

TABLE 12. HIGH-STABILITY FILM RESISTORS; AXIAL LEADS; DATA FOR MIL "RD" SERIES\*

Characteristic	Watts							
	$\frac{1}{20}$	$\frac{1}{10}$	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{3}{4}$	1	2
	Voltage Rating							
B	—	—	—	—	—	—	500	750
D	—	—	200	300	350	500	—	—
C,E	200	200	250	300	350	—	500	—
Characteristic	Characteristic							
	B		C		D		E	
Maximum temp (°C):								
Full load			70	125	70	125		
0 load			150	175	165	175		
Life-test resistance change (max)			±1%	±0.5%	±1%	±0.5%		
Resistance-temperature characteristic (max ppm/°C)			±500	±50	+200	±25		
Moisture resistance test (max change)			±1.5%	±0.5%	±1.5%	±0.5%		

Resistance Values: E96 series (E48 preferred): 1% tolerance;  
E192 series (E96 preferred) 0.5%, 0.25%, 0.1% tolerances.

\*Uninsulated commercial versions have lower temperature limits and greater resistance change. Color coding is the same as previously indicated for composition resistors.

TABLE 13. POWER-TYPE FILM RESISTORS, UNINSULATED

	Axial-Lead and MIL "RD" Series			Commercial Tab-Terminal Styles				
Watts	2	4	8	7	23	25	55	115
Voltage rating	350	500	750	525	1380	2275	3675	7875
Critical resistance (kilohms)	61	62	70	39	83	208	245	540
Maximum temperature (°C):								
Full load	25	25	25	25	25	25	25	25
0 load	235	235	235	235	235	235	235	235
	275 (MIL)	275 (MIL)	275 (MIL)					

Life-test resistance change: ±5% maximum  
Resistance-temperature characteristic: ±500 ppm/°C maximum  
Moisture resistance test: ±3% maximum change  
Resistance values: E12 series (approx. for MIL)

Tolerances: Axial lead:  $\frac{1}{2}\%$ , 1%, 2%, (MIL "RD" Series) 5%, 10%.

Tab lead: 1%, 2%, 5%, 10%, 20%.

where the frequency of adjustment is high. They may be operated manually by human effort or mechanically served by machine. Potentiometers are designed with a long mechanical life in view, generally from 10 000 to 100 000 cycles, with certain types having life capabilities in the millions of

cycles. A cycle, or excursion, consists of wiper traverse from one limit of travel to the other limit and back.

Trimmers differ from potentiometers in that they are designed to be adjusted infrequently, sometimes only once, and normally exhibit greater setting

bility once set. Their employment eliminates the use of expensive precision related components and provides an easily retunable vehicle to compensate for drift or aging in related parts. Normal life designs are rated at approximately 200 excursions. Some typical trimmer characteristics are listed in Table 14.

TABLE 14. TYPICAL CHARACTERISTICS OF 1/2-INCH TRIMMERS

	Resistance Ranges	Typical Resistance Tolerance	Wattage Rating	Rotational Life	Temperature Coefficient of Resistance
Wirewound	10 $\Omega$ - 50 k $\Omega$	$\pm 5\%$	1 W at	200	$\pm 50$ ppm/°C
Cermet	50 $\Omega$ - 2 M $\Omega$	$\pm 10\%$	1 W at 70°C	200	$\pm 100$ ppm/°C
Conductive Plastic	50 $\Omega$ - 2 M $\Omega$	$\pm 10\%$	0.33 W at 50°C	1 x 10 <sup>6</sup>	$\pm 500$ ppm/°C
Carbon Composition	100 $\Omega$ - 2.5 M $\Omega$	$\pm 20\%$	0.33 W at 50°C	200	$\pm 10\%$ °C*

\*Temperature characteristic.

Unlike potentiometers and trimmers, whose primary function is to control voltage, the rheostat is basically a current-controlling device. Rheostats are made in much the same manner as potentiometers and trimmers, but with more attention paid to wiper current-carrying ability and generally higher power ratings. Some rheostats are wirewound tubular ceramic power resistors with a track of exposed wire to allow for the adjustable feature. The wiper is in the form of a dimpled clamp band that is screw-tightened at the desired setting. Due to the heat generated by these units, care should be exercised in the circuit location.

Wattage ratings of adjustable resistors apply only when all the resistance is in the circuit. To avoid overloading any section, never exceed the maximum rated current based on total resistance.

## Types of Adjustable Resistors

**Wirewound Resistors-** Wirewound resistor elements are made by winding a very fine resistance wire precisely around a mandrel. Most resistance wire is made from a nickel-chrome alloy with other elemental additives to enhance its electrical characteristics.

Wirewound adjustable resistors exhibit superior independent linearity characteristics, and it is for this reason that they are frequently specified for direct motion controls. Precision wirewounds are available with independent linearity ratings as low as 0.1%. They are very stable over a wide range of operating temperatures. Panel controls and precision potentiometers are recommended for normal operating temperature ranges from -65° to +125°C, and most trimmers will perform satisfactorily from -55° to +150° C. Temperature coefficients of resistance as low as  $\pm 20$  ppm/° C are available.

Wirewound elements, with rare exceptions,

change value in steps as the wiper traverses each individual winding. Resolution may be improved by using multiturn adjustable resistors. This type of construction increases the winding length and decreases incremental resistance steps from one winding to the next.

Wirewound resistive elements are usually not

suitable for frequency-sensitive rf circuits because of inductive and capacitive effects. They are impractical above a resistance value determined by the winding space available and the smallest resistance wire that can be space-wound. If infinite resolution is required, then a cermet or composition element must be substituted.

**Cermet-Element Resistors-Cermets** are a mixture of fine metal-oxide or precious-metal particles and glass in a viscous organic vehicle. This paste is screened onto a ceramic substrate and fired at vitrifying temperatures.

Cermet adjustable resistors are designed for low to moderate adjustment life. They feature infinite resolution and are generally available having temperature coefficients of resistance of  $\pm 100$  ppm/°C. Sheet resistivities\* are available from one ohm per square (1  $\Omega/\square$ ) to one megohm per square (1 M $\Omega/\square$ ). Ultimate resistance values are limited by substrate geometry.\*\*

**Carbon Composition Resistors-A** mixture of carbon powders and a binder is molded under heat and pressure into a solid mass. In some constructions, the carbon composition is molded at the same time as the plastic substrate. This process is called comolding.

Carbon composition adjustable resistors are the least expensive and most common type of potentiometer for general electronics use. Their low noise makes them ideal for use in live audio controls.

In addition to a linear rotation-vs-resistance

\*Sheet resistivity ( $\Omega/\square$ ) is the resistance of a square sheet of material. It is independent of the units of length used because the resistance increases with length but decreases with width.

\*\*For material of given volume resistivity  $\rho$  (ohm-meter), sheet resistivity given by  $\rho/d$  will increase as depth  $d$  is decreased.

characteristic, composition elements can have a wide range of nonlinear output curves. Standard logarithmic curves (tapers) are used as volume controls for radio, tv, etc.

Temporary resistance changes up to  $\pm 10\%$  can be expected when these devices are operated near the extreme limits of a temperature range of  $-55^{\circ}\text{C}$  to  $+120^{\circ}\text{C}$ . Their use is not recommended for precision controls or in varying hostile environments.

**Conductive** Plastic-Conductive plastic is an ink formulated from carbon, other proprietary materials, a resin, and solvent. It is applied to a substrate by screening, dipping, or comolding. The low curing temperature (150 to  $300^{\circ}\text{C}$ ) of the ink allows it to be applied to a wide variety of substrates.

Conductive-plastic potentiometers are most notable for their high rotational life, and they are used most frequently as machine-operated servo-controls. Another desirable feature is their low noise or output smoothness.

Resistance ranges in sheet resistivities of up to  $50\,000\ \Omega/\square$  are available with temperature coefficients of  $\pm 500\ \text{ppm}/^{\circ}\text{C}$ . As with cermets, ultimate resistance values are limited by substrate geometry.

## Terminal Identification

Industry standards have been developed for identification of potentiometer terminals. Most potentiometer terminals are either numbered or color coded as follows:

- |          |  |
|----------|--|
| 1 Yellow | Always the counterclockwise element limit. |
| 2 Red    | Wiper (or collector).                      |
| 3 Green  | Always the clockwise element limit.        |

For rotary potentiometers, clockwise is always defined by viewing the specified mounting end of the potentiometer.

## Mounting Characteristics

Potentiometers usually must be accessible from the outside of a product, and they are often mounted on a panel by means of a threaded bushing. Most precision potentiometers are manufactured with both bushing and servo-mount options. Servo-mount units are secured by servo clamps to assure precise shaft alignment.

Trimmers are usually not accessible from outside the instrument. Most are circuit-board mounted by their terminals and are small in size to conserve space.

## CAPACITORS-DEFINITIONS

**Dielectric:** A dielectric is a medium that can withstand high electric stress without appreciable conduction. When such stress is applied, energy in the form of an electric charge is held by the dielec-

tric. Most of this stored energy is recovered when the stress is removed. The only perfect dielectric in which no conduction occurs and from which the whole of the stored energy may be recovered is a perfect vacuum.

**Relative Capacitivity:** The relative capacitivity or relative permittivity or dielectric constant is the ratio by which the capacitance is increased when another dielectric replaces a vacuum between two electrodes.

**Dielectric Absorption:** Dielectric absorption is the absorption of charge by a dielectric when subjected to an electric field by other than normal polarization. This charge is not recovered instantaneously when the capacitor is short-circuited, and a decay current will continue for many minutes. If the capacitor is short-circuited momentarily, a new voltage will build up across the terminals afterward. This is the source of some danger with high-voltage dc capacitors or with ac capacitors not fitted with a discharge resistor. The phenomenon may be used as a measure of dielectric absorption.

**Tangent of Loss Angle:** This is a measure of the energy loss in the capacitor. It is expressed as  $\tan\delta$  and is the power loss of the capacitor divided by its reactive power at a sinusoidal voltage of specified frequency. (This term also includes power factor, loss factor, and dielectric loss. The true power factor is  $\cos(90 - \delta)$ .)

**Insulation Resistance:** This is a measure of the conduction in the dielectric. Because this conduction takes a very long time to reach a stable value, it is usually measured after 2 minutes of electrification for nonelectrolytic types and 3 minutes for electrolytics. It is measured preferably at the rated working voltage or at a standardized voltage.

The insulation resistance is usually multiplied by the capacitance to give the ohm-farad value, which is the apparent discharge time constant (seconds). This is a figure of merit for the dielectric, although for small capacitances a maximum value of insulation resistance is usually also specified.

In electrolytics, the conduction is expressed as leakage current at rated working voltage. It is calculated as  $\mu\text{A}/\mu\text{FV}$ , which is the reciprocal of the ohm-farad value. In this case, a maximum value of leakage current is specified for small capacitances.

**Leakage Current:** The current flowing between two or more electrodes by any path other than the interelectrode space is termed the leakage current, and the ratio of this to the test voltage is the insulation resistance.

**Impedance:** Impedance is the ratio of voltage to current at a specified frequency. At high frequencies, the inductance of leads becomes a limiting factor, in which case a transfer impedance method

may be employed. This then measures the impedance of the shunt path only.

**DC or AC Capacitor:** A dc capacitor is designed to operate on direct current only. It is normally not suitable for use above 200 volts ac because of the occurrence of discharges in internal gas bubbles (corona). An ac capacitor is designed to have freedom from internal discharges and low tangent of loss angle to minimize internal heating.

**Rated Voltage and Temperature:** The rated voltage is the direct operating voltage that may be applied continuously to a capacitor at the rated temperature.

**Category Voltage and Temperature:** The category voltage is the voltage that may be applied to the capacitor at the maximum category temperature. It differs from the rated voltage by a derating factor.

**Ripple Voltage:** If alternating voltages are present in addition to direct voltage, the working voltage of the capacitor is taken as the sum of the direct voltage and the peak alternating voltages. This sum must not exceed the value of the rated voltage.

In electrolytics, the permissible ripple may be expressed as a rated ripple current.

**Surge Voltage:** This is a voltage above the rated voltage which the capacitor will withstand for a short time.

**Voltage Proof Test (Dielectric Strength):** This is the highest possible voltage that may be applied without breakdown to a capacitor during qualification approval testing to prove the dielectric. The repeated application of this voltage may cause failure.

**Forming Voltage (Electrolytics):** The voltage at which the anodic oxide has been formed. The thickness of the oxide layer is proportional to this voltage.

**Burnout Voltage (Metallized Types):** The voltage at which metallized types burn out during manufacture.

**Self-Healing (Metallized Types):** A momentary partial discharge of a capacitor resulting from a localized failure of the dielectric. Burning away the metallized electrodes isolates the fault and effectively restores the properties of the capacitor. The self-healing action is also called "clearing."

**Equivalent Series Resistance (ESR):** Equivalent series resistance (ESR) is a single resistive value that represents the sum of the ac losses (due to the leads, electrode plates, and junction terminations), the resistive losses due to leakage currents, and the resistive losses due to the inherent molecular polar-

ization dielectric absorption factors of the base dielectric material.

**Volt-Ampere Rating (VA):** This is the reactive power in a capacitor when an ac voltage is applied.  $VA \cos\theta$  gives the amount of heat generated in the capacitor. Since the amount of heat that can be dissipated is limited, the VA must also be limited and in some cases a VA rating is quoted. (Note that  $\cos\theta = \cos(90 - \delta) \approx \tan\delta$ , when  $\delta$  is small.)

**Scintillation:** Minute and rapid fluctuations of capacitance formerly exhibited by silvered mica or silvered ceramic types but overcome by modern manufacturing techniques.

**Corona Discharge:** Partial discharge of a capacitor due to ionization of the gas in a bubble in the dielectric. On ac or pulse operation, this may occur in dielectric stressed above 200 volts and is a major cause of failure. On dc, such discharges are very infrequent and normally are not a cause of failure.

## CLASSES OF CAPACITORS

Modern electronic circuits require the smallest possible capacitors, which are usually made with the thinnest possible dielectric material since they are for operation at low voltages. There are three broad classes of capacitors.

(A) Low-loss capacitors with good capacitance stability. These are usually of mica, glass, ceramic, or a low-loss plastic such as polypropylene or polystyrene.

(B) Capacitors of medium loss and medium stability, usually required to operate over a fairly wide range of ac and dc voltages. This need is met by paper, plastic film, or high-K ceramic types. The first two of these may have electrodes of metal foil or electrodes of evaporated metal which have a self-healing characteristic.

(C) Capacitors of the highest possible capacitance per unit volume. These are the electrolytics, which are normally made either of aluminum or tantalum. Both of these metals form extremely thin anodic oxide layers of high dielectric constant and good electrical characteristics. Contact with this oxide layer is normally by means of a liquid electrolyte that has a marked influence on the characteristics of the capacitor. In solid tantalum, the function of the electrolyte is performed by a manganese-dioxide semiconductor.

## PLASTIC FILM CAPACITORS

Advances in organic chemistry have made it possible to produce materials of high molecular weight. These are formed by joining together a number of basic elements (monomers) to produce a polymer. Some of these have excellent dielectric characteristics.

Physically, they can be classified as thermoplastic or thermosetting. In the former case, the molecule consists of long chains with little or no branching, whereas in the latter the molecules are crosslinked. Thermosetting materials have no clearly defined melting point and are usually hard and brittle, making them unsuitable for the manufacture of plastic films. A cast film is usually amorphous, but by extrusion, stretching, and heat treatment, oriented crystalline films are produced with good flexibility and dielectric characteristics.

The electrical properties of the plastics depend on

the structure of the molecule. If the molecule is not symmetrical, it will have a dipole moment giving increased dielectric constant. On the other hand, the dielectric constant and  $\tan\delta$  are then dependent on frequency. Generally speaking, nonpolar materials have electrical characteristics that are independent of frequency, while polar materials exhibit a decrease in capacitance with increasing frequency, and  $\tan\delta$  may pass through a maximum in the frequency range.

Figs. 7, 8, and 9 show some characteristics of several types of capacitors. At the present time, two

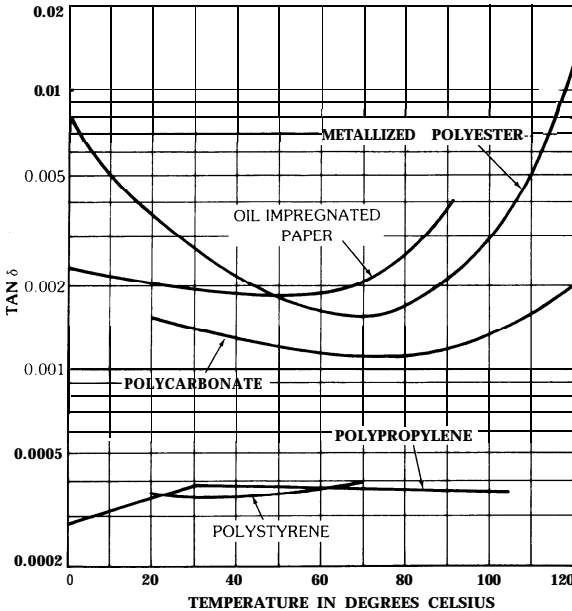


Fig. 7. Variation of  $\tan\delta$  with temperature for various plastic films compared with oil-impregnated paper.

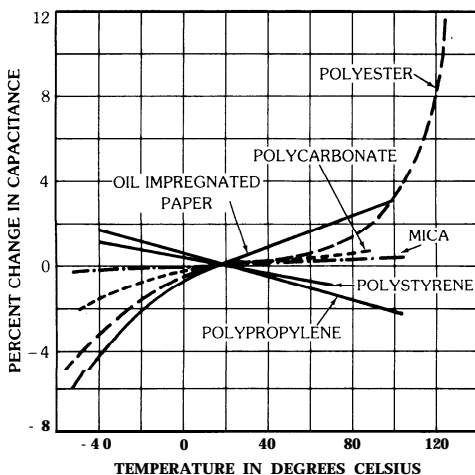


Fig. 8. Typical capacitance characteristics of various capacitors as a function of temperature. Measured on 0.1-microfarad capacitors at 1000 hertz.

classes of plastic film capacitors are recognized.

(A) *Polystyrene and Polypropylene Capacitors.* Polystyrene and polypropylene are nonpolar plastics that have excellent electrical characteristics which are independent of frequency.

(B) *Polyester Films.* Strictly speaking, these are the polyethylene terephthalates (Mylar, Melinex, Hostaphan), but the polycarbonates are now included in this group because they have similar electrical characteristics.

Plastic films for capacitor manufacture are usually of the oriented crystalline type because of their good combinations of characteristics. One important feature of some of these films is that they tend to shrink back to their original shape after being heated. This fact is sometimes exploited in manufacturing the capacitor.

Moisture usually has little effect on the dielectric properties of plastic films, and capacitors made from them require less protection than paper or mica types. This, together with simple processing, has permitted them to be mass-produced at relatively low cost.

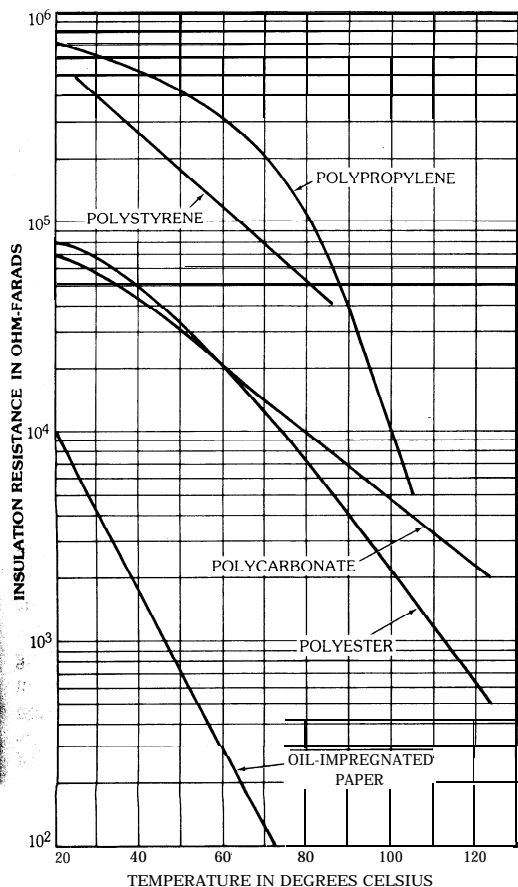


Fig. 9. Variation of insulation resistance with temperature for various plastic films compared with the resistance variation for oil-impregnated paper.

The electrical characteristics of capacitors made with these materials depend on the construction employed. The resistance of metallized electrodes and the shape and method of connection to the unit are particularly important.

Many plastic materials are being used in the manufacture of capacitors for which there are no internationally agreed specifications. In this case, it is necessary to obtain the relevant data from the manufacturer. There is no doubt that in the future the range of plastic film capacitors will be considerably extended.

### Polystyrene Film Capacitors With Foil Electrodes

Polystyrene has excellent electrical characteristics. The film employed is of the oriented crystalline type, which makes it flexible and suitable for forming into thin films. On heat treatment, the film shrinks considerably, and this is used in the manufacturing process to obtain capacitance stability.

The film is affected by greases and solvents, and care must be taken both in manufacture and in use to ensure that capacitors do not come into contact with these materials.

The power factor of polystyrene is low over the whole frequency range, but the resistance of the electrodes may result in an increase of power factor at high frequencies in the larger values, as shown in Table 15.

TABLE 15. POWER FACTOR OF POLYSTYRENE AT VARIOUS FREQUENCIES

Frequency (hertz)	Nominal Capacitance (pF)			
	up to 1 000	1000 to 10 000	10000 to 100 000	Above 100 000
800	0.0003	0.0003	0.0003	0.0003
10 000	0.0003	0.0003	0.0003	0.001
100 000	0.0003	0.0005	0.001-0.003	—
1 000 000	0.001	0.002	0.005-0.02	—

### Polyester Film Capacitors With Foil Electrodes

The generic title "polyester" is usually used to apply to polyethylene terephthalate. It is a slightly polar plastic film suitable for operation up to temperatures of 125° C. Capacitors are available with foil electrodes.

### Plastic Film Capacitors With Metallized Electrodes

Plastic film capacitors with metallized electrodes have superseded metallized paper capacitors in dc applications because of superior electrical characteristics, less tendency for self-healing to occur during service, higher and more stable insulation resistance, and approximately the same space factors. Three types of film are generally used, polyethylene terephthalate, polycarbonate, and polypropylene. For some purposes these are comparable, but polypropylene has a lower loss angle, and polycarbonate has a smaller change of capacitance with temperature. Polyester and polypropylene are also available in thinner films, giving an advantage of space factor.

## ELECTROLYTIC CAPACITORS

Electrolytic capacitors (Fig. 10) employ for at least one of their electrodes a "valve metal." This

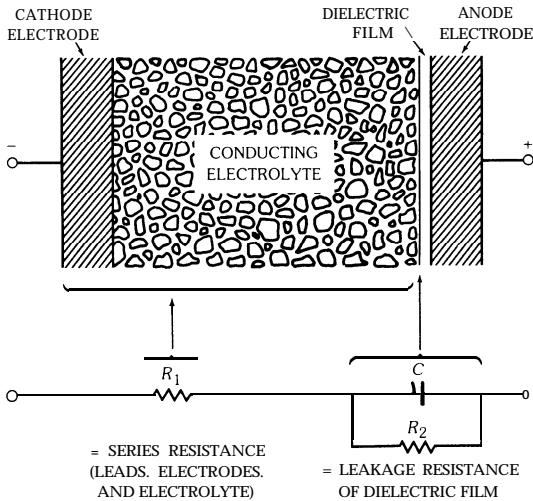


Fig. 10. Basic cell and simplified equivalent circuit for polar electrolytic capacitor.

metal, when operated in an electrolytic cell as the anode, forms a layer of dielectric oxide. The most commonly used metals are aluminum and tantalum. The valve-metal behavior of these metals was known about 1850. Tantalum electrolytic capacitors were introduced in the 1950s because of the need for highly reliable miniature capacitors in transistor circuits over a wide temperature range. These capacitors were made possible by improved refining and powder metallurgy techniques.

The term "electrolytic capacitor" is applied to any capacitor in which the dielectric layer is formed by an electrolytic method. The capacitor does not necessarily contain an electrolyte.

The oxide layer is formed by placing the metal in a bath containing a suitable forming electrolyte, and applying voltage between the metal as anode and another electrode as cathode. The oxide grows at a rate determined by the current, but this rate of growth decreases until the oxide has reached a limiting thickness determined by the voltage. For most practical purposes, it may be assumed that the thickness of the oxide is proportional to the forming voltage.

Properties of aluminum and tantalum and their oxides are shown in Table 16.

TABLE 16. ALUMINUM AND TANTALUM PROPERTIES

Metal	Density	Principal Oxide	Dielectric Constant	Thickness ( $\text{\AA}/\text{V}$ )
Aluminum	2.7	$\text{Al}_2\text{O}_3$	8	13.5
Tantalum	16.6	$\text{Ta}_2\text{O}_5$	27.6	17

The structure of these oxide layers plays an important part in determining their performance. Ideally they are amorphous, but aluminum tends to form two distinct layers, the outer one being porous. Tantalum normally forms an amorphous oxide which, under conditions of a high field strength of the oxide layer, may become crystalline. Depending on the forming electrolyte and the surface condition of the metal, there is an upper limit of voltage beyond which the oxide breaks down. The working voltage is between 25 and 90 percent (according to type) of the forming voltage at which stable operation of the oxide layer can be obtained.

To produce a capacitor, it is necessary to make contact to the oxide layer on the anode, and there are two distinct methods of doing this. The first is to use a working electrolyte that has sufficient conductivity over the temperature range to give a good power factor. There are many considerations in choosing the working electrolyte, and the choice is usually a compromise between high- and low-temperature performance. The working electrolyte also provides a rehealing feature in that any faults in the oxide layer will be repaired by further anodization.

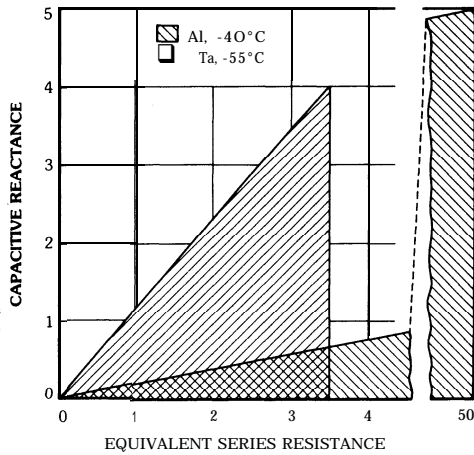
In aluminum electrolytic capacitors, the working electrolyte must be restricted to those materials in which aluminum and its oxide are inert. Corrosion can be minimized by using the highest possible purity of aluminum. This also reduces the tendency of the oxide layer to dissolve in the electrolyte, giving a better shelf life.

Tantalum, on the other hand, is very inert and therefore allows a wider choice of electrolyte. Since there is no gas evolution, better methods of sealing can be employed. The characteristics of aluminum and tantalum electrolytic capacitors are shown in Figs. 11 and 12.

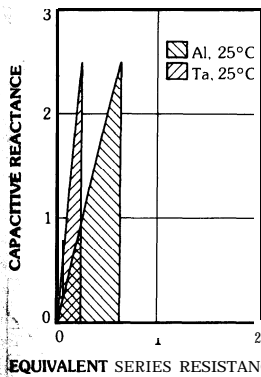
A major problem with all electrolytic capacitors is to ensure that the electrolyte is retained within the case under all operating conditions. In the aluminum capacitor, allowance must be made for gas evolution on reforming. Even the tantalum capacitor usually must employ only organic materials for sealing, and these do not provide completely hermetic sealing. All organic materials have finite moisture transmission properties, and, therefore, at the maximum category temperature the high vapor pressure of the electrolyte results in some diffusion.

An elegant solution to this problem, using a semiconductor instead of an electrolyte, was found by Bell Telephone Laboratories. The semiconductor is manganese dioxide in a polycrystalline form and has a higher conductivity than conventional electrolyte systems. This material also provides a limited self-healing feature at a fault, resulting in oxidation of the tantalum and reduction of the manganese dioxide to a nonconducting form.

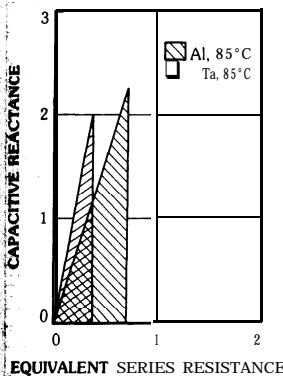
Electrolytic capacitors take many forms, and the



(A) Low temperature.



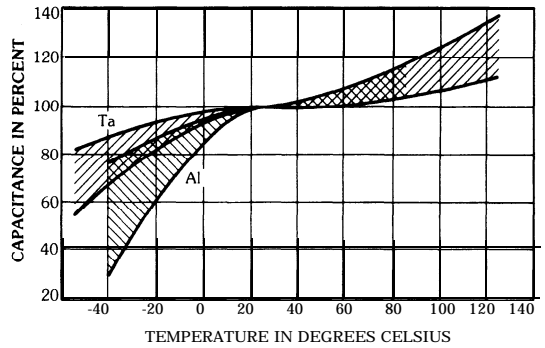
(B) Room temperature.



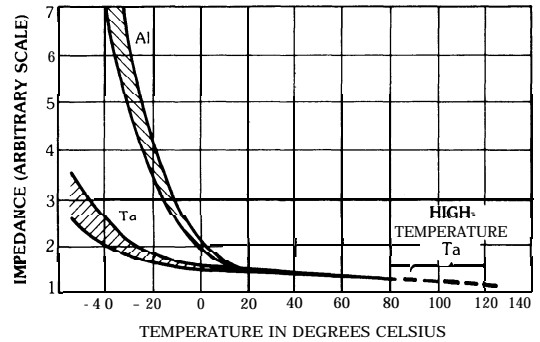
(C) High temperature.

Fig. 11. Typical 120-hertz impedance diagrams for aluminum (Al) and tantalum (Ta) plain-foil polar electrolytic capacitors of 150-volt rating.

anode may be of foil, wire, or a porous sintered body. The foil may be either plain or etched. The porous body may be made with fine or with coarse particles, and the body itself may be short and fat or long and thin. The aluminum-foil capacitor has a



(A) Capacitance.



(B) Impedance.

Fig. 12. Capacitance and 120-hertz impedance as a function of temperature for aluminum (Al) and tantalum (Ta) electrolytic capacitors.

space factor about six times better than that of the equivalent paper capacitor, whereas tantalum capacitors are even smaller and enjoy a space factor up to 20 times better.

When electrolytic capacitors are operated in series-parallel, stabilizing resistors should be used to equalize the voltage distribution. It should also be noted that, even when the case is not connected to one terminal, a low resistance path exists between it and the electrodes. The case must be insulated from the chassis, particularly if the chassis and the negative terminal are not at the same potential.

## Aluminum Electrolytics

The aluminum type is the most widely known electrolytic capacitor and is used extensively in radio and television equipment. It has a space factor about six times better than the equivalent paper capacitor. Types of improved reliability are now available using high-purity (better than 99.99%) aluminum.



Conventional aluminum electrolytic capacitors which have gone six months or more without voltage applied may need to be reformed. Rated voltage is applied from a dc source with an internal resistance of 1500 ohms for capacitors with a rated voltage exceeding 100 volts, or 150 ohms for capacitors with a rated voltage equal to or less than 100 volts. The voltage must be applied for one hour after reaching rated value with a tolerance of  $\pm 3$  percent. The capacitor is then discharged through a resistor of 1 ohm/volt.

### Tantalum-Foil Electrolytics

The tantalum-foil type of capacitor was introduced around 1950 to provide a more reliable type of electrolytic capacitor without shelf-life limitation. It was made possible by the availability of thin, high-purity annealed tantalum foils and wires. Plain-foil types were introduced first, followed by etched types. The purity, and particularly the surface purity, of these materials plays a major part in determining the leakage current and their ability to operate at the higher working voltages.

These capacitors are smaller than their aluminum counterparts and will operate at temperatures up to about 125° C (Figs. 13-15). The plain-foil types usually exhibit less variation of capacitance with temperature or frequency.

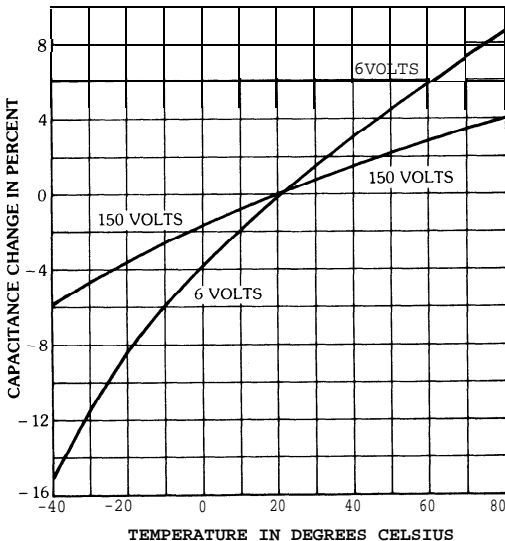


Fig. 13. Variation of capacitance with temperature for plain tantalum-foil electrolytic capacitors.

### Tantalum Electrolytics With Porous Anode and Liquid Electrolyte

The tantalum electrolytic with porous anode and liquid electrolyte was the first type of tantalum elec-

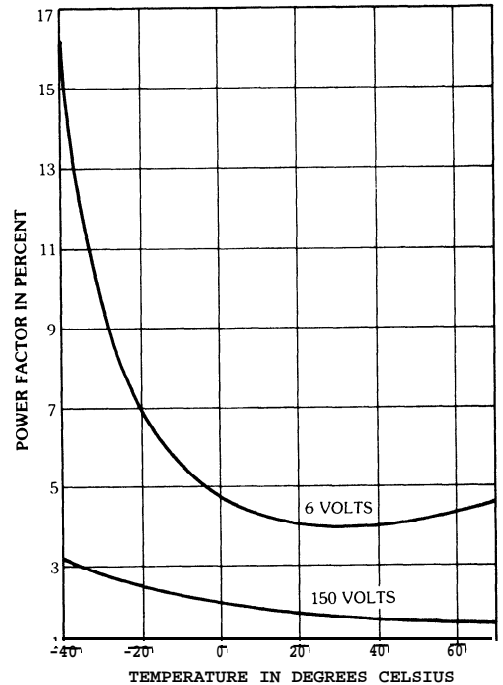


Fig. 14. Variation of power factor with temperature for plain tantalum-foil electrolytic capacitors.

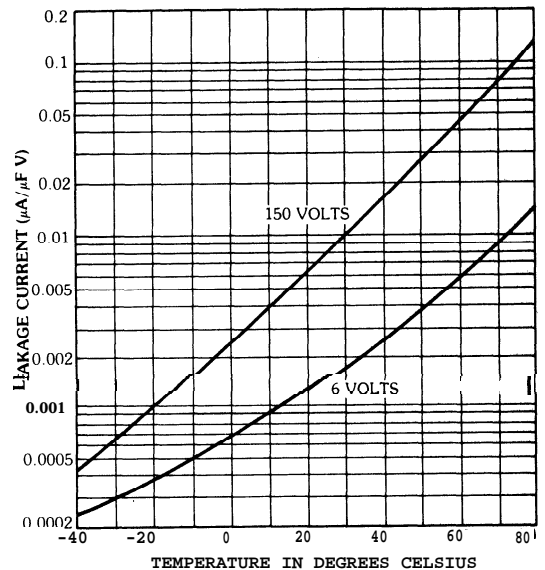


Fig. 15. Variation of leakage current with temperature for plain tantalum-foil electrolytic capacitors.

trolytic capacitor to be introduced and still has the best space factor. Types using sulphuric-acid troyte have excellent electrical characteristics up to about 70 working volts. Other types contain neutral electrolytes.