The Aluminum Electrolytic Condenser [1]

By H. O. SIEGMUND

SYNOPSIS: In this paper the anodic film-forming properties of aluminum are discussed and the unique electrical qualities of film-coated aluminum anodes are described. Special reference is made to an aluminum electrolytic condenser of the type used in low pass electric wave-filters of direct-current telephone power plant equipment. Electrical characteristics of condensers are given and the manner is described in which the operation and life of the units are influenced by variations in composition of the electrodes and the electrolyte.

INTRODUCTION

SINCE the discovery about 75 years ago [2] of the unusual polarizing effect of aluminum it has become well known that certain metals, notably aluminum and tantalum, as anodes in a suitable electrolyte become coated with a film having remarkable electrical properties. Films formed in this manner are characterized by the influence of impressed potential on their electrical resistance.

A representative relationship between applied voltage and resistance per 1,000 sq. cm. of film on an aluminum anode in an ammonium borate electrolyte [3] is shown in Fig. 1. This resistance characteristic imparts to the film the capability of conducting current more freely in one direction than in the other; of breaking down as an insulation between the metallic electrode and the solution when voltages above a critical value are applied; and in combination with the thinness of the film of holding a substantial charge of electricity at potentials below the breakdown voltage.

Each of these characteristics provides the principle around which a distinctive class of electrical apparatus has been developed. The electrolytic rectifier, widely used in small direct-current supply sets for battery charging and radio purposes, employs the unidirectional conducting characteristic. The aluminum electrolytic lightning arrester, used extensively for protection of direct-current railway equipment, depends for its operation upon the breakdown characteristic of the film. And finally the aluminum electrolytic condenser, now being

[1] Presented before the American Electrochemical Society, at Bridgeport, Conn., April 26, 1928.

[2] Wheatstone, *Phil. Mag.*, **10**, 143 (1855).

[3] The exact values of resistance are somewhat unstable, and depend on the time between readings and whether successively increasing or decreasing values of potential are applied. However, the general shape of the curve and the magnitude of the values are representative.

used in direct-current telephone power plant equipment [4] utilizes the dielectric property of the film to provide electrostatic capacity.

ELECTRICAL QUALITIES OF FILMS ON ALUMINUM

There are a number of electrolytes, including various concentrations of phosphates, borates, tartrates, carbonates and others in which films can be formed on aluminum to withstand maximum potentials
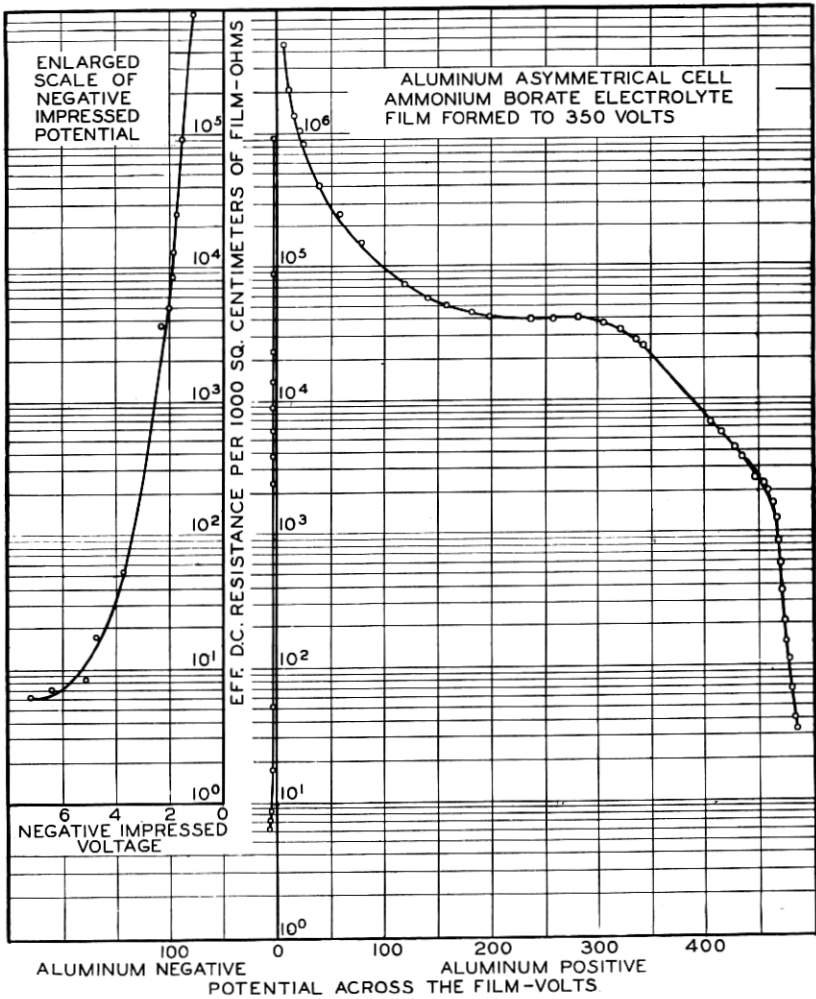

FIG. 1—Influence of impressed potential upon the electrical resistance of the film on an aluminum electrode

[4] Young, R. L., *Bell System Techn. J.*, 6, 708 (1927).

upwards of 300 volts, at least for limited periods. If a film is formed on a piece of aluminum to this maximum voltage and the metal is then made the anode in an electrolytic cell across which variable potential can be applied, a current corresponding to a density of less than a microamp. per sq. cm. of filmed surface will flow when a potential of one tenth the maximum voltage is impressed.
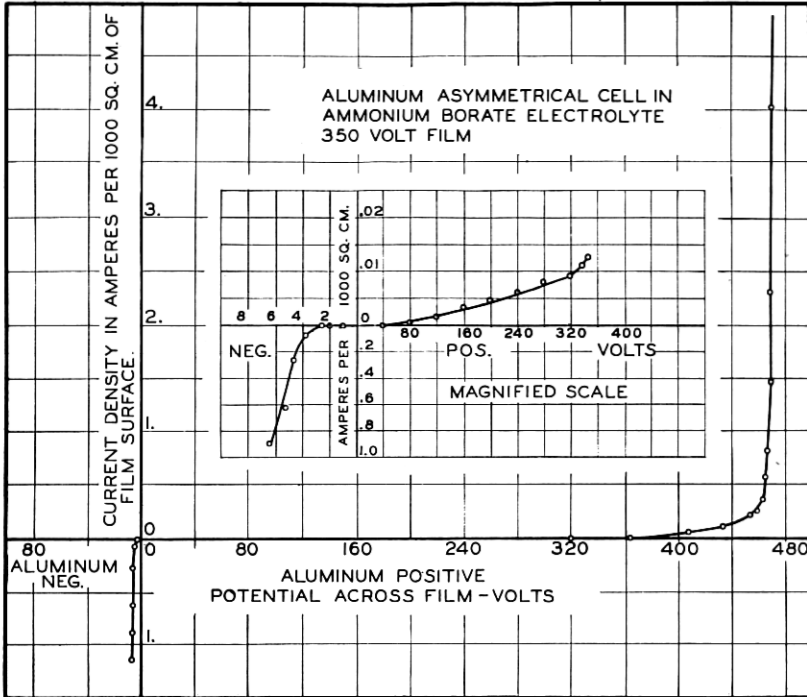

FIG. 2—Influence of potential on the current through an electrolytic cell with a film-coated aluminum electrode

As the potential is increased this "leakage" current will increase at a rate somewhat greater than proportionate to the voltage. As the maximum or breakdown potential is approached it will be noticed, if the room is darkened, that the anode begins to glow uniformly over the surface with a pale light and with further increases in voltage sparks begin to scintillate over the entire electrode, being noticed first at the surface of the electrolyte. The current through the cell becomes appreciable under this condition and increases more rapidly until at voltages slightly above the sparking potential the cell acts virtually as a short circuit.

Upon reduction of the voltage, however, the insulating properties of the film are restored and the current decreases with decreasing potential in substantially the same relation to voltage as before. The sparking over the surface will be observed to cease at about the same potential at which it began, the glow will disappear and the low leakage-current values will be obtained when the voltage is reduced sufficiently.

Upon reversal of potential on the aluminum electrode, however, there is a much larger flow of current, the value of which is limited by a counter voltage of several volts, and by the low internal resistance of the cell with negative potential applied. Typical current-voltage relations for an aluminum cell are shown graphically in Fig. 2. These relations correspond to the curve in Fig. 1, showing the variation of resistance with potential of a "filmed" aluminum electrode in ammonium borate electrolyte.

Capacity of Aluminum Films

Like the ordinary paper or mica static condenser, the electrolytic condenser consists of two conducting surfaces separated by an insulator. The high-resistance film constitutes the insulator in the electrolytic cell, and the electrolyte on one side of the film and the metal of the film-bearing electrode on the other provide the two conducting surfaces. The cathode in this type of cell merely provides a means for making electrical contact with the electrolyte.

When a film is formed upon a smooth polished aluminum surface the coating is transparent. If observed under favorable illuminating conditions the "filmed" surface is seen to be colored and may be either green, yellow, red or blue, depending upon the thickness of the film. This is attributed to light interference and indicates that the thickness of the film is in the order of the length of light waves. The actual thicknesses of films on aluminum have been determined to be from 0.001 to 0.00001 mm.,[5] depending upon conditions of formation.

Because of this extreme thinness of the dielectric and its high insulation resistance when positive potential is applied, unusually large capacities per unit area of surface can be obtained. The capacity of a film formed to 30 volts on aluminum is about 0.18 microfarad per sq. cm. of dielectric surface, or about 1,000 times that of paper condensers. The capacity per unit area is approximately inversely

[5] Zimmerman, *Trans. Am. Electrochem. Soc.*, **7**, 309 (1905); Sutton and Willstrop, *Engineering*, **124**, 442 (1927); Slepian, *Trans. Am. Electrochem. Soc.*, September, 1927, to be printed in Vol. 54 of the *Transactions*.

proportional to the potential at which the film is formed, indicating that the thickness of the dielectric is directly proportional to the voltage of formation.

EFFECT OF IMPRESSED VOLTAGE ON CAPACITY

When an electrolytic cell with a "formed" anode has impressed on its terminals a voltage greater than the formation voltage, the film must build up to the new potential before the electrical characteristics of the cell become stable. At this higher voltage the capacity of the cell will be reduced to correspond to the increased potential. Where large plate areas are involved the direct application of a potential above the formation voltage results in a heavy flow of current, which may overheat and damage the cell if not properly limited.

If a voltage is impressed on a condenser lower than the potential applied during the formation of the film, the cell will operate satisfactorily, but the capacity will not be immediately affected and will correspond to the potential at which the film was originally formed. This is illustrated in Table I, which shows the capacities of an electrolytic cell measured with applied voltages of different values below the voltage of formation.

However, if a condenser operates for a long time at a reduced voltage the excess film will be removed slowly by the chemical action of the electrolyte, and the capacity will increase gradually to a value depending upon the operating voltage. The rate of change of capacity under these conditions is affected by the temperature at which the cell operates, and by the conductivity of the electrolyte. As is illustrated by the curves shown in Figs. 3 and 4 the change becomes more rapid when these factors are increased.

TABLE I

Applied Potential Volts—D.C.	Capacity Readings Microfarads
49.2	1008
43.0	1002
36.7	1008
30.4	1013
24.3	1013
18.3	1013

SERIES CONNECTED CONDENSERS FOR DIRECT AND ALTERNATING CURRENT SERVICE

In the discussion of the current-voltage relations in Fig. 1, it was noted that an aluminum cell with one electrode of non-film-forming metal conducts current freely when the aluminum is cathode. Accordingly this type of cell is capable of holding a charge of electricity and

serving as a condenser only while the aluminum is at a higher positive potential than the electrolyte.

A cell with a non-film-forming cathode makes a suitable condenser to operate on direct-current or pulsating-current circuits, in
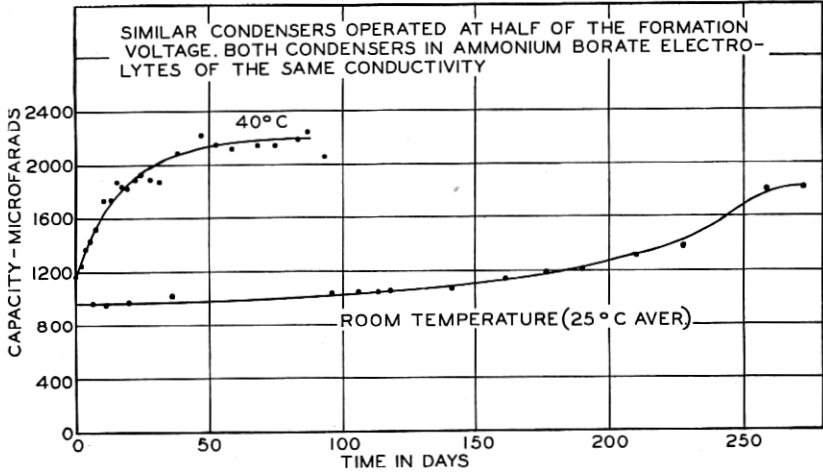

FIG. 3—Effect of electrolyte temperature on the rate of capacity change in condensers operating at voltages below the formation voltage
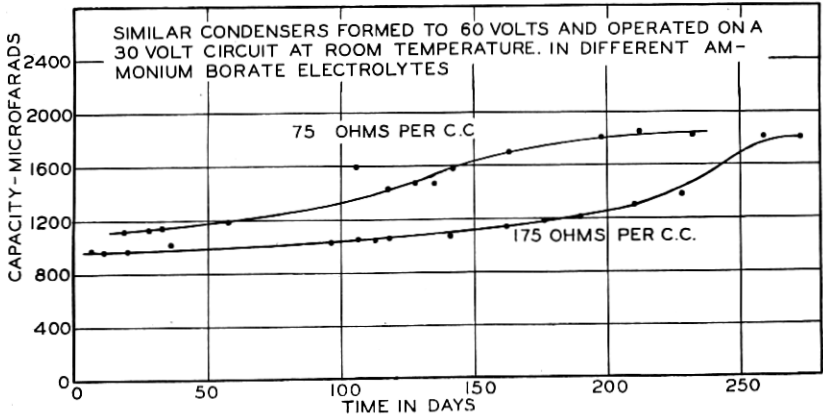

FIG. 4—Effect of electrolyte conductivity on the capacity change due to reduced operating voltage

which the aluminum always remains positively charged. On alternating-current circuits, however, such a cell will operate as a rectifier rather than as a condenser, unless two similar units are connected in a series-opposed relationship.

A suitable condenser for operation on alternating current can also

be made by having two electrodes of film-forming metal in the same solution, the electrical relations between the "filmed" electrodes being the same in this case as in the series-opposed arrangement of two asymmetrical cells. In either case one or the other of the film-forming electrodes opposes the flow of current during each half cycle.

If we consider the conditions that exist at the instant of maximum potential in one direction, the electrode that is then anode acting as a condenser, receives its maximum charge. As soon as the potential begins to decrease from this maximum the accumulated electricity begins to flow from the charged plate through the circuit, but in so doing the opposing film-forming electrode becomes an anode, enabling it to hold the charge given up by the discharging electrode.

In this way, as the alternating potential varies between maximum values in each direction, the charge is transferred from the capacity provided by one film-forming electrode to the other, the sum of the charges on these two electrodes at every instant remaining constant. It can be shown that two series-opposed asymmetrical cells of capacities C_1 and C_2, or two "formed" electrodes of these capacities in the same electrolyte, have a resulting capacity equal to

$$\frac{C_1 C_2}{C_1 + C_2}.^6$$

As illustrated in Table II, which gives the results of measurements on two asymmetrical cells formed to different voltages and connected in various series combinations, it will be noted that this relationship

TABLE II

MEASUREMENTS AT 60 CYCLES

	Biasing Potential Volts D.C.	Capacity Microfarads	Equivalent Series Res. Ohms
Condenser "A"........................	24.6	1529	0.165
Condenser "B"........................	44	962	0.23
"A" and "B" series—aiding............	50	587	0.385
	43.8	582	0.38
	25	588	0.38
"A" and "B" series—opposing			
"B" positive....................	37.3	588	0.395
	18.3	588	0.38
No bias........................	0	594	0.385
"A" positive....................	12	588	0.39
	24	588	0.39
Calculated from measurements of "A" and "B"................................		589	0.395

[6] Zimmerman, *Trans. Am. Electrochem. Soc.*, **7**, 323 (1905).

is true both on alternating and direct-current circuits. If unidirectional potential is applied this relation holds without regard to the polarity or the magnitude of the impressed voltage so long as this voltage does not make the potential across the film opposing the flow of direct current greater than the voltage to which this film was formed.

In the case of asymmetrical cells connected in series-opposed relation the expression is correct either when the positive plates

$$C = \frac{10^6}{2\pi F \sqrt{\left(\dfrac{E_{AC}}{I_{AC}}\right)^2 - \left(\dfrac{W}{I_{AC}^2}\right)^2}}$$

$$R = \frac{W}{I_{AC}^2}$$

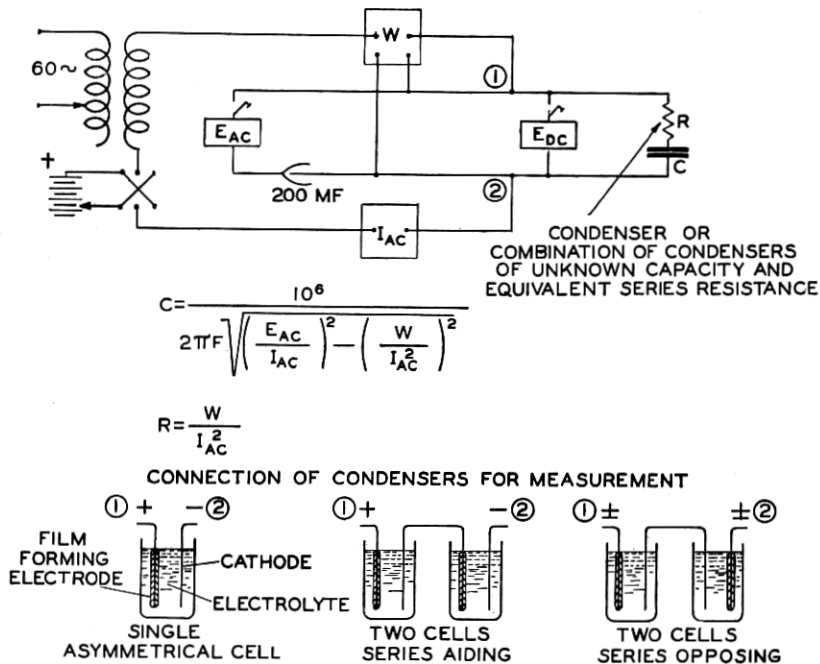CONNECTION OF CONDENSERS FOR MEASUREMENT

FIG. 5—Determination of capacity and equivalent series resistance of electrolytic condensers with 60-cycle alternating current superimposed upon a variable unidirectional potential.

of the two cells are connected together at the mid-point or when the negatives are so connected. On direct current it applies for series-aiding as well as for series-opposed connections.

It will be recognized that the resultant capacity $\dfrac{C_1 C_2}{C_1 + C_2}$ is the same as is obtained when two ordinary static condensers of values C_1 and C_2 are connected in series. However, the internal distribution of electrostatic charges in opposed electrolytic condensers is quite different from that in series-connected static condensers, due to the rectifying characteristic of the films.

These determinations were made with a voltmeter, ammeter and wattmeter at 60 cycles, and were in conformity with measurements over a range of frequencies made on an impedance bridge. In the cases of measurements made with unidirectional potential applied, suitable bias was provided by superimposing the alternating current by means of a transformer in a battery circuit, the d.c. potential of which could be varied by changing the number of cells in series.

The apparatus for these measurements is shown in Fig. 5. It will be noted that a high-capacity blocking condenser is required in the a.c. voltmeter circuit, but is omitted from the potential circuit of the wattmeter. This condenser is inserted to block the unidirectional potential, which otherwise would be read by the voltmeter, but the power that the wattmeter indicates due to this potential is of no importance, and except for direct-current leakage would actually be zero.

Losses in Aluminum Cells and their Effect on Electrical Impedance

In the matter of electrical impedance characteristics, the electrolytic condenser does not approach a perfect capacitance as nearly as the more familiar forms of static condensers. Three sources of energy loss in the electrolytic condenser impart to it an equivalent series resistance, as a result of which the condenser current leads the impressed voltage by a phase angle somewhat less than 90°.

The first of these losses is the dielectric hysteresis loss, which, as in the case of the paper condenser, is approximately proportional to the frequency. The second loss is due to the resistance of the electrolyte and, in the case of aluminum condensers, may be of appreciable magnitude because of the low electrical conductivity of suitable electrolytes. This electrolyte resistance remains practically constant over a wide range of frequencies.

The third possible loss is due to the leakage-resistance of the film, which in its effect is similar to a high resistance in parallel with the condenser. Ordinarily this loss is negligible because the leakage current is less than a microampere per sq. cm. of film surface.

Conditions Affecting the Life of Condensers

To be successful from a commercial point of view an electrolytic condenser must have long life and must not require frequent attention. Otherwise the advantage in the matter of mounting space and the cost per unit capacity is offset by the depreciation and maintenance costs involved. There are two common conditions affecting the life

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of aluminum condensers that must be controlled if the cells are to operate satisfactorily.

The first concerns the chemical action of the electrolyte on the electrodes and the film. This action, which is merely a matter of the film dissolving and forming aluminum hydroxide in the solution, takes place when the cell is off circuit as well as when potential is impressed. With impressed potential, new film forms under the influence of the leakage current to replace that which is dissolved, but in time the fluid becomes saturated with aluminum hydroxide, which may precipitate as a white jelly and adversely affect the life of the condenser.

The second consideration involves corrosion of the positive electrodes. The susceptibility of aluminum to corrosion is well known, and in the use of electrolytic condensers anodic corrosion is the most damaging irregularity that can occur.

Obviously then an electrolyte must be chosen that does not rapidly dissolve the film, and the material for the electrodes as well as for the electrolyte must be selected and prepared to prevent serious corrosion of the "formed" aluminum plates.

Commercial Applications and Designs of Electrolytic Condensers

Reference has already been made to the use in telephone systems of electrolytic condensers. The principal applications of this device involve its use in low-pass electric wave-filters. These filters are placed in the supply circuits associated with central office storage batteries to eliminate noise-producing ripples and pulsations, introduced by battery charging-apparatus and signaling equipment, from the direct current furnished to telephone instruments. That is, the filters are used to exclude hum and other disturbing noises from the subscribers' circuits.

In Fig. 6 is shown an electrolytic condenser of the type designed for direct-current filter service. When prepared for operation on 24-volt d.c. circuits, the capacity of this cell is nominally 1,000 mf. at 1,000 cycles, and for 48 volts is about 600 mf. at the same frequency. The cell is 8 inches wide, 10.25 inches long and 14.25 inches high (20 x 26 x 36 cm.). Completely assembled it weighs about 42 pounds (19 kg.), including 22 pounds (10 kg.) of electrolyte.

The container for the condenser is made of heat-resisting glass which reduces possible breakage due to temperature variations. The electrodes, both of aluminum, are rigid and are bolted to a porcelain cover to keep them in proper space relation. Two supporting bolts,

one from each electrode properly marked with respect to polarity, extend through the cover to provide the terminals for the condenser.

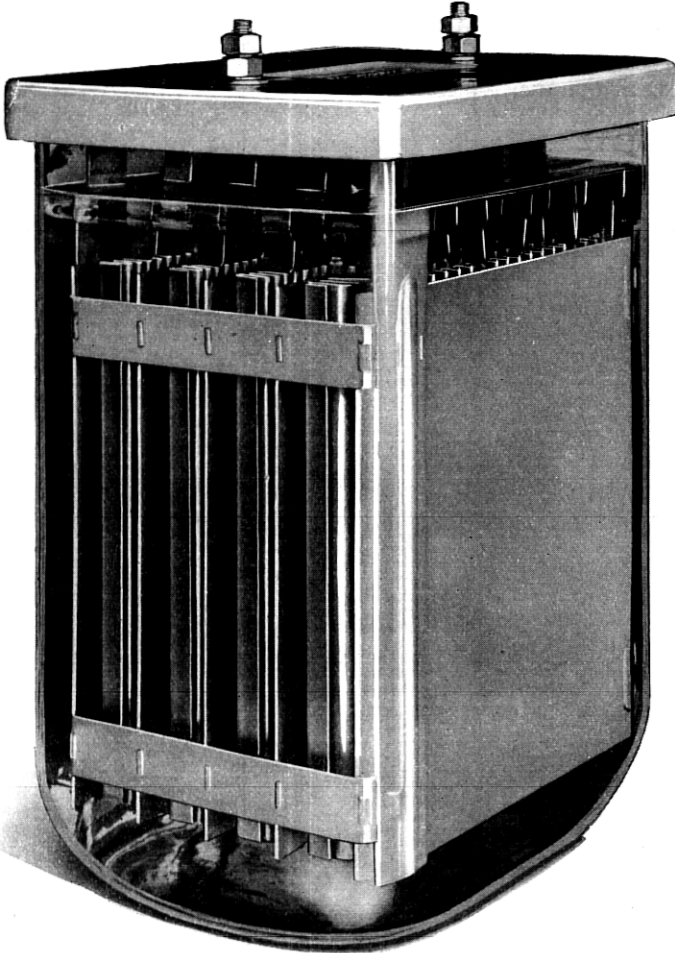A thin layer of high grade paraffine oil is used on top of the con-

FIG. 6—Aluminum electrolytic condenser, designed for direct-current filter service

denser fluid to prevent evaporation and to keep the inside of the cell from sweating under varying room temperature conditions. The cover is sealed to the glass jar with paraffine to provide additional protection against evaporation and to prevent dirt from getting into the cell.

The Anode Construction and Material

The construction of the electrodes is shown in Fig. 7. The positive electrode on which the dielectric film is formed is made of four corrugated aluminum plates, each supported by four integral ears. In an assembled condenser the positive plate surfaces are entirely immersed in electrolyte, the ears extending up through the oil and providing contact with the positive terminal.
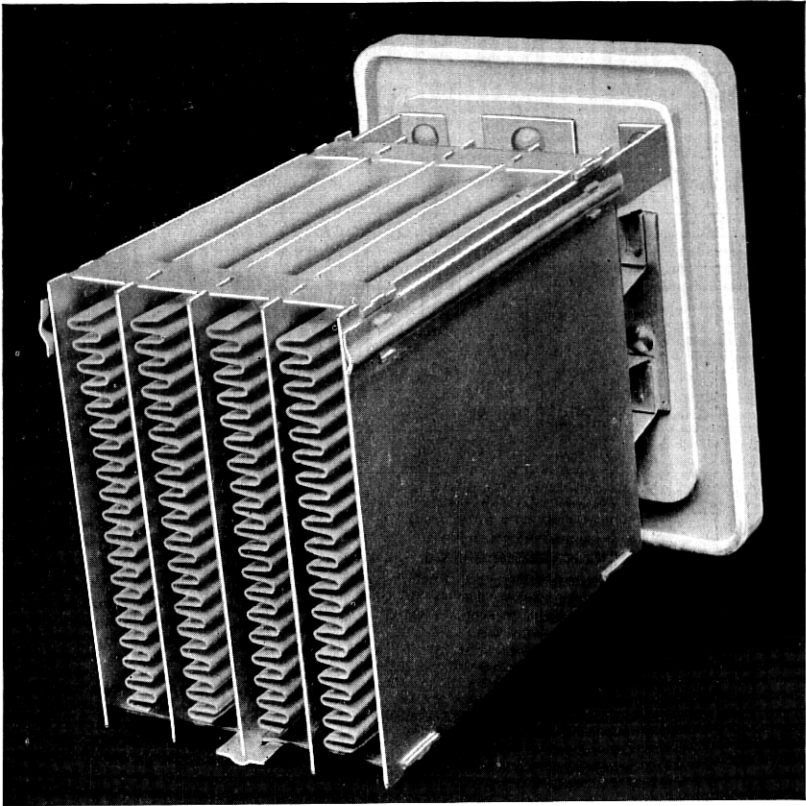

Fig. 7—Aluminum electrolytic condenser, showing construction of the electrodes

The material for the positive plates is aluminum of special composition, selected on a basis of properties which influence the formation of the film, the leakage current and the life of the metal. In general, the higher the purity of the aluminum the more rapid is the formation of the film and the lower is the resultant leakage current.

It has been noticed that the unit-area capacity for high-purity

metals is slightly lower than for metals containing small quantities
of alloying materials, but this difference is of inconsequential im-
portance. The difference in the rate of film formation under similar
conditions between 99.1 per cent aluminum and 99.6 per cent aluminum
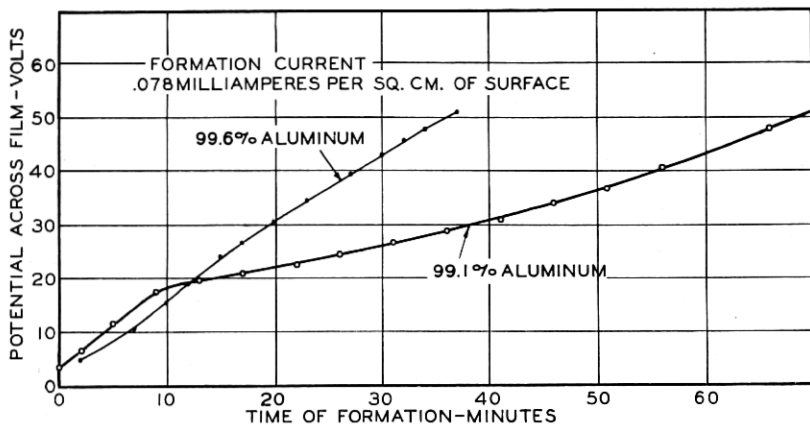is shown in Fig. 8. After 24 hours in these particular cases the

FIG. 8—Rate of film formation as influenced by composition of metal
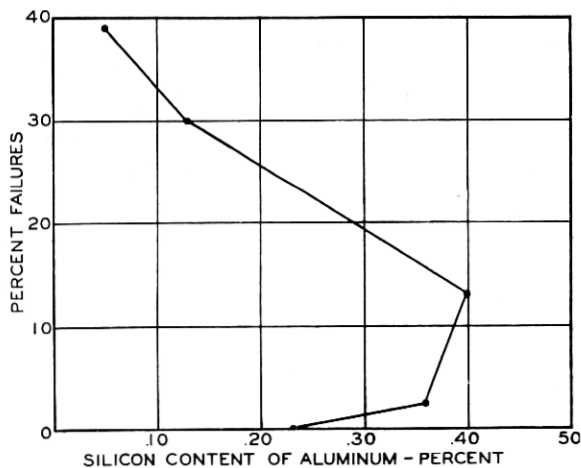

FIG. 9—The relation between silicon contents of anodes and failures due to corrosion
in groups of aluminum condensers classified with respect to anode composition

leakage current of the 99.1 per cent aluminum was about 3 micro-
amperes per sq. cm., or nearly six times that of the 99.6 per cent
material at the formation potential of 60 volts.

In the matter of life, however, the purer metals seem to be more
readily attacked by agencies capable of causing electrolytic corrosion.

This is illustrated by the performance of groups of condensers having anodes of different compositions as represented in Fig. 9. This curve shows the percentage of the cells in each group affected by corrosion in relation to the amount of silicon in the anode aluminum. It will be noted that the group of condensers with anodes of the purest metal (that is, least silicon) gave the least satisfactory results.

THE NEGATIVE ELECTRODE

The negative electrode consists of five rectangular flat plates, having a combined useful surface area about 35 per cent of the total positive surface. The negative plates or cathodes are of aluminum, but they do not have a film formed on them because their sole function is to provide contact with the condenser fluid. In an ammonium borate electrolyte, such as is used in these condensers, there are a number of other materials, including tin and carbon which can be used for the negative electrodes.

However, aluminum was chosen because it is light, relatively strong, easily worked and mounted, and can be cleaned by the same process used to clean the positive plate metal. A question might properly be raised as to the use of an aluminum negative electrode, particularly one having less area than the positive, because the formation of a film on the negative electrode will result in a reduction of the electrostatic capacity of the cell.

In normal operation with aluminum negatives there is a tendency for a film to form, even though the condenser is operated on direct-current circuits, because the negative electrode is an anode during the interval that the condenser discharges. However, this disadvantage with respect to the use of aluminum cathodes is overcome by making these plates of metal, which is really a rich aluminum alloy, containing enough other substances such as silicon to impede the formation of a film on its surface.

With material containing less than 99 per cent aluminum it is possible to have as much as 3.5 amperes a.c. in the condenser circuit or an alternating-current density of about 1 milliamp. per sq. cm. of negative plate surface without forming sufficient film on the negative plates to affect the capacity of the cell.

PREVENTION OF CONTAMINATION IN MANUFACTURE AND INSTALLATION

The initial formation of the film on the positive electrodes is carried out by chemical cleaning and electrochemical formation processes, in which the purity of the materials used as well as the composition of

the electrodes is of importance. Because of the delicate nature of the film and the desirability of keeping it clean, the electrodes are designed so that in the manufacture, packing and installation of the condenser it is unnecessary to touch either the positive or the negative plate surfaces after the film is formed.

The fluid in which the condensers operate is shipped in sealed glass containers to prevent contamination, and the routine to be followed in the installation of the condensers emphasizes the need for cleanliness on the part of the installer. However, the design
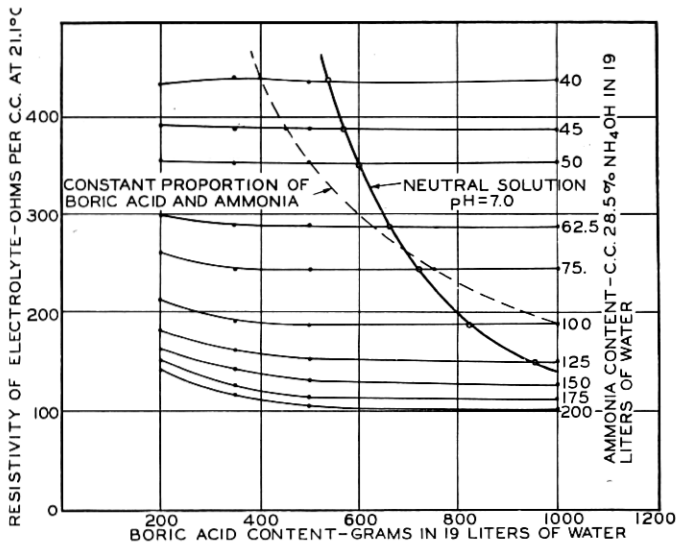

FIG. 10—Specific resistance chart of ammonium borate electrolyte

of the condenser and the method of supplying the condenser fluid have been arranged so that satisfactory installations can be made with ordinary skill and simple precautions.

THE COMPOSITION OF THE ELECTROLYTE

The electrolyte or condenser fluid as the solution is called is a mixture of ammonia, boric acid and water. A chart showing the specific resistance of different ammonium borate electrolytes is shown in Fig. 10. Two curves on this chart illustrate an interesting characteristic of these solutions. The heavy solid curve shows the neutral ammonium borate solutions, that is, those having a hydrogen ion concentration of 10^{-7} mols per liter.

This curve was determined colorimetrically with suitable indicators against standard solutions, and was checked by measurements with

the hydrogen electrode. The dotted curve shows different dilutions for the same proportion of ammonia and boric acid. Since these curves intersect it is evident that the acidity of an ammonium borate solution decreases with dilution, and acid solutions may become alkaline by the addition of sufficient water.

Within the ranges of compositions and concentrations shown, it will also be noted from the set of approximately horizontal full line curves that the specific resistance of the electrolyte is practically independent of the boric acid content. That is, within these limits, the conductivity of the solution is substantially determined by the ammonia content, the amount of boric acid in the electrolyte affecting principally the degree of acidity or alkalinity of the solution.
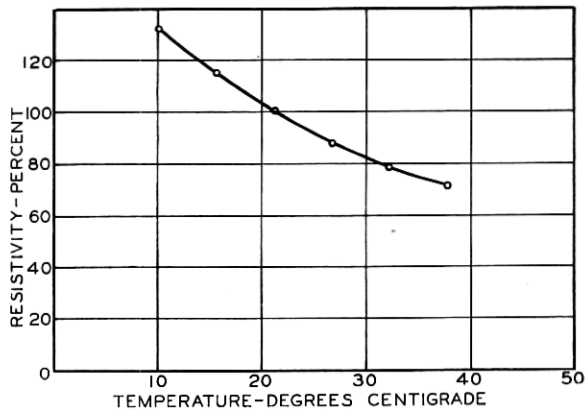

FIG. 11—Effect of temperature on the resistivity of ammonium borate electrolyte

The specific resistance of the solution is, of course, affected by heat and decreases with increasing temperature, as shown graphically in Fig. 11. In this figure the specific resistance in per cent of the specific resistance at 21.1° C. is plotted against the temperature of the electrolyte.

In the selection of a suitable electrolyte for a condenser the choice is influenced by the life of the solution, the effect of the specific resistance of the electrolyte on the electrical characteristics of the cell, and the susceptibility of the electrodes to corrosion in the solution.

The life of the solution, as has been explained, is determined by the rate at which it becomes saturated with aluminum hydroxide. In general, the lower the specific resistance of the solution, the more quickly does aluminum hydroxide form. On this basis the advantage of a high-resistance electrolyte is obvious.

But a limit is reached beyond which increases in specific resistance produce objectionable additions to the electrical impedance of the condensers, because of the high internal resistance set up in the cells.

In a condenser, as shown in Fig. 6 at room temperatures of about 25° C., a fluid having a specific resistance of 75 ohms per cc. will last from six months to a year without need for renewal because of the precipitation of aluminum hydroxide.

With fluid of 150 ohms per cc. the period of useful life is from one to three years, and with a 300-ohm solution is upward of five years, possibly never requiring renewal within the useful life of the cell. The rate at which the precipitate forms in a given solution is greatly accelerated at elevated temperatures and at 40° C., for example, the solution remains free from a white precipitate only about one third as long as at 25° C.

With respect to the effect of the acidity or alkalinity of the solution on the operation of aluminum condensers the difference is not readily distinguishable. Films can be formed and cells can be operated both in acid and alkaline electrolytes, and the electrical characteristics, except for resistance effects due to different solution conductivities, are essentially the same in both kinds of electrolyte. Somewhat better results, with respect to corrosion of electrodes have been obtained, however, with alkaline solutions, particularly under unfavorable operating conditions.

The Relation between Voltage of Film Formation and Operating Voltage

Electrolytic condensers, used on circuits associated with storage batteries, must be capable of operating at potentials throughout the range of voltage variations due to charging and discharging the batteries. Both the 24-volt and the 48-volt type condensers described can be used in circuits up to 140 per cent of their normal voltage, provision for this variation being made by the initial formation of a film to a potential somewhat above the maximum operating value.

After a condenser is connected in service the excess thickness of film is removed slowly by the chemical action of the electrolyte, because the film on the anode is maintained only at a thickness corresponding to the operating voltage. Ordinarily, therefore, the capacities of these condensers increase from their initial values, and stabilize at new values depending upon the maximum potential in the cycle of operating-voltage variations.

Capacity and Resistance Characteristics

The capacity and resistance characteristics plotted against frequency for a condenser of the type illustrated in Fig. 6, with a film formed to 46 volts d.c. are shown in Fig. 12. Curves No. 1 show the values
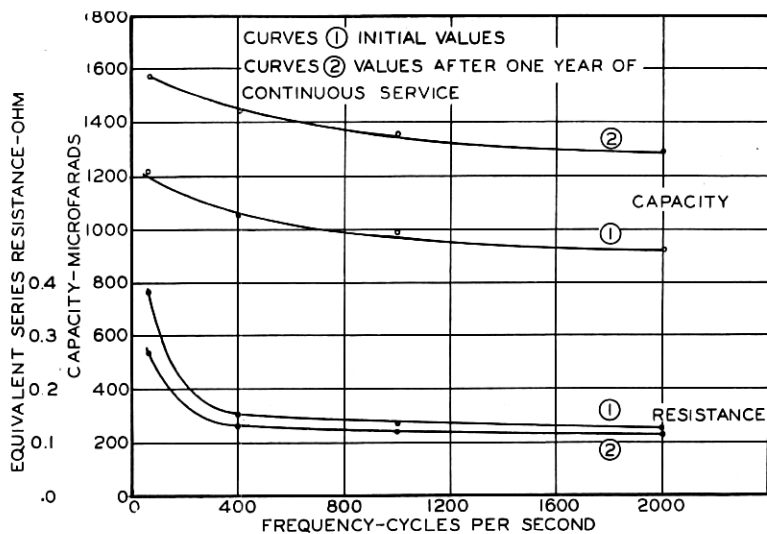

Fig. 12—Effect of frequency on capacity and resistance of an aluminum condenser formed to 46 volts and operated at 28 volts
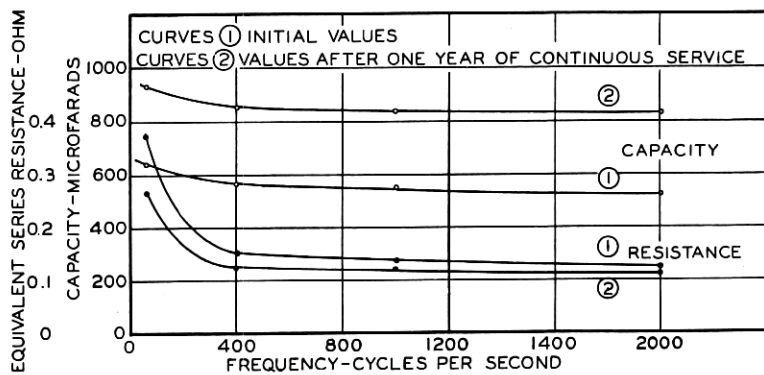

Fig. 13—Effect of frequency on capacity and resistance of an aluminum condenser formed to 100 volts and operated at 66 volts

measured at the time the condenser was put in service, and curves No. 2 show the values after one year of continuous service on a 28-volt battery with maximum voltage of 32. A second set of curves for a similar condenser formed to 100 volts and operated on a 66-volt battery, maximum 75, are shown in Fig. 13.

It will be noted that the capacities of the condensers decrease with increasing frequency. While there is a slight decrease in the unit-area capacity of films that accompanies a rise of frequency [7] this drooping characteristic is due principally to the corrugated shape of the plates on which the film is formed. The resistance through the electrolyte from the negative electrode to the film at the mouth of a "U" shaped corrugation, is less than that to the portion of the film at the bottom of the "U."

Thus, as the frequency increases, the alternating-current density at the mouth of the corrugations increases, while that in the trough decreases, resulting in a decrease of the effective capacity of the unit. The change in capacity due to frequency is greater in con-
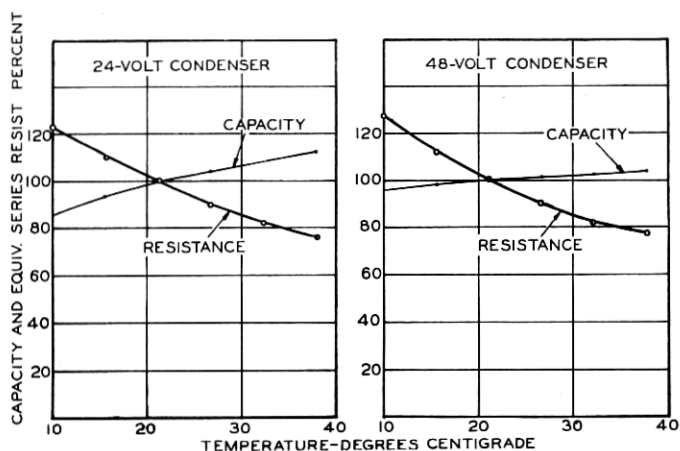

FIG. 14—Effect of temperature upon capacity and equivalent series resistance of 24-volt and 48-volt condensers at 1,000 cycles

densers with high-resistance electrolytes, and is more pronounced in the case of low-voltage films. The series resistance of the condensers is also observed to fall quite rapidly as the frequency is increased. This is due to the inverse proportionality between frequency and the component of the total condenser resistance, representing dielectric loss.

Since the change in capacity with frequency is caused by the difference at the crest and in the trough of the corrugations of the ratios of unit-area capacity to associated electrolyte resistance, changes in electrolyte resistance, caused by variations in temperatures, also influence the effective capacity of the cells.

The temperature effect is particularly noticeable at high frequencies,

[7] De Bruyne and Sanderson, *Trans. Faraday Soc.*, **23**, 42 (1927).

and, as in the case of the change of capacity with frequency, is more pronounced in condensers with low-voltage films. In Fig. 14 the effect of temperature on the electrical characteristics, at 1,000 cycles for 24-volt and 48-volt condensers, is shown. Here the change in resistance is due to the negative temperature coefficient of the electrolyte which, with increasing temperature, causes a reduction in that component of the total condenser resistance representing the resistance of the electrolyte.

In the normal adaptations of these condensers in low-pass electric wave-filters, the inherent changes in capacity and resistance with frequency and temperature cause no serious engineering difficulties. The limitations imposed by these variations are more than offset by the advantages of the corrugated structure in the matter of compactness and simplicity of design.

Corrosion of the Condenser Anodes

Notwithstanding the care taken in the manufacture and installation of condensers, there remains some possibility that the positive electrode will be attacked by corrosion. This corrosion may make its appearance as a gray growth or pitting on the surface of the anodes, or on the anode supports where they extend through the electrolyte. It is usually accompanied by the deposit of a granular or finely divided gray substance, probably aluminum oxide, which collects in the bottom of the condenser jar. Corrosion may occur shortly after a condenser is put in service or months can elapse before it appears.

In cases where corrosion has occurred, provided proper materials were used in the manufacture of the condenser, it has been noticed that the electrical properties of the cells were not seriously impaired. Such units have often continued to perform satisfactorily from a circuit standpoint for a number of years after the electrodes were attacked, even though the mechanical structure of the electrodes was damaged and weakened.

The long life that can be obtained from a corroded condenser under these circumstances is due in part to the tendency for areas affected to heal and restore the condenser to normal conditions. This indicates that the influence responsible for corrosion dissipates itself or it may be carried away from the corroded area by some of the products of the action to lie inert in the bottom of the cell. A number of spots on aluminum anodes have been observed, where the attack on the metal has ceased and a film has formed over the affected surface.

The leakage current of a condenser increases substantially when

corrosion occurs, going up in some cases 20 or 30 times, but this current again decreases and approaches the original value. The capacity likewise increases when corrosion occurs, but this merely lowers the impedance of the condenser which, in most cases, is not objectionable. The performance of a condenser that has corroded and continued to operate satisfactorily is shown in Fig. 15. The curves on the chart show how the leakage current, capacity and resistance varied during continuous operation on a 65-volt d.c. circuit over a period of two years, both before and after the anodes were attacked by corrosion.
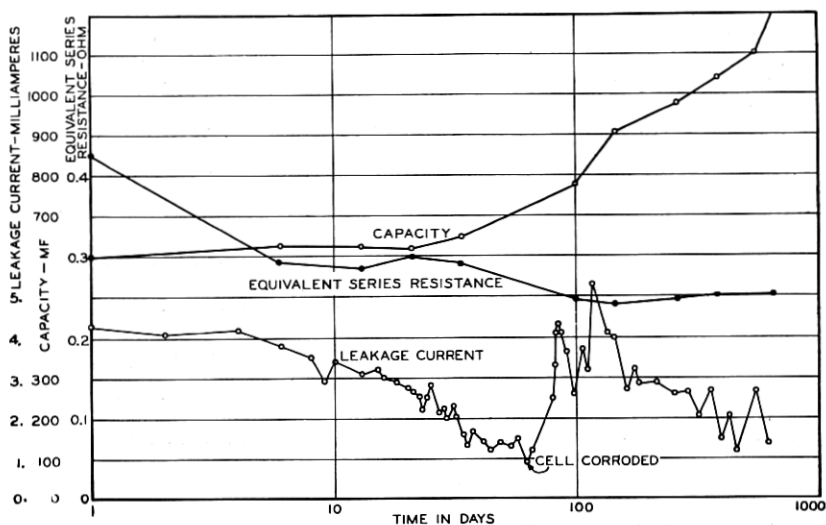

FIG. 15—The performance of a condenser, the anodes of which were attacked by corrosion after 62 days of operation at 65 volts direct current

Under certain conditions it is possible for the products of corrosive action to cause short circuits within a condenser, not by bridging from the positive to the negative plates because the corrosion product, aluminum oxide, is a non-conductor, but by accumulating between the plates and forcing the positive plates out of position into contact with the negative.

Also if corrosion occurs on the positive terminals eating through the supports one of the plates may drop and cause a short circuit. These possibilities of trouble are minimized by suitable design, and can be cleared up when they occur by removing the electrodes from the solution and repositioning or removing the deranged anode plates.

Because of the tendency for the vigor of the corrosive attack on aluminum anodes to decrease as the action continues and because the cell will continue to operate satisfactorily from an electrical standpoint, the best practice for condensers affected by corrosion is to leave them alone unless it is necessary to clear a short circuit due to a buckled plate or a severed anode support. Several cases have been reviewed where condensers are continuing to operate without maintenance, though corrosion was experienced nearly four years ago.
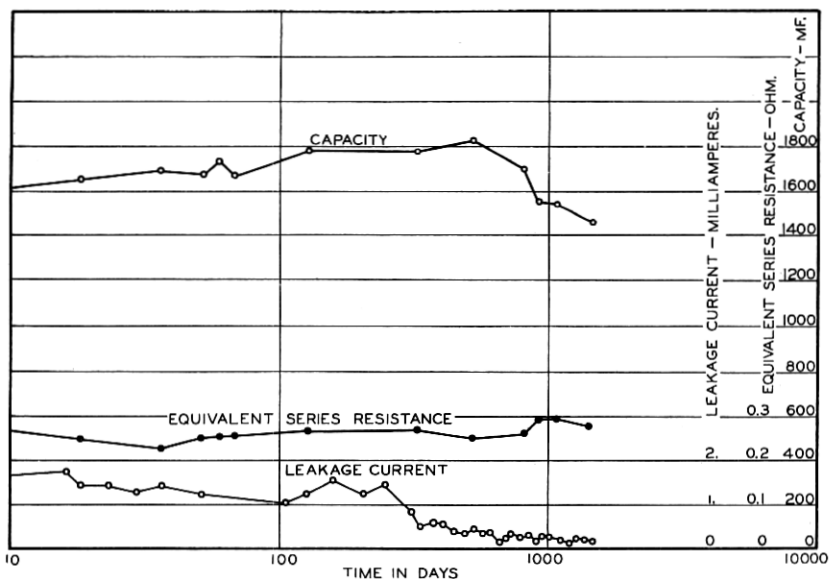

FIG. 16—Performance of a normal condenser operating continuously at 28 volts, direct current

THE LIFE OF ALUMINUM CONDENSERS

With respect to the life of normal aluminum condensers, a number of cells have been on trial in actual service installations for more than five years, and several have been operating under test conditions for about eight years. In general, after the capacity of a condenser has stabilized at the value corresponding to the operating voltage, the cell continues to operate at a comparatively constant but slowly decreasing capacity due, perhaps, to a gradual thickening of the film with age.

The leakage current also decreases with length of service. The capacity, resistance and leakage current of a typical condenser operated for several years is shown in Fig. 16. In this case the fluid had

never been renewed since the condenser was installed and after the period of service shown the electrolyte was still free from the white precipitate of aluminum hydroxide.

What the ultimate life of a condenser of this type will be remains for future determination. Judging from the appearance of cells that have operated for six and seven years there would seem to be years more of useful service to be rendered by these cells.