constructed that the anode stud is emerging from the electrolyte, the vulnerability of the anode is thereby aggravated (see Chapter IV). A severe attack on the stud at the surface of the solution may eventually cause an open circuit. In dry capacitors, the connecting tabs and that portion of the foil from which they are extending or to which they are affixed are most frequently attacked, probably because the current density is there greatest, the potential highest and the film adversely affected by cutting, perforation, riveting and similar operations and eventually by contamination in the course of handling and assembling the section.

Properly constructed electrolytic capacitors seldom show signs of typical corrosion or other deterioration while in storage; as already mentioned, what is ordinarily described as corrosion of the filmed electrode is actually a form of pitting which may take place only when a sufficiently high voltage is impressed across the capacitor. The capacitance and power factor of electrolytic condensers left in storage for years exhibited no perceptible changes.

Although it is usually not possible to predict, merely on the strength of test data, whether a capacitor will fail prematurely under normal operating conditions, its tendency to develop pitting is sometimes indicated by a rather high leakage current. Nevertheless, as long as the electrode or its connector is not *completely* severed, the unit may operate entirely satisfactorily over long periods of time, and tests for capacitance and power factor will not necessarily reveal the approach of its failure.

A complete loss of capacitance may occur in a wet condenser if its solution is electrolyzed or has evaporated or leaked out. A similar condition may be observed in a dry unit if its electrolyte has lost its conductivity because of the evaporation of water, ammonia and other constituents upon the presence of which the ionization of the impregnant depends. When the conductivity of the electrolyte is substantially lost, the effective capacitance of the condenser approaches zero. This trouble, which may be designated as drying out of the spacer-impregnated type of capacitor, is usually due to excessively high ambient temperatures or to abnormal internal heating resulting from prolonged or severe overloads. Certain types of capacitors, particularly those using rather solid electrolytes, are apt to dry out even under normal operating conditions, if their vents open. A partial drying out is reflected in a drop of capacitance corresponding to the degree of the loss of conductivity of the electrolyte. Usually, the reduction in effective capacitance is accompanied by an increase in power factor, as both are influenced by the conductivity of the medium between the electrodes. It should be noted, however, that similar deficiencies may be caused in a capacitor, though less frequently, by certain changes in the dielectric film. Low ambient temperatures also cause drop in capacitance and increase of power factor (but the condensers recuperate after warming up) as the conductivity of the electrolyte is reduced and the properties of the film are probably affected by the fall of temperature.

Attempts have been made to protect electrolytic capacitors to a certain extent from pitting, short and open circuits (caused by surges, or internal discharges) by shunting them with resistors of a suitable value. No conclusive results have been obtained so far in this respect.

There are cases, though comparatively infrequent, when a considerable rise in power factor may be observed without any drop in capacitance of the condenser or a drop in capacitance without a change in power factor. Such changes are usually connected with certain deteriorations of the film, as for instance in the case of an aftereffect due to traces of corrosive agents trapped on the surface of the anode in the course of its pretreating or etching. Gases produced by the electrolysis of the impregnant and accumulating on the electrodes also tend to increase the interface resistance and raise the power factor.

A high leakage current indicates excessive electrical losses in the capacitor and these are reflected in its high power factor. As stated before, if the high leakage is only an effect of deforming and rapidly tapers off to a negligible value in a minute or so, after the voltage is impressed, it may be of little consequence in many applications. In certain cases a considerable initial leakage may even be beneficial as has been already pointed out. But in general, low leakage—both initial and in the course of operation—is considered to be a very desirable feature for electrolytic capacitors and in some cases it is quite essential.

If an electrolytic capacitor remains abnormally leaky at its rated working voltage after a reasonably long re-forming period (10–15 minutes), it may be assumed that this is due to one of the following causes:

Impurities in the electrode (low-grade aluminum) or on its surface.

Inadequate filming, in particular low filming voltage.

Inferior or contaminated filming bath.

Improper etching: imperfect removal of the corrosive etching agents, in particular chlorides; excessive etching, resulting in too great a gain of capacitance per unit area, which may interfere with the subsequent formation of a good dielectric film.

Inadequate operating electrolyte: the ingredients used in its compounding (or their proportions) are not suitable for the voltage rating of the capacitor; in dry units, the water content of the electrolyte may have a particularly potent effect on the leakage characteristics; contamination of the electrolyte with chlorides and other substances which impair the dielectric properties of the film.

In some cases poor impregnation of the spacer is conducive to the increase of the leakage current because of the lack of film-sustaining substances in certain areas of the foils.

Stray currents are usually the result of inadequate insulation of the capacitor can from the chassis or frame of the apparatus or motor on which it is installed (provided that an insulation is required at all). When the can is insulated from the clamping device or protective housing by a layer of paper, humidity and especially some electrolyte leaking out of the capacitor and soaking the paper may lower its insulating properties so much that appreciable and often disturbing stray currents may flow through the can. This is particularly likely to happen if the can serves as one terminal of the capacitor. But even if that is not the case, stray currents may flow through the can if the latter is not thoroughly insulated internally from the electrolyte and if the outer insulator happens to be impaired. These problems have been discussed at greater length in Chapter XIV.

Electrolyte creeping out of the container, particularly in wet capacitors, may build up a high-resistance leakage path between the two terminals or between one of them and the grounded members. Such leakage paths are sometimes responsible for disturbing effects in radio receiver circuits and the like.

Electrolyte leaks from the capacitor are usually detectable on visual inspection. Their effects upon the operation of dry and wet capacitors have been already discussed. It should be noted, however, that even in those cases when the characteristics of the unit are not appreciably affected by the loss of electrolyte, the leakage may still be objectionable. In addition to setting up paths for stray currents, the leaking solution may corrode metal parts, soak the insulation of wires or of apparatus and equipment in the vicinity of the capacitor and eventually cause their deterioration or impair their function. In this respect it is desirable to choose such locations for the installation of capacitors where an eventual leak of electrolyte will cause little or no trouble.

The leaks are ordinarily due to imperfections in the seal of the capacitor, to the opening of the vent or to defects in the container itself. An excessive internal gas and vapor pressure brought about by an electrical overload is often responsible for starting the leak. High ambient temperatures may also contribute to the leaking, especially when the seal and impermeability of the container depend on the application of pitchlike compounds or on the impregnation with wax. Heating of the unit, moreover, increases the fluidity of the electrolyte and thus facilitates its seeping through the imperfections of the seal, vent, and the like.

Blowouts, or bursting of electrolytic capacitors, are due to excessive gas and vapor pressure built up within the container and failure of the vent to operate in time. Blowouts seldom occur in actual service in the field, though they are not uncommon on accelerated life tests and are even more frequent on breakdown tests. The original cause of the blowout is usually an overload (see Chapter XIV) in the form of an abnormally high voltage impressed across the capacitor, reversing the polarity in connecting a polarized unit; the cause may also be, in the case of a.c. capacitors for intermittent service, prolonged and too frequent voltage applications.

Because of the overloading, excessive electrolysis may take place (particularly in wet capacitors) and the voids in the container may be filled with an explosive gas mixture. It may happen, though very rarely, that under these circumstances a spark flashes between the electrodes; if ignited, the gas may cause the bursting of the capacitor.

Emergency Repairs

It is the usual practice to discard an inoperative electrolytic capacitor and replace it with a new unit of a suitable rating. This procedure is justified since the cost of the unit is relatively low, while the repairs *inside* the capacitor are difficult and call for special precautions (troubles on the outside of the capacitor, such as broken or loose terminal lugs and joints, or severed wire leads, can be, of course, readily taken care of).

There are cases of emergency, however, when the reconditioning of a damaged capacitor is essential, as when replacements are unobtainable while it is necessary to resume promptly the operation of the equipment of which the capacitor is a component. The several suggestions listed in the following may, on many occasions, enable the serviceman to repair the defective unit. It is recommended, however, that a new capacitor of the proper type be installed as soon as possible in place of the reconditioned one.

1. *Short-circuited dry capacitors.*—After it has been determined that the trouble is not on the outside of the device, the lid is carefully disengaged from the container; it happens sometimes that the tabs are dislocated and touch each other or that both tabs are in contact with the can. The tabs should be correctly positioned and protected from improper contacts by the insertion of pieces of varnished paper.

If the short circuit took place inside the section, the latter should be unwound until the defective zone is reached. In case the breakdown was severe and several layers of the spacer were badly burnt, the repair of the unit is inadvisable. Frequently, however, the damage is localized around the puncture of one or two layers, and the section can then be fixed by placing strips of impregnated spacer over the punctured spots; such strips are conveniently cut off from the outer turn of the winding. The section is then carefully rewound; if a tab was broken while the section was unrolled a new tab can be made by slitting the outer end of the respective foil, or the severed tab pieces can be joined by means of an aluminum rivet. After the section is replaced in the container, the open end of the latter is sealed with a wax of high melting point or with pitch, to prevent the ingress of moisture and impurities. In case the container was damaged while the capacitor was disassembled a clean tin can may be used as a substitute.

2. *Open-circuited dry capacitors.*—The trouble may be due to loose or corroded tab joints which can be readily fixed. A tab may be severed by corrosion or by other causes; a new tab can be formed or the severed pieces united as described in the preceding paragraph. If

the outer turn of the foil is corroded, the affected strip is cut off, a new tab is made and the foils are carefully separated from each other with the spacers. The section is then replaced in the container and sealed.

3. *Loss of capacitance due to drying-out of the section.*—Reconditioning should not be attempted unless the unit is very urgently needed and irreplaceable. An impregnating electrolyte solution is prepared in a clean vessel, preferably one of aluminum or heat-resisting glass.[1] Glycerin and boric acid in substantially equal quantities (by weight) are put in the vessel and about 20% (of the weight of this mixture) of strong ammonia water is added. The whole mass is mixed, then placed on a hot plate and stirred continuously. A thermometer is inserted in the mixture to indicate the gradually rising temperature. When the thermometer reads 250°F, the capacitor section (disconnected from the lid and freed from the wrapper, and so on) is immersed in the solution. The section is thus subjected to impregnation at a continuously rising temperature; when the latter reaches 280°F the vessel is removed from the hot plate and the section left in the solution until the temperature has dropped to 180°F. Then it is taken out of the impregnating bath and allowed to cool in a clean, closed vessel. As soon as the section has reached room temperature, it should be reassembled and re-formed on d.c., as described in Chapter VIII.

4. *Wet capacitors.*—Troubles of a mechanical character (dislodged or loose lugs, joints, severed wire leads, and so on) are taken care of as in the case of dry capacitors. If the unit has lost its capacitance because the electrolyte had leaked out or evaporated, an attempt may be made to replace the solution (after the container has been fixed). Usually, it will be necessary to remove the lid in order to refill the unit. An electrolyte which will often serve the purpose may be prepared as follows: Enough boric acid is dissolved in hot distilled water to obtain a precipitate on cooling; the saturated solution thus obtained is decanted into a clean vessel and about 1% (of the weight of the solution) of borax is added to the same and allowed to dissolve. The capacitor is reassembled and enough of the solution poured in to cover the entire anode. Before the unit is sealed, it is re-formed as described in the foregoing. If sparking or sizzling persists during the re-forming, the solution is poured out, diluted with distilled water and after the capacitor has been refilled is checked again. When the re-forming is completed, the unit is carefully sealed and tried out in its operating circuit.

Whenever a capacitor is opened for repair, elaborate precautions

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[1] Fair results are obtainable in many cases if the dried out section is soaked for a couple of hours in pure glycerin or ethylene glycol, at about 250°F.

must be taken to preclude its contamination with impurities (in particular chlorides) and moisture. In the preparation of the electrolyte, only distilled water and C.P. (chemically pure) ingredients should be used.

Replacements

Replacement units should be of the same capacitance, voltage and frequency rating as that of the original condenser (unless the manufacturer advises otherwise). Furthermore, the container, insulating box or sleeve (if any) and mounting accessories must fit the installation.

If a replacement unit of exactly the same description is not available, a condenser of a higher voltage or frequency rating but of the same or somewhat greater capacitance is usable.

When circumstances are pressing, certain improvisations, with the proper care, may be attempted. For instance, two condensers of the same voltage and frequency rating, but of a smaller capacitance than the original one, can be connected in parallel to obtain the required capacitance. Likewise, two similar units of sufficiently large capacitance but of a lower voltage or frequency rating within the proper limits may be placed in series to meet safely the circuit requirements. (Formulae 6 and 8 are to be taken into consideration.)

XVIII

The Design of Electrolytic Capacitors

The choice of the type of electrolytic capacitor and its design are governed by the expected operating conditions, the available space for its mounting, the permissible weight, cost, and similar factors. Outstanding in importance among the operating conditions are the following:

The normal and expected maximum and minimum voltages applied to the capacitor. When a.c. is superimposed on d.c., which is usually the case with polarized units, it is not sufficient to know the total peak voltage, but information must be supplied also as to the magnitude of each of the components.

Possible voltage surges and temporary overloads. In the case of a.c. capacitors for intermittent service, the maximum duration of the voltage applications and their number per hour.

The frequency of the a.c. flowing in the capacitor circuit.

The normal, minimum and maximum ambient temperatures.

Unusual humidity and the presence of corrosive vapors, sprays, fumes, and so on.

The required capacitance, the acceptable tolerances and the permissible changes of the capacitance in the course of the use of the condenser.

The acceptable power factor and its permissible increase during the operation of the capacitor.

The mounting position of the device.

Safety factor requirements.

Special functions to be performed by the condenser besides providing capacitance (voltage regulation, and so on).

When all these items are taken into consideration, certain types of capacitors will be automatically ruled out in a number of applications. In many cases a compromise will have to be reached to reconcile the efficiency of the capacitor with the available space. Frequently, the price may not permit the use of the most suitable winding or container, for example.

In choosing between the wet and dry electrolytic capacitor, due consideration must be given to the features discussed in Chapter III. Dry capacitors are often classified according to the physical state of their electrolytes, which may at room temperature be fluid, viscous or substantially solid. Nevertheless, if properly constructed and housed, all three classes can compete with each other practically in every application. There are differences among them but these are mostly of secondary importance as brought out in Chapter III.

Between the etched and plain foil[1] *polarized* capacitors the former offers advantages as to compactness and lower cost and is generally preferred, provided the etching is faultless. In a.c. condensers the extremely thin (0.0005″) plain foil electrode competes in price with the much heavier (0.003″–0.005″) etched electrode of the same capacitance and voltage rating though of smaller area. While the etched a.c. capacitor is usually moderately smaller in bulk, the difference can be reduced, if desired, practically to nothing by employing a thinner spacer in conjunction with the 0.0005″ plain foil. Etched foils make the adoption of heavier spacers necessary because of the increased current density resulting from the greater capacitance per square inch of electrode foil. Most important is the consideration that the reduction of the bulk of an a.c. capacitor, if carried to the extreme, is of questionable advantage and not infrequently decidedly a disadvantage. This follows from the fact that the heat dissipation in an a.c. condenser is appreciable and its rate governed by the capacitance, the applied voltage, frequency and the power factor, irrespective of the bulk. If, therefore, the physical dimensions (and consequently the cooling surface and heat absorption capacity of the unit) are drastically reduced, the condenser will be apt to overheat, its operating characteristics may be impaired and its life may be shortened.

Although the aluminum-sprayed electrodes have not found any extensive application in a.c. capacitors, they compete with the etched electrodes in the polarized type, especially where extreme compactness is of major importance.[2] The great capacitance of the sprayed elec-

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[1] It may be stated in a general way that when plain foil is used it is easier to make capacitors of somewhat lower power factor and to maintain the capacitance within narrow tolerance limits. The plain foil capacitor appears also to be less affected by strong variations in the ambient temperature.

[2] An important advantage of the sprayed electrode is its freedom from eventual contamination with corrosive substances (in particular chlorides) which are apt to attack the film or the underlying aluminum. Such corrosive substances do not have to be used in the fabrication of the sprayed electrode (contrasting

trode is brought about by depositing on gauze or some other suitable material a multitude of minute molten aluminum particles according to the Schoop process, U.S. patent 1,128,059. As these particles solidify and interlock they produce a large, rough and rather porous conducting surface. When this is exposed to the electrolyte a correspondingly large capacitance per square inch of electrode sheet becomes available. The cleansing and filming of this electrode surface may be effected in a manner similar to that described for the conventional aluminum electrodes. As the deposited aluminum coating is quite brittle and the continuity of the circuit may suffer because of cracks sustained in winding the electrode, a modified construction, as described below, is sometimes used. Two strips of metallized or aluminum-coated cloth are put together and bonded to a narrow strip of rather heavy aluminum foil. The latter thus insures the continuity of the circuit all along the electrode and brings about the full utilization of the entire exposed aluminum surface for producing a capacitance effect, regardless of the presence of cracks across the electrode strips.

After the particular type of electrolytic condenser is chosen, a determination must be made of the required (projected) electrode area per unit of capacitance (MF). This determination is the starting point in the design and as upon it depend to a high degree the reliability, efficiency and, in general, the performance of the capacitor, it must be done very carefully and judiciously. If plain aluminum electrodes are to be used, two strips of the metal of a definite area are cut and prepared for the subsequent building of an experimental unit. One or both (for a.c.) strips are filmed in the regular forming electrolyte to be used in production, to a voltage in excess of the maximum total peak voltage expected in operation. This peak is the sum of the d.c. component and the peak of the a.c. In a straight a.c. capacitor the peak is the effective or RMS voltage times 1.414 (assuming a sine wave). The excess over the computed peak voltage constitutes a safety factor and its magnitude must be very carefully chosen with regard to the service conditions listed above, including the voltage fluctuations on the line. This excess is often around 10%, but may be much greater.

In the manufacture of a.c. capacitors the filming voltage will de-

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the treatment of the etched electrode). At the same time, by the use of spraying, the active surface per unit of projected electrode area may be made very great, as in the case of etching.

One serious problem to be considered in producing sprayed electrodes is the uniformity of metal deposition, as upon it depends the capacitance per unit of projected electrode area.

pend not only on the operating voltage but also on the frequency. Everything else being the same, the alternating current increases in direct proportion to the frequency, in accordance with the formula

$$I = E \times 2\pi fC. \tag{15}$$

The greater current in turn causes more heat dissipation and therefore tends to weaken the dielectric. Consequently, units rated, for example, for 110 V at 60 cycles will require electrodes filmed to a considerably higher voltage than those rated for 110 V at 25 cycles. Similarly, prolonged and more frequent voltage applications call for the reinforcement of the a.c. capacitor, which is accomplished by using a higher filming voltage, by using a heavier spacer and by providing a greater area for heat dissipation (a container of larger dimensions and eventually the use of fins, and so on).

In polarized capacitors the magnitude and frequency of the alternating voltage component must also be given adequate attention, apart from the computation of the total peak resulting from the superimposition of the a.c. upon the d.c. potential. As in a straight a.c. capacitor, the a.c. component (or ripple voltage) in the polarized capacitor will cause heating because of electrical losses. Hence in this case, too, higher voltages and frequencies will require the reinforcement of the capacitor by the above-mentioned expedients.

At this time it should be mentioned that in electrolytic capacitors the effect from the frequency variation may not be entirely limited to the change of the magnitude of the current and the heat dissipation resulting immediately therefrom. The frequency may also have a direct bearing on the properties of the film, the higher frequencies exerting a more potent deforming or weakening action on it (analogous to the reduction of the passivity effect by alternating current). As a result of this eventual weakening of the dielectric, the leakage current and the power factor of the capacitor would be increased, and this in turn would cause greater losses and ultimately additional heating. It is difficult, however, to segregate the various cumulative effects brought about by the change in frequency.

The quality of the electrode, in particular the purity of the aluminum, may also have some influence upon the final determination of the filming voltage. If aluminum of a comparatively low grade is to be used, an increase of the filming voltage will tend to reduce the undesirable effects resulting from the inferiority of the electrode metal. The higher filming voltage ordinarily increases the breakdown voltage of the capacitor; it reduces both the leakage current and the power factor, which in turn lowers the heat dissipation.

Although it is generally conceded that the forming of the film at a higher potential improves the over-all quality of the electrolytic capacitor, it is worth mentioning that under certain operating conditions electrodes filmed at a lower voltage have given excellent results in withstanding surges. It appears plausible that the weaker film will exhibit lightning-arrester properties to a higher degree, as it is yielding more readily to transients (but is still re-forming instantaneously after they are over). In some cases of intermittent service the charges remaining in the capacitor may tend to produce deteriorating effects (pitting and the like) upon the electrodes and a weaker film will be conducive to a rapid internal leakage, thus eliminating or minimizing the charge and its undesirable effects. However, these cases should be viewed rather as exceptions; normally, the higher filming voltage is preferred whenever compatible with the other requirements and it is considered that in general it tends to increase the safety factor of the capacitor. As the electrode area required for a given capacitance increases quite consistently in direct proportion with the filming voltage, the upper limit for the latter is ordinarily set by considerations of bulk, weight and cost of the unit, all these items being correlated with the electrode area.

When with the aid of a series of preliminary tests (leakage, capacitance, power factor and breakdown) and with regard to the above-mentioned items, the required electrode area per MF has been determined, the total active electrode area necessary for the desired capacitance can be computed in a simple manner. Table III gives some information as to the electrode areas actually used in several types of commercial plain and etched dry capacitors.

If the determination of the capacitance per square inch of foil is to be made for a dry unit of the conventional wound type, the experimental electrode samples used for this purpose should be preferably also wound into a roll to duplicate the actual position of the foils. This is important for several reasons, one of them being that in a wound section both sides of the electrodes are active. To the computed area of the electrodes of the dry capacitor sufficient foil should be added to compensate for the folding of the tabs and for that portion of the outside foil in the last turn of the roll which is not fully utilized for supplying capacitance. Similar minor corrections are sometimes made to take care of a little waste of electrode surface at the start of the winding and on account of a possible misalignment of the two foils.

When the electrodes are etched, the determination of the required area is carried out as above described, except that prior to the filming

TABLE III

Electrode Area in Dry Electrolytic Capacitors

ETCHED FOIL

Polarized Condensers	*Rated Capacitance MF's*	*Rated Voltage*	*Square Inches of Foil for the Anode*
	8. MF	450 working d.c.	25

PLAIN FOIL

Non-Polarized Condensers	*Rated Capacitance MF's*	*Rated Voltage RMS*	*Rated Frequency*	*Square Inches in One Foil*
Single Section	70–85	125	60	360
Two Sections in Series	40–50	220	60	400 (in one foil of one section)

ETCHED FOIL

Nonpolarized Condensers: About 25 or 30% of the foil area as used in the plain-foil condensers of the same rating, but the thickness of the foil is 6 to 10 times greater.

the experimental strips or plates are etched chemically or electrochemically. By controlling the etching process as stated in Chapter IX, the desired gain in total surface area in contact with the electrolyte (as contrasted with the projected area or measured square inches of plate or foil) is obtained and consequently the capacitance correspondingly increased. In this case, the actual capacitance per square inch of plate will be determined by a combination of two factors—the effectiveness of the etch and the magnitude of the filming voltage. In other words, the same capacitance per unit plate area can be obtained by using a deep etch, followed by the formation at a high voltage, or by employing a mild etch and filming at a correspondingly lower voltage. Which of the two alternatives is to be preferred depends primarily on the comparative operating advantages of the two types of electrodes for the given application of the capacitor; the decision will be usually based on experimental determinations. The practical considerations as to the depth of the etch have been discussed in Chapter IX.

Regardless of the type of electrodes selected, once the basic constants relative to the capacitance per square inch of electrode plate are established and checked experimentally for a given voltage and set of operating conditions, the computation of the electrode dimensions for the same type of capacitor and for the same operating conditions but for different voltage ratings is comparatively simple. This is due to the fact that the inverse proportionality of the capacitance per square inch vs. filming voltage holds quite well throughout the range of voltages ordinarily considered for the use of electrolytic condensers.

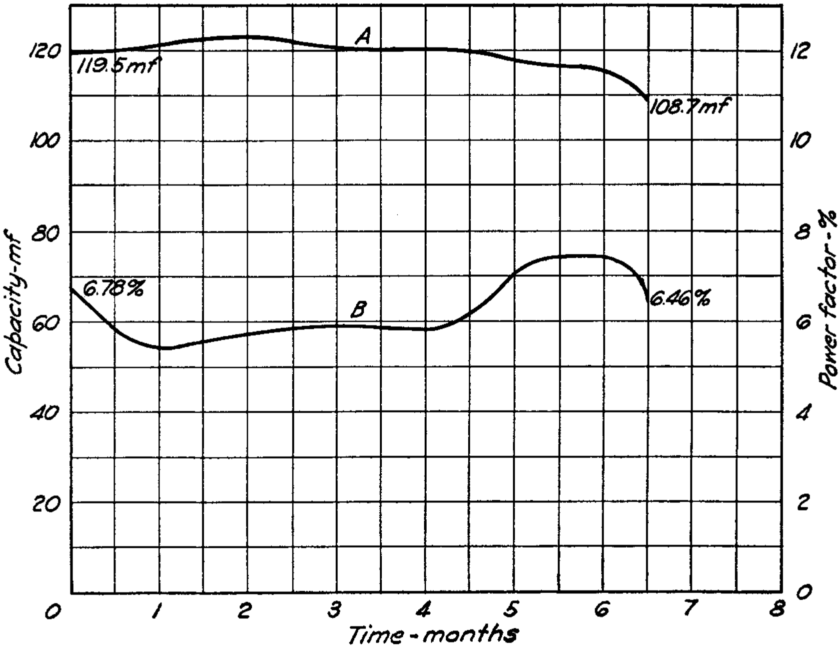

FIG. 58.—Life test of a dry, nonpolarized electrolytic capacitor used for the starting of a fractional HP single-phase induction motor. Three starts per minute, 300 watt load. Total starts with load, 330,000; additional 450,000 starts without load.

A—capacitance vs. time.
B—power factor vs. time.

There are circuits in which it is essential to maintain the capacitance of the condenser strictly above a certain minimum. In such cases it is advisable to allow for some capacitance drop, say 10% or so, which is not unusual with electrolytic condensers over long periods of time, especially under adverse operating conditions (temperature, load, and so on), as shown in Fig. 58. If the ambient temperature is apt to fall very low at times, the temperature characteristics of the particular type of condenser must be taken into consideration and eventually an adequate excess of capacitance provided to take care of the drop.[3] Should the circuit be rather critical as to capacitance changes in either direction, it will be found that the increase in filming voltage will tend to stabilize the capacitance; at the same time the higher filming voltage will minimize the chances for overloading the condenser. Changes in capacitance, usually its decline over long periods of operation, are often due to the deterioration of the electrolyte or of the film, both of which may result from overheating caused by *overloading*. Operating peak voltages, in excess of the original forming voltage, may also tend to effect a drop in capacitance because they are conducive to the continuation of the film formation to a higher level.[4] Still greater stability in capacitance may be obtained, but with a considerable increase in bulk and cost of the unit, if a series combination of two and sometimes three condenser sections is used. Both higher filming voltage and the series arrangement tend also to lower and stabilize the power factor of the electrolytic capacitor.

Contrary to the case with nonelectrolytic condensers, where the total thickness of the paper spacer is one of the factors governing the capacitance, in the electrolytic condenser this item has a rather negligible effect upon the capacitance. The explanation is that in the latter type, the film and not the paper constitutes the dielectric. A thick paper spacer may only slightly increase the equivalent series resistance and the power factor of the electrolytic capacitor. However, the thickness and type of the paper spacer (and the resistance of the impregnant) strongly affect the safety factor of the unit as explained in the foregoing. The thickness and absorbency of the spacer determine also the quantity of electrolyte maintained between the electrodes; this in turn determines the heat-absorbing capacity of the condenser and may have some bearing on its longevity, particularly under adverse service conditions. In general, the higher the operating voltage and frequency and the greater the probability of overloading and excessive heating, the heavier the spacer must be.

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[3] With dry electrolytic motor-starting capacitors the effect from a low ambient temperature is usually slight. As soon as the switch is turned on, current starts flowing in the unit, rapidly warms it up and consequently raises its capacitance to its normal value. The motor therefore starts promptly, in spite of a low ambient temperature.

[4] On the other hand, when an electrolytic capacitor is operated at a considerably lower peak voltage than the voltage of its film formation, there is a tendency toward a *very slow* adjustment of the film to the prevailing operating voltage. As a result of this adjustment the capacitance of the condenser will tend to increase. The change is pronounced with wet polarized capacitors, less noticeable with dry polarized units and very slight with nonpolarized capacitors for intermittent service.

In the improvement of the operating characteristics of the dry capacitor by providing a thicker spacer, a limit is again set primarily by the bulk, weight and cost of the device. When higher voltages are impressed across the unit, it is advantageous to supplement the increase of the total spacer thickness by the use of at least one dense paper layer in the spacer combination.

Breakdown tests, life tests and results in the field will ultimately indicate whether the various factors, upon which the performance of the capacitor depends, have been properly evaluated and taken into consideration by the designer.

When the space available for the mounting of the capacitor is strictly limited or of some particular shape, the design of the unit may differ considerably from that of conventional types. For instance, the installation of the capacitor in the base of a motor may necessitate the winding of the section on a very large arbor and its subsequent flattening out, Figs. 26 and 47. As stated in Chapter XII, the choice of the arbor may be also influenced by the length of the winding. Capacitors mounted in the end plate of a fractional HP motor must usually be made much smaller than the average capacitors of the same rating to fit into the available cavity, as in Fig. 46. In addition to these limitations, such undersized units are operating under adverse conditions because of the higher ambient temperature. To compensate for this, the very best materials (foil, paper, electrolyte) are selected for their construction and the processing (etching, filming, winding, impregnation, and so on) is carried out with the utmost care. When excessive humidity or corrosive fumes prevail in the place the capacitor is to be installed, modifications in its construction, as indicated in Chapter XIV, may become necessary.

If it is desired to house two or more wet capacitors in one can, the latter serving as the common cathode, precautions must be taken to minimize stray currents and other disturbances arising from potential differences between the anodes. The anodes are usually shielded from each other by properly shaped metallic members, which are grounded to the can as indicated in Fig. 59. Series combinations of wet capacitors immersed in the same electrolyte bath are avoided, because of the high leakage current caused by the considerable interelectrode potential difference and the comparatively low resistivity of the aqueous electrolyte.

When the dry type of electrolytic capacitors is used, several sections can be readily assembled in one container, for their insulation from each other is comparatively easy. If one of the foils of each of the polarized sections is at the same potential, this foil (usually the cathode) is ordinarily used to provide a complete outer turn to eliminate electrostatic coupling between the sections and to minimize any tendency toward leakage current between the sections. The subdivision of one large capacitor into two or more sections connected in parallel and the winding of several capacitors into one roll with a common cathode have been discussed in Chapter XII. In the same chapter were also outlined various series combinations of dry electrolytic capacitors, their advantages and limitations. Dry electrolytic sections are sometimes connected in series to increase the safety factor and improve the operating characteristics of the capacitor as indicated in the foregoing. The series combination, however, becomes a necessity when the operating voltage is so great that a single film cannot withstand it. Depending on the quality of the aluminum electrode, the electrolyte used in filming, the forming process, the type of operating electrolyte, spacer, and the like, and also on the operating conditions, the maximum voltage withstood by the film will vary considerably. Nevertheless, the single film on aluminum electrodes could hardly be considered safe at peak voltages in excess of 600 V even if the alternating component of the potential is a small proportion (less than 10%) of the total. If this component is increased, the operating potential across the single film must be correspondingly reduced.

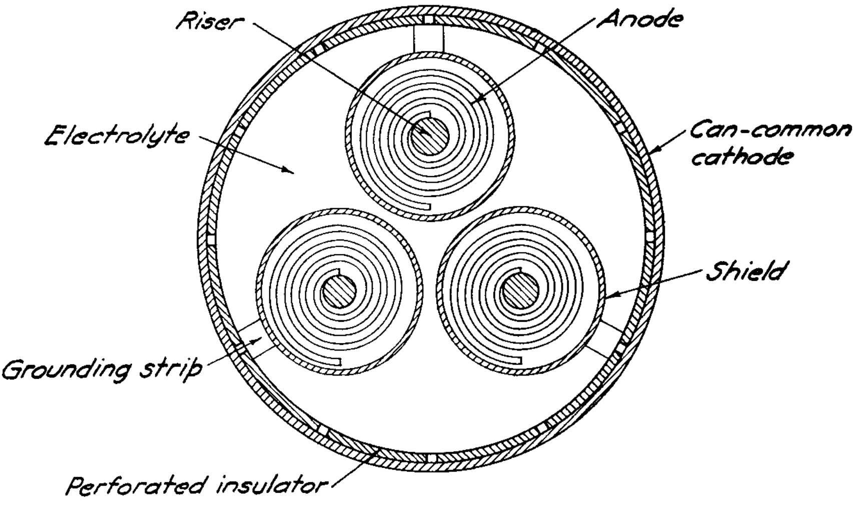

Fig. 59.—Schematic drawing of a wet electrolytic capacitor with three anodes; the can serves as a common cathode.

As a rule, polarized capacitors (even of very low voltage ratings) should not be operated with an a.c. component of a magnitude sufficient to cause the impression of a negative potential on the anode during the negative half cycles. In actual practice only much smaller a.c. components are permissible. An exception to this rule may be the intermittent use of polarized capacitors for the starting of single-phase induction motors, as discussed in Chapter XXI.

In the conventional a.c. electrolytic capacitor, operated intermittently, without the superimposition of any polarizing (d.c.) voltage, the application of a potential in excess of 220 V RMS across a single film is rarely practicable, although the limit depends also on the frequency of the current, the duration of the voltage applications and their number per hour, the ambient temperature, the spacing of the electrodes, the cooling surface of the unit, and so on. It should be noted in this connection that a nonpolarized a.c. capacitor, though having films on both foils, is ordinarily viewed as having only one active dielectric at any instant, namely the film on the foil which happens to be at this moment the anode. The dielectric on the foil which is at that time the cathode is considered substantially ineffective. A.c. capacitors used in circuits of odd frequencies—100 cycles or so—may call for the combination of two sections in series even at 110 V, or of three sections at higher voltages.

When two polarized sections are put in series, the arrangement may be according to Fig. 60–A, i.e., in opposition, which is essentially equivalent to a single nonpolarized section (Fig. 60–B). They may be also connected as in Fig. 61, i.e., additive, where both films are fully effective with one polarity and none is substantially active with the opposite polarity. In either case the capacitance of the combination is computed according to formula (8). The latter combination must be used when unidirectional potentials of a magnitude greater than permissible for a single film are impressed across the capacitor assembly. The voltage distribution of the d.c. component between the sections will be in direct proportion to their insulation resistances. Consequently, there will be a tendency to subject to a greater strain the section which has a better dielectric film. To insure the best performance for the series-connected couple, it is desirable to have films of about the same forming voltage and quality on both anodes and to select sections of substantially equal capacitance.

There are cases where the danger exists of connecting polarized capacitors in the circuit with reversed polarity, because of possible errors. To obviate damage to the capacitor and associated apparatus which could result from the excessive leakage current (Fig. 3) in case

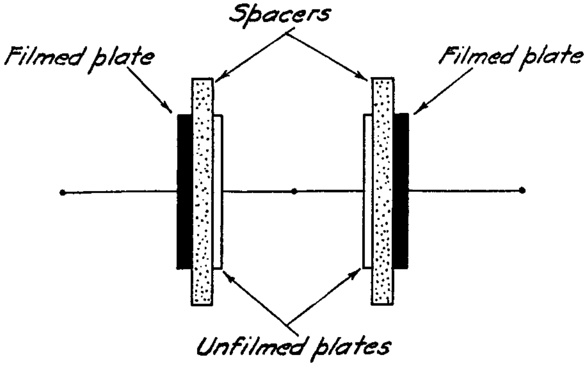

FIG. 60–A.—Two polarized capacitors connected in series-opposition.

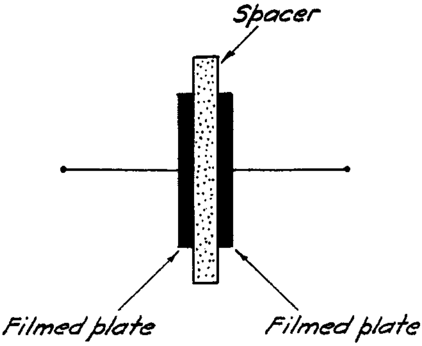

FIG. 60–B.—Nonpolarized capacitor.

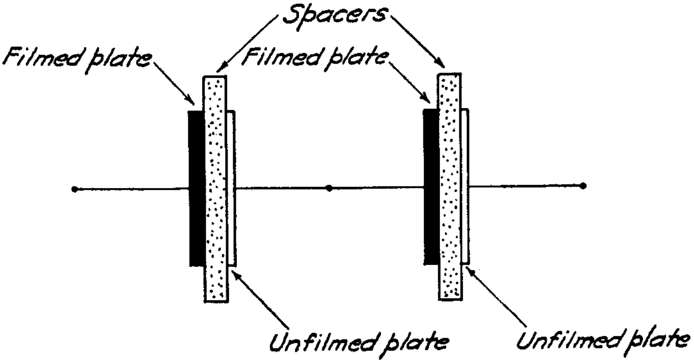

FIG. 61.—Two polarized capacitors connected in series, additive.

of such errors, the cathode may be filmed (or made particularly susceptible to filming by special pretreatment), though to a voltage much lower than that of the anode; this will usually limit the current to a safe value in case of an inadvertent polarity reversal. Other things being equal, a conventional polarized condenser has substantially twice the capacitance of a nonpolarized condenser (of the same foil area and filming voltage). If, however, the cathode is filmed but to a lower voltage than the anode, the capacitance of this *semipolarized* condenser will be between that of the polarized and the nonpolarized unit, the exact value depending on the film-forming potentials for the two foils. Semipolarized units could be eventually also used for experimental and special purposes when a controllable distortion of the current wave form is desired.

Within a wide range of commercial frequencies the capacitance of electrolytic condensers is only slightly affected by the frequency. Even an increase as great as from 60 to 1,000 cycles per second is reflected in only a moderate drop of capacitance for dry condensers, usually around 10%; for wet condensers, however, the capacitance reduction is much greater.

In certain radio-receiver circuits an electrolytic capacitor may perform the function of passing currents of high audio- and even of radiofrequencies. It will be found that on very high frequencies the effective capacitance of an electrolytic condenser is only a small fraction of its value at commercial frequencies. This sharp drop in effective capacitance may eventually be interpreted as an indication that at very high frequencies the device ceases to operate as a typical electrolytic capacitor, i.e., the film is possibly no longer the only dielectric and the electrolyte does not act as an efficient condenser electrode. Other factors,[5] however, may also interfere with the effectiveness of the electrolytic capacitor at such high frequencies, as, for instance, changes in the dielectric constant of the film, increased losses (dielectric absorption, skin effect, and other losses), and so on.

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[5] If it is assumed that the polar nature of the solvent is a factor determining the capacitance of the condenser, the drop in capacitance with lower temperatures and higher frequencies could be expected, since the dielectric constants of polar solvents are strongly affected by variations in temperature and frequency

XIX

Trends in the Development of Electrolytic Capacitors

During the last two decades much progress has been made in the development of electrolytic capacitors in general and of the dry type in particular. In line with this, the applications for these capacitors have become more diversified and the number of units put in use has greatly increased.

Primarily because of the improvements in filming and in general processing of the electrodes and because of the perfection of the operating electrolyte, it has become possible to reduce drastically the bulk, weight and cost of the condenser as referred to a unit of capacitance at a given rated voltage and frequency. In many instances the bulk of dry capacitors has been cut to one fourth and even a smaller fraction of the dimensions as known only ten years ago. Much has also been contributed in this respect by the replacement of the heavy gauze with comparatively thin paper separators and by the introduction of etching, which increased several fold the capacitance per unit area of the electrode plates. A similar effect has been brought about by the use of "aluminum-sprayed" electrodes in polarized capacitors. The gradual reduction of the gauge of aluminum foil from 0.006″, as often used some fifteen years ago in dry capacitors, to 0.002″, 0.001″ and even 0.0005″ in plain (nonetched) capacitors, has also helped to make the device much smaller and less expensive.

The reduced physical dimensions of the capacitor would have made it more difficult to prevent its overheating were it not for the simultaneous lowering of the leakage current and the power factor (and the resulting decrease in power dissipation) which was due to the improved dielectric film, better operating electrolyte, superior quality of the spacer and the more thorough impregnation of the section. Although power factors of 20 and even 30% were quite common with the early electrolytic capacitors, they are nowadays of the order of 5 to 10%; in some cases the power factor is as low as 2 to 3%.

The maximum operating voltages per single section of electrolytic capacitors have been raised and the breakdown characteristics in general improved, which, coupled with the lower power factor, made their intermittent use in a.c. circuits more practicable; thus, the field for their application was substantially expanded. Continuous-duty a.c. electrolytic capacitors have not been used extensively and successfully, except perhaps at very low voltages. The ordinary single-section nonpolarized or a.c. electrolytic capacitor deteriorates quite rapidly when subjected (without intermission) even to moderate potentials like 110 V at 60 cycles, at room temperature, in spite of the fact that the films may have been formed at a much higher voltage. Under such operating conditions the unit gradually heats up and fails usually within one hour (certain types of a.c. capacitors, which are otherwise satisfactory for intermittent use, break down in five minutes or so if left continuously in the circuit). If several nonpolarized sections are connected in series, the impressed voltage thus being subdivided among them and the current density at the electrodes greatly reduced, the assembly may last for hundreds and even thousands of hours, but its capacitance for a given bulk and weight is then comparatively small, the cost high and the advantage over an oil-paper condenser of the same rating questionable.

A survey of the many experiments and life tests carried out with continuous-duty a.c. electrolytic capacitors points, however, to some encouraging results. There have been cases when single sections of about 100 MF and of standard construction have withstood 110 V 60∼ for hours. It is possible that an accidental combination of favorable conditions—purity of electrode metal, excellent surface condition of the foil and a high-grade film, superior operating electrolyte, and similar factors—was responsible for such outstanding results. Aluminum of still higher purity and better fabrication than available commercially at present, more knowledge about the true nature of the film and the conditions which govern its formation and preservation, combined with more efficient operating electrolytes will probably pave the way to radical improvements in the operating characteristics of electrolytic capacitors in general and of continuous-duty a.c. units in particular. Of special interest and importance in this respect seem to be a more definite immunity from voltage surges, the reduction of the power factor to less than 1%, better temperature characteristics and the stability of the film when subjected to a pure a.c. (without the superimposition of a polarizing voltage). A more effective removal of the heat generated in the unit is also an essential point in this development.

If and when the electrolytic capacitor is perfected to the point that it can be employed in an economic manner continuously on commercial a.c. lines, the field for its use will be immensely expanded. The many opportunities for power factor correction alone will permit the absorption of millions of such devices; in this application the electrolytic capacitor will serve the additional purpose of by-passing voltage surges, thus protecting the circuit. It may also contribute to the elimination of radio interference.

The improvement of the temperature characteristics of the electrolytic capacitor is of considerable practical importance in many cases. Very low temperatures, of the order of 20° and 30°F below zero, and high temperatures approaching 200°F, at which capacitors are sometimes required to operate, are serious limitations to the use of the electrolytic type. The temperature characteristics of electrolytic capacitors depend particularly on the properties of the film and the type of operating electrolyte.

Another possible development is outlined in the following chapter. It is concerned with capacitors closely related to the conventional dry electrolytic type; they comprise, however, an impregnant of exceptionally high resistivity.

XX

Semi-electrolytic Capacitors

It has been brought out in preceding chapters that the resistivity of the operating electrolyte may vary within very wide limits, depending on the type of electrolytic capacitor in which it is incorporated. Usually, the resistivity of the electrolyte in the dry type is considerably greater than in the wet. It has been also pointed out that the general trend is to increase the resistivity of electrolytes when they are intended for use in capacitors of higher voltage ratings. Experiments carried out by the author with dry electrolytic condensers have shown that their effective capacitance may be only slightly reduced and their power factor will be hardly raised by increasing the resistivity of the electrolyte several times, say from 2,000 to 6,000 ohms per cubic centimeter at room temperature. Only with a much greater increase in resistivity does a radical change in operating characteristics take place. If the resistivity is raised to several hundred thousand ohms per cubic centimeter, for example, the impregnating medium may eventually be considered as a semi-electrolyte, which is the case when glycerin, ordinarily sold as C.P. (chemically pure), is used without the addition of any other substance. A condenser comprising the usual *filmed* aluminum foils and paper spacers and impregnated with C.P. glycerin (or ethylene glycol) alone has all the characteristics of an electrolytic capacitor, namely: exhibits the rectifying effect; high capacitance per unit electrode area (of the same order as obtained with a conventional electrolyte); the capacitance is governed by the filming voltage and substantially independent of the thickness of the spacer; the leakage current is high and drops for quite a long time as the film is being reformed; the leakage-voltage characteristics are similar to those in conventional electrolytic capacitors; the power factor is much greater than in a nonelectrolytic (wax- or oil-paper) capacitor.

Minute quantities of boric acid, sodium borate or other ionizable substances remaining on the foil surface after the filming process (in spite of the usual rinsing with distilled water) may contribute to the electrolyte properties exhibited by the glycerin in these capacitors.

However, even the additional thorough cleansing of the foils with distilled water, alcohol, or the like, does not eliminate the above-listed characteristics typical of electrolytic capacitors. Such elaborate cleansing may perhaps lower somehow the effective capacitance, increase the power factor and reduce the re-forming properties of the film.

Similar results may be eventually obtained if the glycerin is replaced by a number of other substances (usually having a high dielectric constant) such as, for instance, the glycols. The dielectric properties of the film will tend to reduce the leakage current and improve the breakdown characteristics of capacitors comprising such impregnants.

The above experiments bring out the following interesting facts:

1. C.P. glycerin (and some other substances) as obtainable on the market, possibly to some extent because of the little water always present in it, is sufficiently ionizable to serve as an electrolyte in *dry electrolytic capacitors*, though it may not be usable as an electrolyte in most other applications.
2. An extremely slight conductivity of the impregnating medium is sufficient to bring out the typical characteristics of a dry electrolytic capacitor, especially so if a satisfactory dielectric film is formed on the aluminum electrodes.
3. In capacitors impregnated with such semi-electrolytes the power factor may rise to 20–30% and even higher; this is due to the great losses within the impregnating medium caused by its extremely high resistivity; the losses, however, may be enhanced by the poor re-forming of the dielectric resulting from the deficiency of high-grade ionizable film-forming substances.

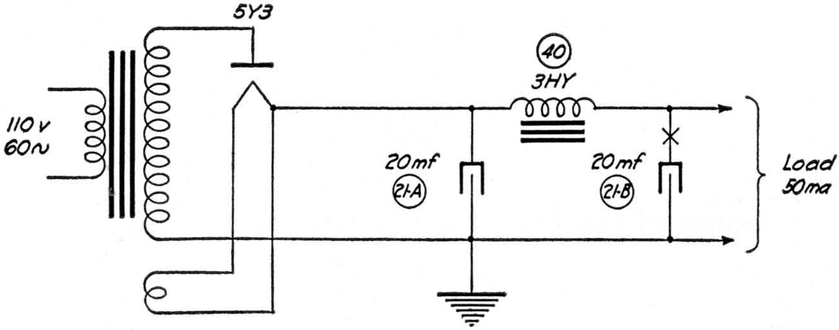
One of the special features (which may be considered as advantages) of this class of capacitors resides in the fact that their impregnating medium (if of the type of glycerin) is not adversely affected by prolonged heating to high temperatures, because it is rather homogeneous, has a high boiling point and is not likely to dry out or decompose at temperatures that occur ordinarily in the operation of capacitors. Another feature is that some of these impregnants are typical antifreeze substances and are therefore usable at low temperatures. Finally, in case some of the impregnating fluid leaks out, it is not likely to cause trouble (by establishing paths for stray currents) because of the great resistivity of the substance.

A spacer-wound capacitor, comprising filmed aluminum foils and impregnated in a very slightly ionizable medium like C.P. glycerin, could be designated as semi-electrolytic, because it has the functional characteristics of an electrolytic capacitor but is impregnated with a substance which may be considered as a semi-electrolyte. If we go now a step farther and use a nonelectrolyte, like castor oil, for impregnation, the capacitor will function as a nonelectrolytic unit, in spite of the fact that filmed aluminum foils are used for its electrodes. The capacitance, power factor and leakage current of such oil-impregnated condensers will be low and, in general, they will exhibit the characteristics of nonelectrolytic condensers. This combination of filmed electrodes with a nonelectrolyte may present, however, possibilities of practical value. One advantage consists in the fact that to the oil-impregnated paper is added a supplementing dielectric—the film. Another advantage, which may be expected of such capacitors, will be outlined here. If, in the course of operation, the insulating properties of the oil show signs of deterioration (because of oxidation, contamination with moisture or otherwise) and there is a perceptible tendency toward its ionization, the leakage current of an ordinary nonelectrolytic capacitor will increase and the breakdown characteristics of the latter are likely to be impaired. However, if filmed aluminum foils were used in the winding of the capacitor, the slightly ionized impregnating medium may tend to co-operate with the film and strengthen its dielectric properties. As a result, there will be a counteraction to the increase in leakage current and to the tendency of the combined dielectric (film and oil-impregnated paper) to break down under the electric stress.

XXI

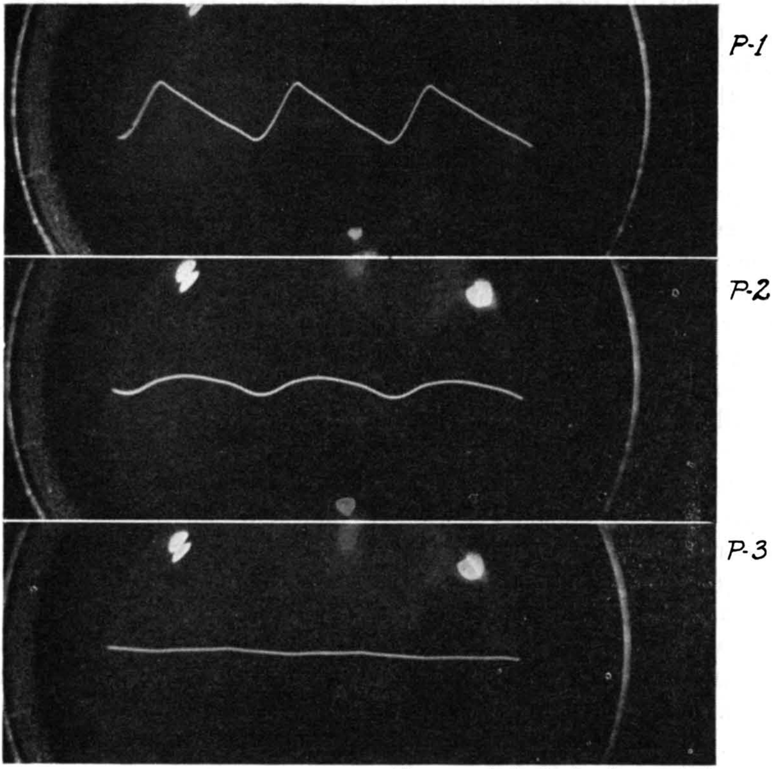
Some of the Uses for Electrolytic Capacitors

The structural features and operating characteristics of electrolytic capacitors suggest the fields in which they may be used most satisfactorily. The application must be so chosen that one or more of the good points of these capacitors prove to be of particular value in it, while their inherent weaknesses are of little consequence. For instance, in filter circuits, where the ripples of the rectified current are to be smoothed out, the great electrostatic capacitance per unit of bulk and weight of the device, the low cost at which the required microfarads at the specified voltage are made available, the ability of the electrolytic condenser to withstand surges and its self-healing properties, the voltage-regulating characteristics, and so on, are all of considerable value. On the other hand, the limitations of the film as to its unidirectional dielectric properties; the rather high power factor of the condenser; the marked instability of the capacitance and particularly its increase with rising temperature; the inability of the film to withstand without intermission alternating potentials of considerable magnitude are all points that must be classified as undesirable for electric condensers in general, but of little importance for a filter condenser. The reason for this is that the latter is operated on a rectified current in which the a.c. component is usually small and that in most filter circuits rather high power factors and considerable capacitance variations (particularly an increase) of the condensers are tolerable. The comparatively high leakage current, especially after periods of idleness, which is so typical of electrolytic capacitors, would be also held against them on general grounds but, if not excessive, is permissible and in some cases even advantageous in filter circuits. Of course, the slight possibility of trouble arising from electrolysis, corrosion or pitting, the presence of the vent and the temperature limitations for the use of electrolytic capacitors are undesirable features. The effects from these shortcomings, however, are minimized or suppressed when well-designed and properly constructed capacitors are employed in radio receivers and similar apparatus.



(*Courtesy of the Crosley Corporation.*)

FIG. 62.—Electrolytic capacitors used for plate supply filter in Crosley receiver chassis 73 and 86.

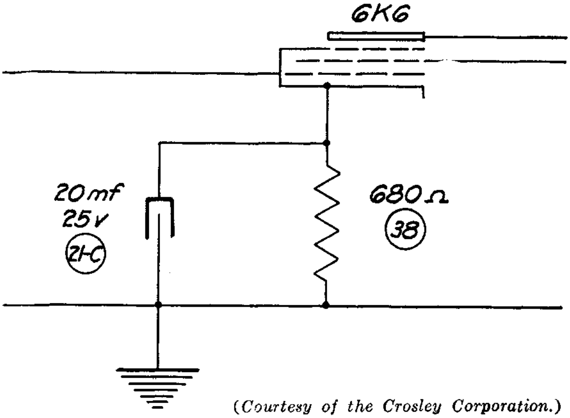


(*Courtesy of the Crosley Corporation.*)

FIG. 63.—Successive stages of filtering. (See also Fig. 62.)

P–1—oscillogram of voltage A to ground.
P–2—oscillogram of voltage B to ground with 21–B disconnected at X.
P–3—oscillogram of voltage B to ground, with 21–B connected.
(Ref: Drawing No. C–132565–5, Crosley "Fiver" Model 52–TK.)

Figs. 62–63 pertain to a filter circuit for radio receivers in which electrolytic capacitors are employed; similar units are also used in low-power transmitters. In these applications the a.c. component or ripple voltage is of a small magnitude as compared with the d.c. or polarizing voltage. Such operating conditions, as already stated, are favorable for the use of electrolytic capacitors.



(*Courtesy of the Crosley Corporation.*)

Fig. 64.—Electrolytic capacitor used for cathode by-pass in Crosley receiver chassis 73 and 86. (Ref: Drawing No. C-132565-5, Crosley "Fiver" Model 52-TK.)

By-pass electrolytic capacitors are widely used in radio circuits; Fig. 64 gives an example of this application. These condensers are ordinarily of a substantial capacitance, frequently around 20–30 MF; but as their voltage rating is low, mostly of the order of 20–25 V, they can be built to very small dimensions and are inexpensive. In this in-

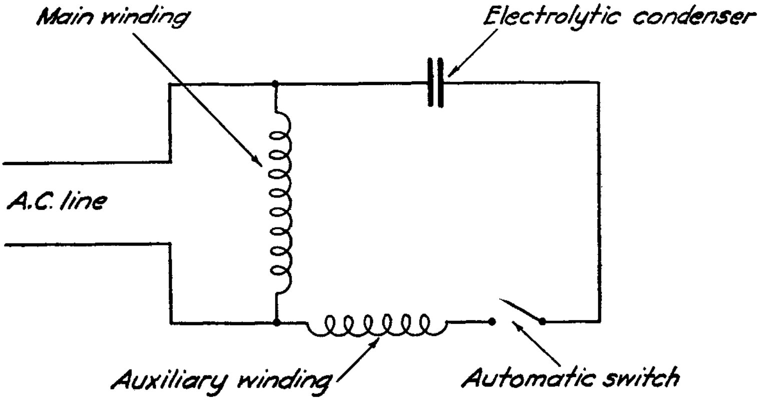
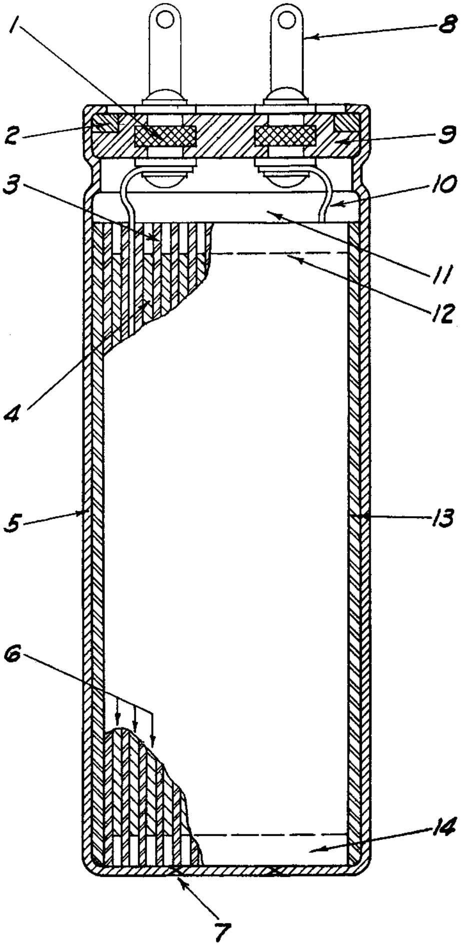


Fig. 65.—Conventional circuit of a capacitor-start induction motor.

stance, full advantage is taken of the ease with which the construction of electrolytic capacitors is adapted to low-voltage operation, as explained in Chapters II and V. Thus, a 25 MF, 20 V by-pass electrolytic capacitor, for instance, may be of smaller dimensions than an 8 MF, 400 V electrolytic filter capacitor (or a 1 MF paper-wax capacitor).

It may be stated at this point that the replacement of paper-wax capacitors with the electrolytic type in filter and by-pass circuits has contributed considerably to the reduction of the size and cost of radio receivers.



1—aluminum terminal.
2—rubber gasket.
3—paper spacers.
4—capacitor section.
5—capacitor can.
6—foil.
7—weak spot vent.
8—soldering lug.
9—Bakelite lid.
10—tab.
11—chamber for gas and vapor.
12—foil edge.
13—varnished paper wrapper.
14—paper spacer.

FIG. 66.—Cutaway view of a dry motor-starting capacitor rated for 150–185 MF, 110 V, 60~, $3\frac{15}{16}$″ long, 1.5″ OD.

In certain telephone circuits (noise filters and so on) and in similar cases where a thorough suppression of disturbing ripple voltages due to commutation (mostly in connection with low-voltage d.c. generators), rectification, and the like is necessary, condensers of great capacities are often used. Ratings of thousands and tens of thousands of MF's at a low voltage are not unusual, and such capacitors are inexpensive and compact. Electrolytic condensers of large capacitance rating have also been used in conjunction with electrical welding equipment.

For about twelve years the dry electrolytic capacitor has been employed very extensively and successfully for the starting of fractional HP single-phase induction motors. More recently these capacitors have also been used for the starting of larger single-phase motors. Fig. 65 shows a conventional circuit of a condenser-starting motor. The capacitor, connected in series with the auxiliary winding, causes a phase displacement of the current flowing in it by somewhat less than 90 electrical degrees with respect to the current in the main winding. Consequently, the starting is effected as in a two-phase motor. When

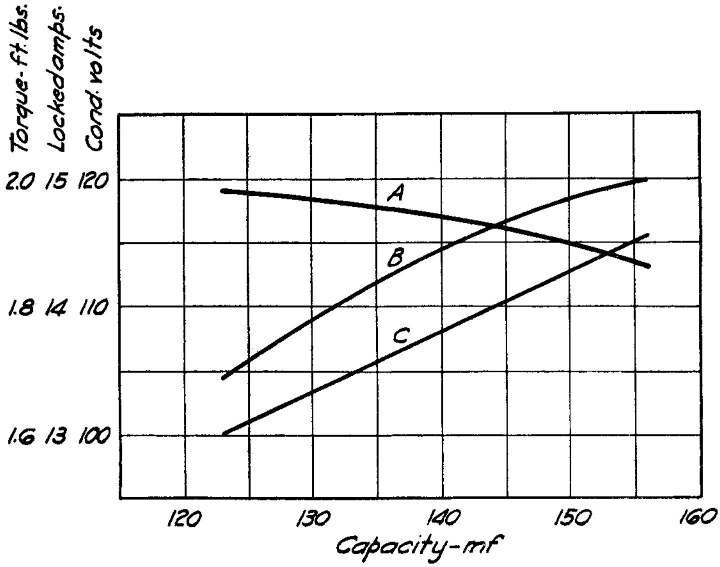


FIG. 67.—Voltage across motor-starting capacitor, starting torque, "locked amperes," vs. capacitance; ⅕ HP, 110 V, 60~, 1750 RPM capacitor-start single-phase motor.

A—voltage across motor-starting capacitor.
B—starting torque.
C—locked amperes.

the rotor comes up to speed, the auxiliary winding is cut off by an automatic switch and the capacitor remains idle until the next start. Usually, such motor-starting capacitors are in actual operation for a total of only several minutes a day, as the starting periods are of the order of one second and often as short as one third of a second. Thus, ample time is available for the cooling and recuperation of the device. For such intermittent service the electrolytic capacitor is eminently suited and can be built very economically in compact units as illustrated in Fig. 66.

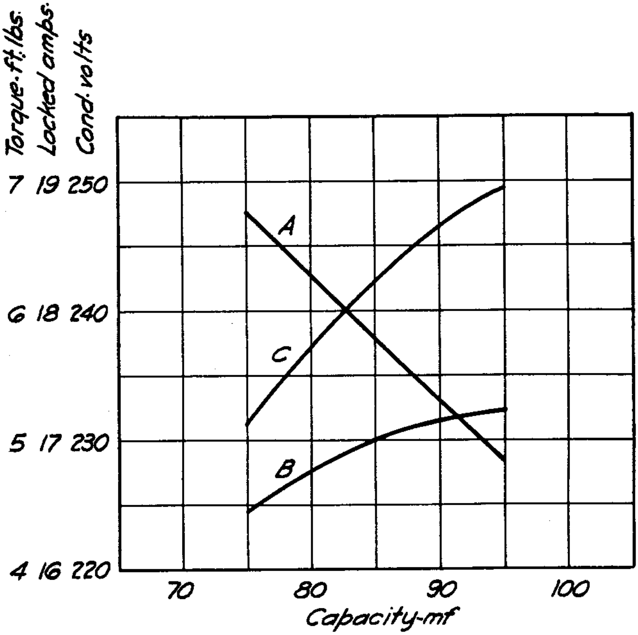


FIG. 68.—Voltage across motor-starting capacitor, starting torque, "locked amperes," vs. capacitance; ½ HP, 220 V, 60~, 1750 RPM capacitor-start single-phase motor.

A—voltage across motor-starting capacitor.
B—starting torque.
C—locked amperes.

The curves in Figs. 67–68 show the relationship between the capacitance of the condenser in MF's on the one hand and the starting torque of the motor in foot-pounds, the "locked amperes" and the voltage across the capacitor on the other. It will be noted that beyond a certain value the increase in capacitance of the starting condenser is useless. In fact, if the capacitance were raised still more, the starting torque would decline. For best results the capacitor must match the motor; either too low or too great a capacitance tends to impair the starting characteristics of the motor. However, a certain excess of capacitance, as compared with the computed optimum value, is usually less objectionable than low capacitance, as far as the starting torque characteristics are concerned. A moderate excess may be even beneficial inasmuch as it results in a lower voltage being impressed across the capacitor and therefore it reduces the danger from a breakdown of the latter. On the other hand, a great increase in the capacitance of the condenser, besides being uneconomical, may be the cause of an abnormally high starting current for the motor.

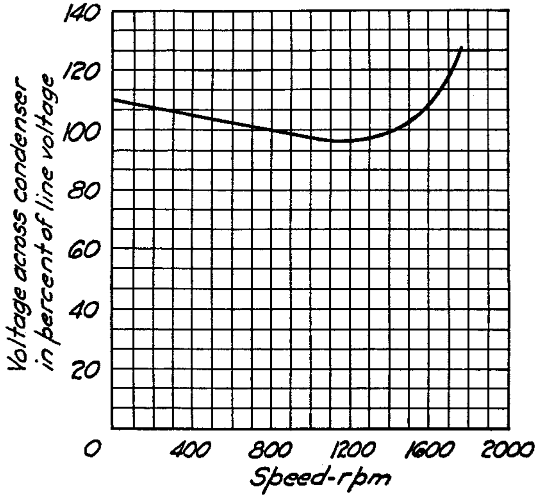


FIG. 69.—Voltage across capacitor vs. motor speed. ⅛ HP, 1750 RPM motor.

The capacitance rating of a motor-starting condenser is usually indicated on its name plate by a minimum and a maximum figure and the actual capacitance of the unit must be within these limits. If the microfarads are indicated by one number only, a tolerance of − 5 and + 20% is often implied. The actual RMS voltage which may be safely impressed across the a.c. capacitor is usually about 20% in excess of the voltage marked on the plate. As previously stated, it is also advisable to mark on the capacitor the maximum frequency for which it was designed. The information given in the last paragraphs on the matching and rating of capacitors should be taken into consideration when ordering replacement units. The starting characteristics of the motor and its reliability may depend to a large measure on the choice of the capacitor.

For the cutting out of the capacitor and the starting winding, centrifugal, thermal and electromagnetic switches are used. The centrifugal switch opens when the rotor exceeds about 75% of the synchronous speed of the motor. Upon the proper response of the switch depends to a considerable degree the protection of the capacitor from overvoltages and overloading in general. If the switch is sluggish and the opening of the starting circuit retarded, the period of the voltage application on the capacitor is prolonged. Moreover, the voltage impressed on it is apt to be excessive, as can be seen from the curve in Fig. 69, indicating the variation of this voltage as a function of the rotor speed. In Fig. 70 is shown an oscillogram taken at the capacitor during the starting period of the motor. Other possible defects or irregularities in the starting switch may influence the performance and shorten the life of the capacitor; a "fluttering" or "chattering" switch, for example, may be the cause of subjecting the capacitor to abnormal voltage surges.

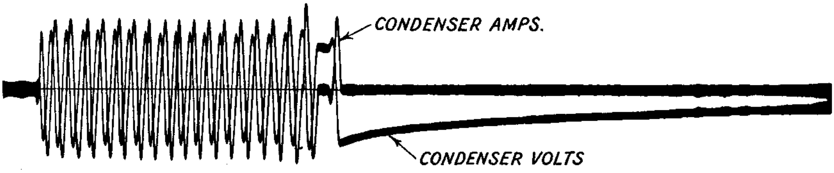


Fig. 70.—Oscillogram taken at electrolytic capacitor used for starting of a fractional HP, 110 V, 60~ induction motor. Capacitor rating 130–165 MF, 110 V, 10~.

It follows from the above that, for the proper design of a motor-starting condenser, in addition to data on the required capacitance, line voltage and frequency, information is needed on the maximum voltage *impressed across the condenser* (which may be very much different from the line voltage), the duration of the voltage applications (and in connection with this the characteristics of the cutout switch) and the number of starts per hour. Information on the ambient temperature, unusual humidity and other operating conditions is also essential. Finally, in determining the capacitance and voltage rating of the required starting condenser due attention must be given to resonance effects in the starting phase, as they may be responsible for an excessive voltage across the condenser and its short life in service.

Apart from providing a great starting torque for single-phase motors (as much as four or five times greater than in corresponding split-phase motors), electrolytic capacitors prove to be useful in reducing the current surge on the line at the time the motor is switched on. In some cases electrolytic condensers of suitable capacities are employed primarily for the latter purpose. The capacitor-starting motor is noted for its high starting efficiency (great torque per ampere) and good power factor at starting.

U. S. patent 2,057,214 indicates a method of using electrolytic capacitors for both starting single-phase motors and improving their running characteristics. Three or more condensers of the proper rating are connected in parallel while the motor is started, and their capacities being thus added are great enough to secure the required torque. After the rotor has reached the predetermined speed, an automatic switch changes the connections of the condensers to a series combination (Fig. 71), which brings about the required reduction of capacitance for the most efficient operation of the motor. With the series connection the voltage across each capacitor is only a fraction of the potential impressed across the entire assembly, and the current density at the electrodes and also the heating of the device are correspondingly reduced. This arrangement makes the continuous operation of electrolytic

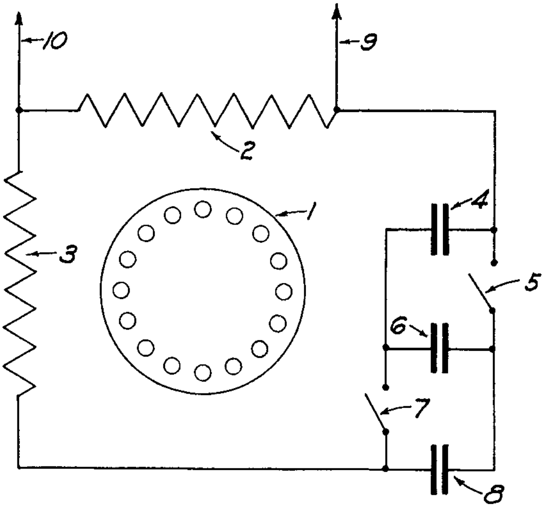


FIG. 71.—Circuit of a special capacitor-start, capacitor-run single-phase induction motor. Only electrolytic capacitors are used. The three capacitors are connected in parallel during the starting and switched over automatically to a series combination for the running position.

capacitors possible, resulting in an improved power factor of the motor and its better running characteristics in general.

Combinations of electrolytic and nonelectrolytic capacitors have also been used whereby the two types are in parallel during the starting period. The electrolytic unit is cut off at the proper time, while the nonelectrolytic (which is rated for a much smaller capacitance) remains in the circuit, after the motor has come up to speed.

It may be of interest to mention that, in the past, thousands of *polarized* capacitors, with the anode formed to a suitable voltage, have performed satisfactorily as motor-starting capacitors. The impedance of the auxiliary circuit and the residual dielectric properties of the film prevent disturbing effects during the half cycles when the unfilmed foil is subjected to a positive potential.

Fig. 72 shows the circuit of a split-voltage, capacitor-starting motor for operation on 220 V 60 in conjunction with a capacitor rated for 110 V 60~. Because of the modified connection of the auxiliary winding, only about one half the voltage (as impressed across the condenser in the conventional circuit) is applied to this condenser. The capacitance of the latter, however, must be correspondingly greater than the capacitance of a 220 V unit required for the conventional circuit, in order to secure the desired starting torque (the starting torque of the motor is proportional to the volt-ampere input to the condenser or to the square of the voltage across the condenser).[1]

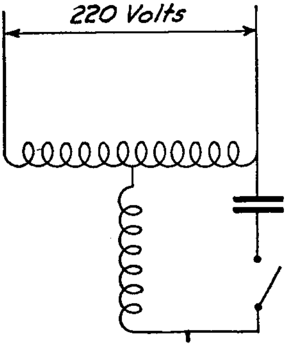


FIG. 72.—Circuit of a 220 V single-phase capacitor-start motor permitting the use of a capacitor rated for 110 V.

The blocking of the current in one direction only (reverse current

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[1] The employment of the lower voltage-high capacitance condenser becomes a necessity when the motor must be made adaptable for use on either 110 or 220 V.

cutout) in d.c. circuits by means of polarized capacitors, the voltage regulation and the lightning arrester effects of special electrolytic capacitors have been discussed in previous chapters. Electrolytic capacitors have been used also to some extent in conjunction with solenoids and for the suppressing of arcing on the opening of inductive circuits.

Glossary

Absorption—taking up of one substance into another substance.

Adsorption—the condensation or taking up of gases, liquids or dissolved substances on the surface of solids (or liquids).

Alternating current (a.c.)—a current which varies periodically in amplitude and direction.

Alternation—one half of one cycle (positive or negative) in an alternating current.

Amperage—electricity flowing in a conductor per second, measured in amps.

Ampere (amp.)—unit of electric current. One ampere of unvarying current flowing for one second through an aqueous solution of silver nitrate will deposit 0.001118 gram of silver (under specified conditions). Another definition is derived from Ohm's law:

$$I = \frac{E}{R}$$

$$\begin{aligned} \text{where } E &= \text{voltage,} \\ R &= \text{resistance,} \\ I &= \text{current.} \end{aligned}$$

A current of one ampere will flow through a resistance of one ohm when the electric pressure measures one volt.

Anode—the positive electrode of a galvanic cell, of an electrolytic capacitor, and so on.

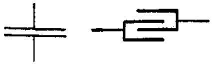
Anodic film—the coating produced on the surface of certain conductors when subjected to anodizing.

Anodizing—treatment of a conductor in an electrolytic cell by connecting it to the anode of the cell.

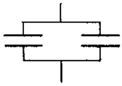
Capacitance—electrostatic capacity—ability of conductors, separated by dielectrics, to store electrostatic charges. Unit of capacitance—farad.

Capacitor—electrostatic condenser—device for storing of electrostatic charges.

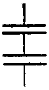
Symbols for a *single fixed capacitor*



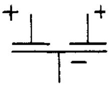
Symbol for two capacitors connected in *parallel*



Symbol for two capacitors connected in *series*



Symbol for polarized sections having one *common cathode* foil and two anodes



Cataphoresis—migration of electrically charged particles (suspended in a liquid) toward the electrodes, under the influence of an electric field.

Cathode—the negative electrode of a galvanic cell, electrolytic capacitor, and so on.

Colloid—(from the Greek word for *glue*)—examples of colloids: gum arabic, starch, aluminum hydroxide. *Colloidal solution*—dispersion of a substance in a liquid medium, the dispersed particles being of ultramicroscopic dimensions, but larger than simple molecules (contrasted with true solution in which molecules or atoms are dispersed). The dispersed particles in a colloidal solution are electrically charged with respect to the dispersion medium.

Coulomb—quantity of electricity transported in one second by a current of one ampere.

Current density—current flowing through unit of cross-sectional area of the conductor (amperes per square foot).

Dielectric—an electrically nonconducting or insulating material.

Dielectric absorption—penetration of the electrical charge into the mass of the dielectric for an appreciable time, following the almost instantaneous charge when a capacitor is connected to a continuous voltage through a very low resistance. The current caused by the absorption is steadily decreasing and when the dielectric is saturated with the charge, only leakage current is flowing in the circuit. The leakage current is steady and ordinarily of an exceedingly small value.

On short-circuiting, the *free charge* is released almost instantaneously, but if the capacitor exhibits absorption and is left open-circuited for a while, it may be again discharged (once or several times) as the *residual charge* is slowly seeping out of the dielectric. The residual charges are of a smaller magnitude than the free charge.

Absorption effects are accompanied by heat dissipation (only a part of the soaked-in charge being recoverable) and constitute the main portion of losses in solid dielectrics observed when these are subjected to alternating (or fluctuating) potentials. Absorption occurs primarily in solid dielectrics—glass, wax, Bakelite, and so on; its magnitude depends on the nature, composition and purity of the material. Moisture present in the dielectric reduces the insulation resistance of the dielectric and thus tends to suppress absorption, but it increases the leakage current. The apparent capacitance of a condenser may be strongly affected by absorption effects; when the unit is measured at low frequencies it may appear to have a much greater capacitance than at high frequencies. (See also *Dielectric losses.*)

Dielectric constant—(K)—specific inductive capacitance—a factor pertaining to that property of the dielectric upon which depends the capacitance of a condenser (incorporating this dielectric) of given physical dimensions. The dielectric constant varies with the frequency and possibly, to some extent, with the magnitude of the applied voltage, and with the temperature; it is strongly influenced by the moisture content of the material.

Dielectric hysteresis—one of the dielectric losses; it is attributed to molecular movements in the insulating material, when the latter is subjected to alternating electric stresses. This effect is somehow analogous to the magnetic hysteresis. The dielectric hysteresis increases with the frequency of the applied voltage. Views are expressed, however, that the losses ascribed to the dielectric hysteresis are actually dielectric absorption losses.

Dielectric losses in electrostatic condensers depend on the nature of the dielectric and the applied voltage (steady, pulsating or alternating). The major portion of these losses in solid dielectrics is due to dielectric absorption; the leakage current ordinarily contributes very little to the losses. The dielectric losses increase with the temperature, voltage and frequency and are influenced by the purity of the insulating material. The total dielectric losses are reflected in the power factor of the insulating material.

Dielectric strength or puncture voltage—the minimum voltage required to disrupt a specimen of the insulating material of unit thickness (when the specimen forms the dielectric between the electrodes). The dielectric strength is lowered with the increase of temperature and frequency. Contamination with moisture may greatly reduce the breakdown voltage of the material. Thicker specimens will withstand a lower potential *per mil* than thin layers of the same material. The puncture voltage is also affected by the size and shape of the electrodes, small and sharp or pointed electrodes lowering the voltage.

Dipole—see *Polar liquids.*

Direct current (d.c.)—continuous current.

Effective alternating current—root mean square (RMS) current; it is equal in value to a continuous current which will dissipate the same power in a given resistance. For a sine wave the value of such continuous current is equal to the maximum value of the alternating current divided by $\sqrt{2}$. (Unless otherwise specified, RMS values are referred to in the text.)

Effective alternating voltage—root mean square (RMS) voltage.

Electric leakage—(leakage current) of capacitors—measured in milli- or microamperes per MF (microfarad) at a standard continuous voltage. The higher the insulation resistance of the capacitor, the lower its leakage current.

Electrode—pole—conductor by which the current enters or leaves an electrolyte.

Electrolysis—the flow of electricity through an electrolyte and the effects resulting from such passage of electricity.

Electrolytes or electrolytic conductors—conductors of the second class in which the conduction of electricity is associated with the migration of electrically charged particles of matter called *ions*. Solutions of acids, bases and salts (also molten salts) are electrolytes. Contrasted with these are the conductors of the first class (metals, carbon) in which the conduction is electronic, without the transport of any ponderable quantity of matter.

Electrostatic electricity—electricity at rest.

Electrostatic field—the electrostatic lines of force within the space (dielectric) between energized electrodes (as, for instance, between the plates of a condenser). The energy consumed in charging a condenser is stored in the dielectric, in the form of an electrostatic field.

Energy or work. Unit of energy—Joule = watt second. One joule is dissipated in a resistance of one ohm when a current of one ampere flows through it for one second.

Equivalent (or effective) **series resistance** of a condenser—a noninductive resistance of such value that when it is placed in series with a condenser having no losses, of a capacitance equal to that of the condenser under consideration, it will cause the same amount of power dissipation (due to the charging and discharging currents) as takes place in the given condenser. The value of the equivalent series resistance decreases with the increase of the frequency of the current.

Esterification—the reaction between an alcohol and an acid (mineral or organic) resulting in the formation of an ester (salt) and water. In this case the alcohol acts as a metallic hydroxide which, when reacting with an acid, produces a salt and water.

Farad—unit of capacitance—capacitance of a condenser which is charged to a potential of one volt by one coulomb.

Frequency—(f)—number of cycles ($\sim$) per second of an alternating current or voltage.

Impedance (Z)—opposition to the flow of alternating current due to the combination of resistance and reactance (inductive or capacitive). Impedance is measured in ohms and is computed from the formula:

$$Z = \sqrt{R^2 + X^2}$$

where Z = impedance,
R = resistance,
X = reactance.

Inductance (L)—property of generating an electromotive force in a circuit when any change of current flow takes place in the same circuit (self-inductance) or in a near-by circuit. Inductance opposes the changes of current flow in the circuit. Recoverable energy is stored in the electromagnetic field produced by the inductance when current is flowing in the circuit.

Unit of inductance—henry (h). When one volt of electromotive force is generated by a current changing at the rate of one ampere per second the value of the inductance is one henry.

Insulation resistance of a condenser—the resistance offered by a condenser to direct current, usually measured in ohms or megohms *per microfarad* (for a given type of condenser the resistance varies inversely with the capacitance). The steady current flowing through or over the surface of a condenser (when a continuous voltage is applied) is ordinarily very small and is known as leakage current. The insulation resistance drops with rising temperature and increased voltage. It is also reduced when moisture is present in the condenser.

The insulation resistance is measured at standard (steady) voltages, and readings are ordinarily taken one or several minutes after the voltage is applied, when the current flowing in the circuit is stabilized.

Ionization or electrolytic dissociation of an electrolyte—breaking up of molecules of the dissolved electrolyte into electrically charged particles called *ions*. The particles charged positively are the *cations* and those charged negatively the *anions*.

Megohm—one million ohms.

Microfarad—(MF or MFD)—one millionth of a farad.

Nonpolarized or symmetric electrolytic capacitor has both electrodes (poles) anodically formed and the films on both electrodes have substantially identical characteristics (are symmetric). Such capacitors are used in alternating circuits.

Ohm—(Ω)—unit of electrical resistance—the resistance of a mercury column of one square millimeter cross section and 106.25 centimeters long at 0°C.

Passivity—insolubility of certain metals (particularly of the iron group and chromium) when dipped in certain acids; under such conditions these metals behave like noble metals. *Anodic passivity* may take place when the metal is made the anode of an electrolytic cell. Chlorides and other halogen ions tend to interfere with passivity, while oxidizing agents enhance it.

The pH value designates the negative logarithm of the H^+ (hydrogen ion) concentration of a solution; it therefore indicates the *acid* or *basic intensity* of the solution. Distilled water of the highest purity and strictly neutral solutions have an equal concentration of H^+ and OH^- (hydroxyl) ions and their pH index is 7. The pH number of acid solutions is less than 7; the greater the acid intensity, the lower the pH number. Basic solutions have a pH above 7; the greater the alkali intensity the higher the number, 14 being the maximum on the scale.

Phase of alternating currents and voltages—if they rise and fall simultaneously, they are said to be "in phase." If they are out of phase, they reach their maximum and zero values (points) at different times; the displacement of these points, determined in electrical degrees, is the phase angle (ϕ).

Phase angle of a capacitor (ϕ)—the angle by which the current flowing in the capacitor is leading the impressed voltage. The smaller the electrical losses in the capacitor, the nearer is the angle to 90 degrees.

Polar liquids contain molecules which exhibit strong mutual attraction and a tendency to orient themselves in an electric field (as they have equal charges of opposite polarity at opposite ends); such molecules are called "dipoles." The orientation of the dipoles greatly increases the dielectric constant of the substance.[1]

Polarization—opposition to the current flow in an electrolytic cell (counterelectromotive force) due to concentration effects and chemical action at the electrodes, which in turn result from the current passing through the cell (electrolysis). In the presence of chlorides, polarization effects are minimized or suppressed.

Polarized or asymmetric electrolytic capacitor has only one of the two electrodes (poles) anodically formed. If connected to a d.c. source, a capacitor of this class will act in an entirely different manner (is asymmetric) with one polarity connection as compared with its action when the polarity is reversed. Such capacitors are ordinarily used in circuits where unidirectional currents are flowing.

Polymerization—combination of two or more molecules of the same substance with the formation of a compound of the same percentage composition, but of a different (multiple) molecular weight and of distinct properties.

Power—energy supplied per unit of time. Unit of power—watt = one volt-ampere (at unity power factor).

Power factor (PF) or cos ϕ—ratio of the dissipated to the apparent power input in a circuit—watts: volt-amperes.

In a circuit containing only resistance, the power factor is equal to unity.

The power factor of a capacitor expresses the total losses of the device; it varies with the temperature, voltage and frequency.

Power loss in a capacitor in watts—$W = I^2R$,
where W = watts,
I = amps.,
R = ohms (effective or equivalent series resistance).

Pulsating current—unidirectional current, the amplitude of which is fluctuating periodically.

Reactance (X)—the reactive component of impedance, measured in ohms. Reactance is the opposition to the flow of alternating current due to inductance (positive reactance X_L) or capacitance (negative reactance X_C). The inductive reactance ($2\pi fL$) is directly proportional and the capacitive reactance $\left(\frac{1}{2\pi fC}\right)$ is inversely proportional to the frequency in the circuit. When in series, the two reac-

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[1] Alcohol and acetone are examples of polar liquids; mineral oil is nonpolar.

tances are opposing each other. If they are of equal value, the one balances out the other, and the current flow (at this particular frequency) is opposed only by the resistance of the circuit; this is the condition of series resonance. At resonance, the voltage and current in the circuit are in phase; the voltages across the two reactances are equal, are of opposite polarity and may be very large.

Rectifier—one-way electrical valve-device for converting alternating current (by unilateral conduction) into pulsating direct current. The device passes freely alternations of one polarity only and blocks those of the opposite polarity.

Resistance—(R)—opposition to the flow of current which causes heat dissipation (loss of electric energy). Contrasted with it is reactance, where opposition to the current flow is associated with storing of (recoverable) energy. The effect of the resistance is the same for a.c. or d.c. while the effects of reactances (positive and negative) are entirely different for a.c. and d.c.

The current flowing in a circuit with pure resistance only is in phase with the voltage.

Resonance—see *Reactance.*

Specific conductance or conductivity—the reciprocal of resistivity. The conductivity of electrolyte solutions increases with temperature.

Specific resistance or resistivity of an electrolyte—the resistance (in ohms) of a quantity of the electrolyte one centimeter long and having a cross section of one square centimeter.

Throwing power—a term used in electroplating to indicate the degree of uniformity of metal deposition on the cathode (the object being plated) when the various parts of the surface of the latter are at different distances from the anode (have a nonuniform accessibility). A similar effect is observed in anodizing, but in this case it is the degree of uniformity of *film formation* on the various parts of the surface of the anode (of nonuniform accessibility).

Viscosity of a fluid is due to its internal friction. Fluidity or mobility is the reciprocal of viscosity. One way to measure the viscosity of a liquid is to determine the time required for the flow of a certain quantity of the liquid through a narrow aperture, under strictly determined conditions. The viscosity decreases with the increase in temperature.

The specific viscosity of a liquid is obtained by comparing its viscosity with the viscosity of pure water at a definite temperature.

Volt (V)—unit of electromotive force. It can be based on the electromotive force of the standard cell or derived from Ohm's law (see *Ampere*).

$$\left.\begin{array}{l}\textit{Voltage}\\ \textit{Electromotive force}\\ \textit{Potential}\end{array}\right\}\text{Electric pressure.}$$

Watt (W)—see *Power.*

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1891

445,687	T. D. Bottome
458,652	T. D. Bottome

1901

669,802	A. Nodon
672,913	C. Pollak
673,952	L. W. Hildburgh
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1902

714,400	M. C. Rypinski
715,126	A. Nodon
716,000	L. DeForest, *et al.*
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1903

719,791	R. Grisson
732,631	C. Hambuecher

1904

766,468	W. Scheidel

1906

809,770	M. Buettner

1908

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996,583	J. L. R. Hayden
1,002,069	A. B. Marvin
1,004,533	E. E. F. Creighton
1,008,860	F. W. Peek
1,012,889	R. D. Mershon

1912

1,022,695	W. Morrison
1,023,092	W. Morrison

1913

1,068,410	L. W. Chubb
1,074,231	C. I. Zimmerman

1914

1,097,801	A. Heinz
1,117,240	E. Presser
1,121,764	C. C. Ruprecht

1915

1,155,649	N. Fallek

1917

1,250,141	L. W. Chubb

1918

1,128,059	M. U. Schoop
1,255,391	J. Coulson
1,266,557	J. Coulson
1,270,784	L. W. Chubb

1919

1,305,443	L. W. Chubb
1,305,458	C. L. G. Fortescue

1920

1,330,581	J. Coulson
1,344,752	L. W. Chubb
1,348,206	L. W. Chubb
1,348,207	L. W. Chubb

1921

1,367,097	C. J. Rottman
1,381,356	J. S. Slepian

1,382,899	C. L. G. Fortescue
1,387,471	J. Coulson
1,390,505	J. Coulson
1,390,575	F. H. Miller

1922

1,412,513	J. Coulson
1,412,514	J. Coulson
1,439,525	R. D. Mershon

1923

1,456,941	J. Slepian
1,473,883	J. Slepian

1924

1,514,736	H. O. Siegmund

1925

1,526,127	F. B. Flick
1,543,729	J. Slepian
1,543,225	R. D. Mershon
1,558,859	C. L. G. Fortescue
1,565,024	R. D. Mershon

1926

1,600,397	C. C. Carpenter

1927

1,637,328	C. A. Aalborg
1,637,795	E. F. Andrews
1,647,649	W. Morrison
1,647,650	W. Morrison
1,648,963	E. Romanelli

1928

1,658,976	P. E. Edelman
1,662,075	A. B. Muntyan
1,675,828	H. O. Siegmund
1,682,846	H. C. Kremers
1,684,684	W. C. Read
1,686,316	E. W. Engle

1929

1,703,680	H. N. Miller
1,707,423	B. F. Bailey
1,707,424	B. F. Bailey
1,709,427	V. Bush
1,710,073	S. Ruben
1,711,816	G. Steerup
1,714,191	S. Ruben
1,721,886	I. A. Shulimson
1,724,065	C. W. Balke
1,727,963	C. C. Carpenter
1,729,429	E. F. Lundeen
1,730,725	P. E. Edelman

1930

1,744,014	J. Slepian
1,749,145	E. F. Lundeen
1,758,255	A. E. Hudd
1,758,947	L. Hammond
1,769,228	E. F. Lundeen
1,769,837	A. W. Hull
1,771,910	G. D. Bengough, *et al.*

1931

1,815,768	A. Georgiev
1,829,177	V. Yngve
1,829,178	V. Yngve
1,837,394	B. F. Bailey

1932

1,845,067	E. A. Weaver
1,850,702	A. L. Allen
1,866,604	H. O. Siegmund
1,889,415	R. D. Mershon

1933

1,908,316	V. Bush
1,912,223	S. Ruben
1,914,114	P. H. Estes
1,915,457	H. J. Tyzzer
1,916,586	P. Robinson, *et al.*
1,920,799	J. E. Lilienfeld
1,925,307	J. Hendrik de Boer, *et al.*
1,930,578	J. J. Barrett
1,935,395	E. W. Engle
1,935,860	P. Robinson
1,936,084	J. D. Edwards
1,936,252	F. W. McNamara
1,938,464	P. Robinson

1934

1,941,725	H. J. Tyzzer
1,948,289	H. I. Danziger
1,948,864	R. D. Mershon
1,950,119	J. E. Lilienfeld
1,950,352	J. T. Curtis
1,951,476	P. E. Edelman
1,951,720	M. Bergstein
1,956,365	W. C. Van Geel, *et al.*
1,959,130	C. Hambuechen, *et al.*

1,959,415	E. W. Engle
1,959,780	H. I. Danziger
1,960,834	H. J. Tyzzer
1,963,049	A. Georgiev
1,966,163	F. M. Clark
1,966,297	J. G. Jackson
1,969,630	R. C. Sprague, *et al.*
1,970,776	A. Smith
1,973,544	H. L. Sklar
1,973,694	D. E. Briggs, *et al.*
1,973,852	A. Georgiev
1,974,579	R. D. Mershon
1,979,916	H. J. Tyzzer
1,981,352	H. F. Fruth
1,983,469	M. Knab

1935

1,986,779	J. E. Lilienfeld
1,987,420	H. V. Siegmund
1,989,129	J. M. Booc
1,989,622	J. E. Lilienfeld
1,989,623	J. E. Lilienfeld
1,992,545	P. Robinson
1,998,202	P. Robinson
1,999,373	H. L. Sklar
2,001,698	H. G. André
2,001,790	J. E. Lilienfeld
2,005,055	R. C. Sprague, *et al.*
2,005,279	W. C. Van Geel, *et al.*
2,006,713	A. Georgiev
2,009,494	P. Hetenyi
2,011,461	R. C. Sprague, *et al.*
2,011,519	G. Holst, *et al.*
2,012,481	P. Robinson
2,012,691	J. A. Poitras
2,012,692	J. A. Poitras
2,016,302	R. C. Sprague
2,017,835	A. Georgiev
2,018,500	L. A. McDermott
2,021,455	J. E. Lilienfeld
2,023,522	F. W. Godsey, Jr.

1936

2,028,590	F. M. Clark
2,028,775	P. Hetenyi
2,029,451	W. C. Van Geel, *et al.*
2,029,550	R. K. Albert
2,030,122	W. F. Straub, *et al.*
2,031,128	A. Raines
2,031,793	P. Robinson
2,033,309	H. O. Siegmund
2,035,022	P. Robinson and J. L. Collins
2,036,669	V. Yngve
2,036,878	J. E. Lilienfeld
2,037,848	J. B. Brennan
2,038,616	W. C. Van Geel and J. H. de Boer
2,039,154	H. Emmens, *et al.*
2,042,283	A. E. Van Arkel, *et al.*
2,043,038	J. D. Edwards
2,047,452	V. F. Zahodiakin
2,048,417	H. J. Meerkamp
2,049,553	F. A. Weaver
2,049,671	J. K. Sprague
2,050,062	R. D. Mershon
2,051,592	J. R. T. Craine
2,052,575	J. E. Lilienfeld
2,052,962	J. M. Booe
2,055,216	P. E. Edelman
2,057,314	P. Robinson
2,057,315	P. Robinson
2,060,022	J. B. Brennan
2,060,866	P. Hetenyi
2,062,543	H. Waterman
2,066,154	J. L. Lotsch

1937

2,066,912	S. Ruben
2,067,730	P. Robinson
2,070,801	J. J. Moynihan
2,071,103	M. Bergstein
2,071,104	M. Bergstein
2,073,060	A. T. Harding, *et al.*
2,075,351	J. E. Lilienfeld
2,076,904	J. E. Lilienfeld
2,076,905	J. E. Lilienfeld
2,078,772	A. T. Pitt
2,079,081	R. D. Mershon
2,079,516	J. E. Lilienfeld
2,080,390	J. M. Booe
2,081,068	P. Robinson
2,083,254	H. D. Cowles
2,084,046	J. T. Owen
2,085,413	S. Bloomenthal
2,085,958	J. T. Curtis
2,089,683	F. M. Clark
2,089,684	F. M. Clark
2,089,685	F. M. Clark
2,091,616	E. R. Stoeckle

2,091,920	F. W. Godsey, Jr.
2,094,048	S. Siegel
2,096,673	J. Katzman
2,096,674	J. Katzman
2,098,745	A. Georgiev
2,099,599	C. DeLange
2,099,797	R. W. Clark

1938

2,104,018	J. B. Brennan
2,104,019	J. B. Brennan
2,104,732	J. B. Brennan
2,104,733	J. B. Brennan
2,106,208	P. McK. Deeley
2,107,780	H. I. Danziger
2,108,995	S. Ruben
2,111,993	P. Robinson
2,119,628	P. Robinson
2,120,426	W. Hermann
2,120,815	N. Schnoll
2,130,073	C. DeLange, *et al.*
2,134,273	V. Bush

1939

2,143,392	G. K. Sziklai
2,149,086	J. R. T. Craine
2,151,806	N. Schnoll
2,155,086	A. Georgiev
2,158,363	A. Georgiev
2,164,742	A. T. Harding
2,165,090	F. M. Clark
2,165,091	F. M. Clark
2,168,135	F. Pavelka
2,168,156	F. M. Clark
2,172,604	C. M. Blackburn
2,174,841	P. Robinson
2,177,018	A. F. P. J. Claassen

1940

2,196,057	F. M. Clark
2,198,494	A. Georgiev
2,206,050	P. Robinson
2,209,820	J. C. Koonz
2,214,878	F. M. Clark

1941

2,230,208	E. C. Armstrong, *et al.*
2,232,320	A. Georgiev
2,234,608	P. Robinson
2,235,067	A. Georgiev
2,242,780	A. Georgiev
2,243,814	W. Dubilier
2,253,506	F. M. Clark
2,264,899	A. Georgiev
2,264,900	A. Georgiev

1942

2,297,608	G. M. Blackburn
2,297,669	P. Robinson, *et al.*

Foreign Patents

Austrian

1903

12,505	Siemens and Halske

Belgian

1929

364,801	A. Soulier

British

1896

933	Pollak
1,069	Pollak

1928

290,901	Gower

1930

329,190	Kuttner

1935

425,983	Ruben Condenser Co.

1936

448,163	Dubilier Condenser Co., Ltd.
448,616	The Plessey Co., Ltd.
448,830	F. C. Stephan, *et al.*
449,645	The Plessey Co., Ltd.
453,986	N. V. Philips' Gloeilampenfabrieken
454,047	J. B. Brennan
454,202	Hydrawerk A. G.
456,254	Hydrawerk A. G.

1937

467,024	N. C. Moore, *et al.*
472,097	Philips' Gloeilampenfabrieken
472,377	Philips' Gloeilampenfabrieken
476,555	G. C. Gaut
476,688	Dubilier Condenser Co.

1938

479,401	British Thomson-Houston Co., Ltd.

French

1909

401,355	J. R. Russenberger

1912

440,516	P. A. Felix

1931

711,858	Thomson-Houston, *et al.*

1934

770,929	N. V. Philips' Gloeilampenfabrieken

1935

785,674	Siemens and Halske A. G.

1936

802,374	Telefunken-Gesellschaft fuer Drahtlose Telegraphie

German

1929

484,477	Accumulatoren Fabriken A.G.

1934

602,332	Allgemeine Elektrizitaets-Ges.
607,083	Dr. Gustav Schweikert

Russian

1935

43,460	D. N. Zukova

Swiss

1917

81,050	Greinbacher

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(Continued from front flap)

he discusses briefly electrolytic capacitors versus nonelectrolytic capacitors. He points out possible defects in the former, their causes and detection, and suggests methods of emergency repairs. And he includes a chapter dealing with trends in the development and probable further applications for electrolytic capacitors.

Numerous drawings, photographs, and graphs illustrate construction details, manufacturing processes, and the behavior of the various types of electrolytic capacitors. The latter, particularly, will help the designer to choose the type best suited to a given application and existing operating conditions.

A glossary of technical terms, a comprehensive bibliography, and a thorough review of the important patents (U. S. and Foreign) granted in the capacitor field, add to the value of the book.

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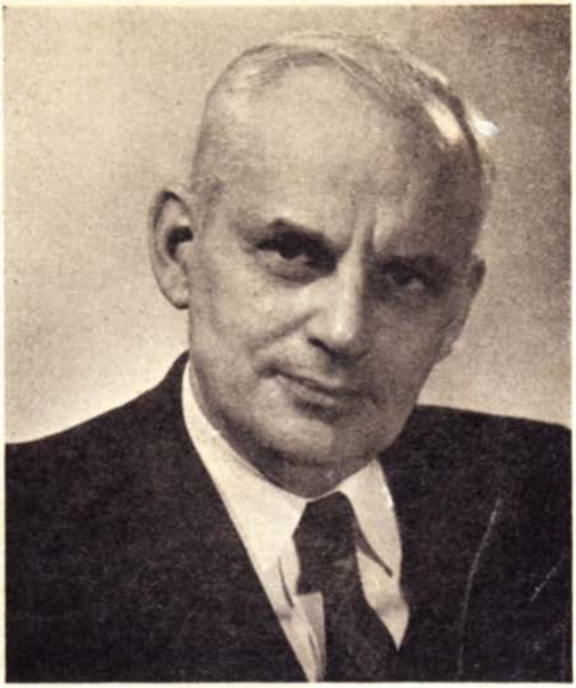

ALEXANDER GEORGIEV is well qualified to write on the subject of electrolytic capacitors. Mr. Georgiev, born in Sofia, Bulgaria, began his technical training in Russia, where he graduated from the Engineering School Nikolaeff in St. Petersburg. The knowledge he gained there was later supplemented by studies at the Technische Hochschule in Berlin and at Columbia University in New York. The material in this book is based on fifteen years of experience, in Europe and America, in the development and manufacturing of electrolytic capacitors as well as on a thorough search through the literature and patents in English, French, German, and Russian. The author developed the first high-voltage (500V) dry electrolytic capacitor, and he has been granted nineteen U. S. patents (two in conjunction with co-workers). He has been employed by leading electrical manufacturers in both Europe and America. For the past several years he has been associated with the Delco Products Division of General Motors Corporation. He is the author of several articles in technical journals, and he has been consulted as an expert in a number of litigations involving electrolytic capacitors.

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