Capacitor Application and Maintenance Guide

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REPORT SUMMARY

Capacitors are energy storage devices that are widely used in many electronic and electrical applications. They provide filtering (blocking, isolation, and other functions) in both electronic and power circuits. Capacitor use in electronic circuit applications is second only to resistors.

Background

Capacitors can remain in storage for a considerable time before use. Plant personnel must have some assurance that the devices in storage will be usable or have guidance on when to remove unusable devices from inventory. Also, equipment that depends upon capacitors for proper operation can be affected by some of the same considerations used to determine capacitor capability.

Objective

- To review plant practices related to capacitors and equipment that relies on capacitors
- To understand what conditions affect capacitors in storage and, therefore, affect capacitor shelf life
- To understand conditions that affect capacitor performance
- To provide procurement and storage recommendations for capacitor users.
- To provide maintenance recommendations related to testing and condition monitoring of capacitors in operation and in storage

Approach

The project team reviewed various industry sources and literature to determine industry practices related to capacitors. In addition, plants were surveyed to identify capacitor issues and the approaches being used to deal with capacitors and equipment that uses capacitors. Capacitor performance and failure information was also reviewed.

Results

This guide discusses the various types of capacitors and their general design. The stressors that affect capacitors during storage and operation are described here. There has been limited industry and regulatory guidance provided for operating and maintaining capacitors. Research and vendor recommendations appear to be geared toward predicting capacitor operating life under design conditions. Maintenance recommendations in this document are geared toward providing as optimal life for capacitors in storage and reasonable availability of equipment that relies on capacitors. Aluminum electrolytic capacitors were the most widely used in the applications that concern plant personnel.

EPRI Perspective

The work that has been presented by vendors and others provides a fairly conservative approach to dealing with capacitors in storage. There is extensive information related to operating life estimation for capacitors in service. There is a missing link in that there is very little guidance provided for condition monitoring and what can be measured by plant personnel to detect impending capacitor failure. This missing link warrants investigation.

A study to take both naturally aged and artificially aged capacitors, compare parameters, test capacitors until failure, and take measurements to determine if failure can be anticipated would provide the industry with valuable data. The results of a program of this nature would provide a predictive maintenance tool for capacitor users.

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1 OVERVIEW OF CAPACITORS

The ability to store a charge was demonstrated by experiment in the 1700s in the Netherlands at the University of Leiden. The early term for these storage devices was “Leyden Jars,” and they were later called condensers. In the mid 1800s, Michael Faraday developed a method to explain the concept of capacitance by using electric and magnetic field lines to help visualize the charge and discharge of a capacitor. The unit of capacitance, the farad (F), is named for him.

Capacitors are energy storage devices that are widely used in electronic and electrical applications. They provide filtering and other functions in both electronic and power circuits. Capacitor use in electronic circuit applications is second only to resistors.

1.1 Fundamentals

Capacitance is a property that exists between any two electrical conductors separated by a dielectric material, such as air, a vacuum, or any material with high resistivity. When an electric potential is applied across the conductors, the charge tends to collect on one conductor in an opposite relation to the charge on the other conductor. The level of charge depends on the applied voltage, the hindrance to charge flow, and the capacitance of the system. The variation in charge flow and other characteristics are governed by the materials used in the construction of a capacitor [A.3.1, A.5.2, A.5.3].

A parallel plate capacitor (see Figure 1-1) is constructed of two thin metal plates or sheets separated by an insulating (or dielectric) material. The capacitance (C) of a typical capacitor can be expressed by the equation:

$$C= \varepsilon_0 \varepsilon A/d$$

where,

ε_0 is the permittivity of free space (8.85 pF/m)

ε is the permittivity of the dielectric

A is the area of the plates (conductors)

d is the distance between the plates (dielectric thickness)

As shown by the equation, capacitance can be made larger by:

- Increasing the dielectric constant (permittivity)
- Increasing the surface area
- Decreasing the dielectric thickness

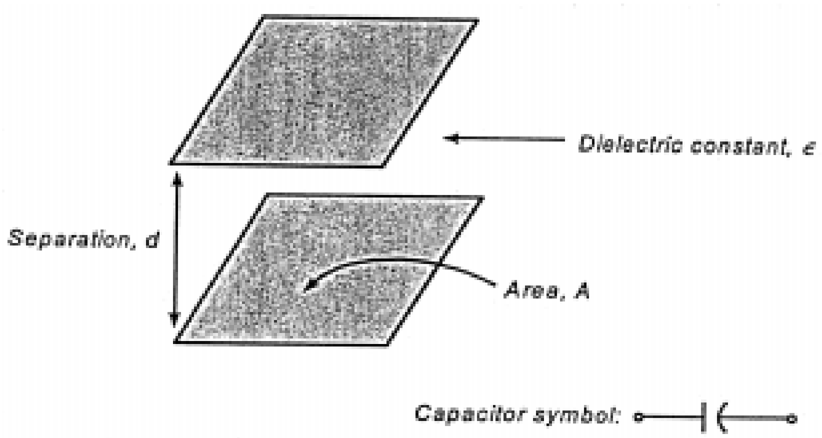


Figure 1-1
Capacitor Characteristics [A.3.1]

The capacitance doubles if the surface area doubles and the capacitance halves if the dielectric thickness is doubled.

The capacitance (C) is expressed as a ratio of the electric charge (Q) to the applied voltage (V)

$$C = Q/V$$

where,

Q = charge (coulombs), V = voltage (volts), and C = capacitance (farads)

A capacitor has a capacitance of one farad when it receives a charge of one coulomb at a potential of one volt. One farad is a very large capacitance, which is never needed in electronic circuits. Instead, capacitance often encountered in electronic circuits is in the range of the microfarad (1 μF = 10^{-6}F) and the picofarad (1 pF = 10^{-12}F). The electrostatic energy in watt-seconds or joules in the capacitor is given by $J = \frac{1}{2} CV^2$.

A capacitor is thought to block dc current and pass ac current. This is not exactly true, but the observable behavior of a capacitor tends to support the general blocking theory. In actuality, a capacitor does not pass any current through it; however, when ac current is applied to a capacitor, current flow moves to and from the individual capacitor plates and simulates a current flow due to alternating current.

1.2 Capacitor Characteristics

There are several key characteristics that are used to define the capability of any capacitor. Several of these characteristics are discussed here, but the two primary sets of characteristics are electrical and environmental [A.5.2, A.5.3, A.5.8].

1.2.1 Electrical Characteristics

The ability of a capacitor to operate within its limitations depends greatly on the electrical ratings of the capacitor. The voltage rating, current rating, and dielectric strength of the capacitor materials determine its capability.

1.2.1.1 Voltage Rating

The rated voltage of a capacitor (V_R) is the designed operating voltage for a particular capacitor. This voltage is the maximum voltage that a capacitor should to be exposed to during continuous operation without substantial degradation. This voltage is also referred to as the dc working voltage. The voltage typically indicated on a capacitor is its dc voltage rating unless the capacitor is designed specifically for ac applications.

A capacitor can be exposed to reverse voltage and also certain levels of surge voltage for short periods of time without damage. These types of voltage variations should be seldom and short-lived. The withstand levels for reverse and surge voltages should be designated by the capacitor manufacturer. Industry standards also address acceptable levels for surge voltage and reverse voltage based on the voltage rating of the capacitor.

In some applications, a ripple voltage can be applied to a capacitor. This superimposed voltage tends to be additive to the dc voltage of the capacitor. The capacitor should not be exposed to a voltage greater than the rated voltage. Therefore, if a capacitor will be exposed to a ripple voltage, the sum of the dc voltage and ripple voltage should not exceed the capacitor's rated voltage.

Dielectric absorption is the phenomenon that occurs when a fully charged capacitor is discharged and allowed to remain open circuited for a period of time and a second voltage is measured. This second voltage is a measure of the charge that was absorbed by the dielectric of the capacitor due to dipole realignment. The dielectric absorption is usually stated as the ratio of the voltage to which a capacitor recovers after a discharge to the original charging voltage.

1.2.1.2 Current Rating

The current rating of a capacitor is the current that would cause the dielectric to reach its maximum operating temperature. The current rating is usually specified as the rms current that a capacitor should be capable of withstanding without damage. The heat generated is due to the power that is dissipated in the dielectric and case materials.

The rate at which current flows into and out of a capacitor is called the ac ripple current. The ripple current rating is specified by most manufacturers at 120 Hz and at some given operating temperature (for example, 85°C or 185°F). There is also a surge current rating that is specified by some manufacturers.

It is possible for a capacitor to pass an appreciable amount of current during steady state conditions (when dc voltage is applied). This current is known as the leakage current. Leakage current occurs in a capacitor due to imperfections in the dielectric material of the capacitor.

1.2.1.3 Capacitance

Capacitance is a measure of the ability of a device to store a charge. The capacitance of a capacitor is usually determined by measuring the ac impedance or measuring the charge that a device will hold when dc voltage is applied. The two methods will yield slightly different values for capacitance. Typically, the dc method yields higher values of capacitance than the ac method. The values vary from about 1.1 to 1.5 while the maximum variation occurs with capacitors of low voltage ratings.

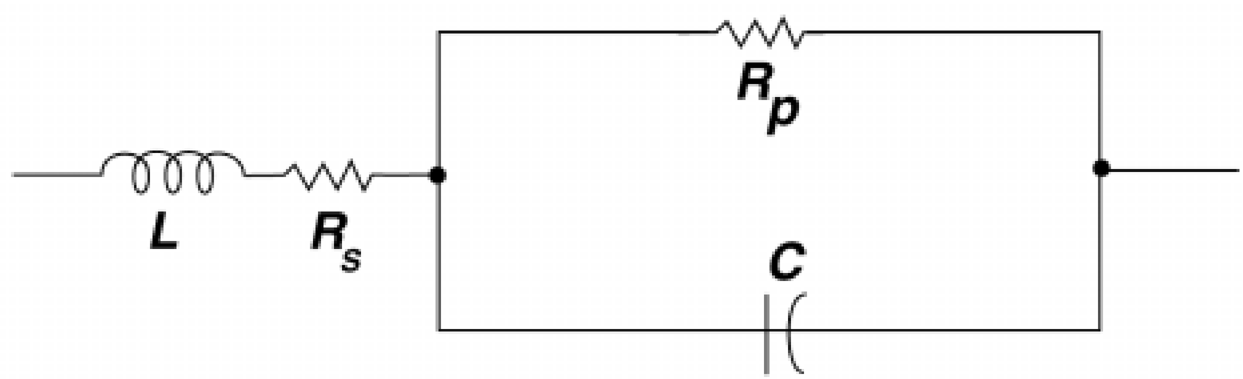
The method used for determining capacitance depends on the applications where a particular capacitor is used. There are applications where the dc method is more appropriate, such as discharge circuits and timing functions. The ac method is used for aluminum electrolytic capacitors that are used in filtering or coupling applications. The capacitance is determined by applying an ac voltage to the capacitor. Because the ac capacitance depends on frequency and temperature, capacitance is measured at a standard frequency and temperature, typically 60 Hz or 120Hz at 70°F (21°C).

The listed capacitance is usually the ac capacitance value and is the value stamped on the capacitor. The rated capacitance is determined by specific measurement methods that are presented in applicable standards (EIA 395 or IEC 384). The value of capacitance can vary considerably in terms of tolerance. It is not unusual for a capacitor to have a tolerance –0 to + 100%. The long-term stability of a capacitor is measured by the change in capacitance over a capacitor's operating life.

1.2.1.4 Impedance

The dielectric of a capacitor determines many of the characteristics of a capacitor. The properties of the dielectric affect the capability of a capacitor, such as the maximum voltage that can be applied to the capacitor before breakdown.

In addition to capacitance, a practical capacitor has inductance and resistance. An equivalent circuit useful in determining the performance characteristics of a capacitor is shown in Figure 1-2.



R_s = Series Resistance Due to Wire Leads, Contact Terminations, and Electrodes (Ω)
R_p = Shunt Resistance Due to Dielectric Resistivity, Case Material (Ω), and Dielectric Losses
L = Stray Inductance Due to Leads And Electrodes [A.5.3]

Figure 1-2
Capacitor Equivalent Circuit

The equivalent series resistance (ESR) is the ac resistance of a capacitor that represents both the series resistance R_S and the parallel resistance R_P at a given frequency so that the loss of these elements can be expressed as a loss in a single resistor R in the equivalent circuit. It is derived from lead resistance, termination losses, and dissipation in the dielectric material.

The equivalent series inductance (ESL) is the self-inductance of the capacitor and leads. The capacitor section has very little inductance because the plates are in close proximity. The plates carry equal and opposite currents that cancel the inductive effects. Most of the inductance in the capacitor is due to the connecting tabs and terminal configuration. The package inductance can be minimized by keeping the tabs and terminals as close to each other as possible. For this reason, a single-ended configuration always has lower inductance than the axial leaded capacitor. The series inductance of a capacitor can usually be ignored for low frequencies.

The ESR, inductance, and capacitance are frequency dependent because the resistance (R) and capacitance (C) are distributed along the surface of the plates. Based on the frequency dependence of a capacitor’s ohmic values, the following relationships can be be observed:

$$Z = [R^2 + (X_L - X_C)^2]^{1/2}$$

$$\cos\phi = R/Z$$

$$\tan\delta = R/X_C$$

where,

R is the ESR

$$X_L = 2\pi fL = \omega L$$

$X_C = 1/(2\pi fC) = 1/\omega C$

$f = \omega/2\pi$ is the frequency in hertz

$\cos\phi$ is the power factor of the capacitor

$\tan\delta$ is the dissipation factor of the capacitor

In a perfect capacitor, there should be no energy loss as a result of applied voltage. Since there is no such device, there is energy lost due to dissipation in the electrolyte. This loss is attributed to insulation resistance and is referred to as the dissipation factor or $\tan\delta$. The dissipation factor is the ratio of the ESR to X_C, otherwise stated as the ratio of the effective power to the reactive power based on the equivalent series circuit model. It is an indicator of the dielectric quality at some specified temperature and frequency. When discussing dc voltages, the resulting loss is attributed to the capacitor leakage current. The dissipation factor expresses the amount of power lost in a capacitor. It is an important consideration in applications where series resistance is of concern.

The power factor of the capacitor can be used to find the proportion of the ac signal that is dissipated as heat in the body of the capacitor. When the series resistance is low, the angle δ is small, and the power factor is approximately equal to the dissipation factor. This tends to hold true for most practical capacitors. The dissipation factor and power factor vary with environmental conditions. For instance, the dissipation factor is sensitive to the presence of moisture, and the power factor decreases as the temperature decreases. These variations are not linear, but manufacturers have graphs or tables that display these complex behaviors.

1.2.1.5 Frequency

The performance of a capacitor and many of the measured values are affected by the operating frequency. All of the ac characteristics of a capacitor are affected by the operating frequency. At low frequency, the ac voltage must be kept below the maximum dc voltage rating of the capacitor. Also, the dc leakage and the time constant effects are important. As the frequency increases, the loss in the parallel resistor (R_p) becomes important. At the resonant frequency, the ESR is predominant. At high frequency, the impedance of the dielectric shunts, the parallel resistance (R_p) and the series effects of series resistance (R_S) and series inductance (L) begin to dominate. Figure 1-3 illustrates a capacitor’s behavior as frequency changes.

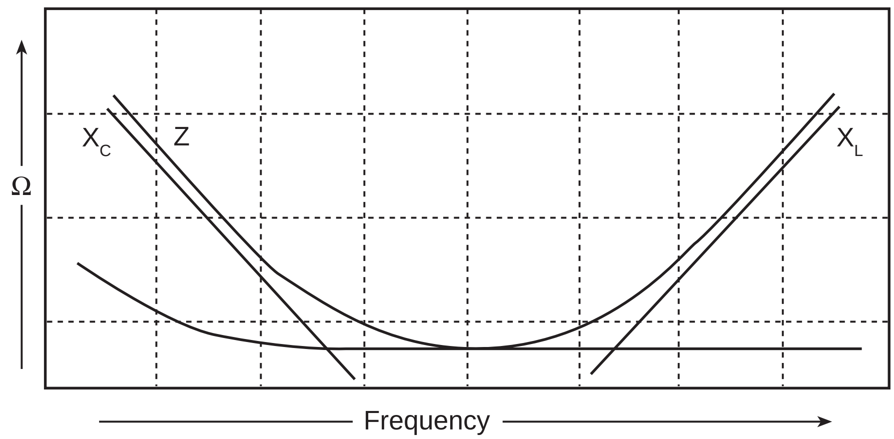


Figure 1-3
Impedance vs. Frequency Behavior of a Typical Capacitor

Frequency affects ripple (voltage, current), impedance (dissipation factor, dielectric absorption), and capacitance. All of these factors vary with the operating frequency.

1.2.2 Environmental Characteristics

The performance of a capacitor can be greatly affected by the conditions under which it is used. However, many of these parameters are also impacted by the internal operating conditions of the capacitor. Temperature by far has the predominate effect on operating parameters and operating life of a capacitor.

1.2.2.1 Temperature

Parameters such as voltage (operating and ripple), current (operating, ripple, and leakage), capacitance, impedance, dissipation factor, and dielectric absorption are affected by temperature. Leakage current increases as temperature increases and decreases as temperature decreases; therefore, it is important to observe a minimum and maximum temperature for operation and storage.

The maximum operating temperature is the temperature at which a capacitor can be continuously operated. If the maximum temperature is exceeded for an extended period, the capacitor might fail prematurely (see service life). The operating temperature of a capacitor is a function of both its ambient and operating parameters.

The minimum operating temperature should be observed in order to maintain the parameters within proper operating range. Unlike high temperature, low temperature does not damage a capacitor, but it will affect the conductivity of the capacitor’s electrolyte. A low operating temperature increases the ESR and dissipation factor of a capacitor. The increases in these parameters are permissible up to a point. It should be noted that at low temperatures because of the increased ESR and if there is a ripple current present, the temperature of the capacitor will increase to a point such that the capacitance will be adequate and equipment operation will not be affected.

1.2.2.2 Humidity

Often higher than normal temperatures also bring with them higher than normal humidity. If a capacitor is stored for an extended period of time under humid conditions, the humidity will cause the lead wires/terminals to oxidize and thus make it difficult to install. Lead oxidation could also promote open circuit failures in capacitors. Humidity can also degrade seals and capacitor case materials (for example, metal cans).

1.3 Typical Capacitors

Commercially available capacitors come in a wide variety of types and values. The value of capacitance is determined by the dielectric constant of the material used, its thickness, and its area. Table 1-1 lists common capacitor types along with ranges of available capacitance. Some of the common dielectric materials are listed in Table 1-2 along with their associated dielectric constants.

Table 1-1
Commercial Capacitor Properties [A.3.1]

Type Of Capacitor	Typical Dielectric Material	Typical Range Of Capacitance	Voltage Range
Ceramic	Barium titanate	0.1 pF to 12 µF	3 to 40k V dc 12,000 V ac
Glass	Glass ribbon	0.1 pF to 12 µF	25 to 30k V dc
Mica	Mica	1 pF to 10 µF	1 to 50k V dc
Paper Paper (oil-filled)	Impregnated paper Askarel, silicones, mineral oil, castor oil	50 pF to 200 µf 100 pF to 200 µF	50 to 4k V dc 50 to 200 k V dc
Plastic film	Mylar, Teflon, polystyrene polycarbonate	20 pF to 400 µF	50 to 4k V dc
Electrolytic tantalum aluminum	Tantalum oxide Aluminum oxide	1,000 pF to 8,000 µF 0.5 µF to 2F	1.25 to 630 V dc (Range varies with electrolyte makeup) 3 to 700 V dc

As can be seen in Table 1-1, electrolytic capacitors generally have the largest value of capacitance and are often used for power supply filtering applications. Instrument power supplies routinely use electrolytic capacitors in the capacitance range of 1 to 1,500 µF, well above the capability of other capacitor types. Plastic film, mica, and ceramic capacitors are also used in power supplies for lower capacitance applications.

Table 1-2
Comparison of Capacitor Dielectric Constants [A.5.15]

Dielectric	K (Dielectric Constant)
Air or vacuum	1.0
Paper	2.0–6.0
Plastic	2.1–6.0
Mineral oil	2.2–2.3
Silicone oil	2.7–2.8
Quartz	3.8–4.4
Glass	4.8–8.0
Porcelain	5.1–5.9
Mica	5.4–8.7
Aluminum oxide	8.4
Tantalum pentoxide	26
Ceramic	12–400,000

1.3.1 Ceramic Dielectric Capacitors

A ceramic capacitor consists of a ceramic dielectric on which a thin metallic film, usually silver, has been fired at a very high temperature (sintered). Terminal leads are attached to the electrodes by pressure contact or by soldering. Ceramic capacitors are usually encapsulated to protect the dielectric from the environment and to electrically insulate the capacitor.

Ceramic capacitors are available in a wide range of dielectric constants. The dielectric constant can be varied by changing the proportion of ceramic mixtures of the dielectric. These variations allow for the development of many different types of ceramic capacitors. These capacitors are moisture resistant and almost impermeable. They also have fairly stable temperature characteristics.

There are four common types of ceramic capacitors:

- Disk
- Buttonhead
- Doorknob
- Chip

The disk ceramic capacitor is the most common type of ceramic capacitor and usually has voltage ratings of 100, 500, and 1000 V. Disk and thin-plated subminiature ceramic capacitors are extremely compact and have an inherent low series inductance because of their construction. These types of capacitors have high insulation resistance and low leakage current along with small physical size.

The buttonhead ceramic capacitor is designed using a ceramic disk or monolithic disk inside the head of a small metal button or screw. The design provides for a minimum lead inductance to ground, thus providing the highest possible self-resonance frequency.

The doorknob ceramic capacitor gets its name from its appearance. It is a disk capacitor with a dielectric thickness that provides exceptional voltage capability (up to 40 kV dc and 12 kV ac).

Chip ceramic dielectric capacitors are made without leads and are not encapsulated. They can be of either single-wafer or monolithic construction in many different ceramic compositions.

1.3.2 Glass Dielectric Capacitor

Glass dielectric capacitors are composed of alternate layers of glass ribbon and the electrode material (metal). After assembly, the units are sealed together by high temperature and pressure and enclosed in a glass or enamel case. These capacitors provide a fixed temperature coefficient, high insulation resistance, low dielectric absorption, and resistance to high humidity and temperature.

1.3.3 Mica Dielectric Capacitor

Mica dielectric capacitors can be constructed from foil, film, or metallized sheets. For the foil and film construction, the mica is interleaved with tin-lead foil and stacked to give the desired capacitance value. These stacks are encased in various enclosures depending on the application. Molded plastic, ceramic casing, and epoxy resin are some of the enclosures used to encapsulate the mica stacks. The enclosures are used to protect the mica from moisture and to provide mechanical strength. A metal case in the shape of a button is sometimes used as an enclosure.

The metallized mica capacitor is made from silver paste screened onto the mica dielectric. The individual mica capacitors can be stacked in series and parallel to obtain the required capacitance value. These capacitors are also called silver mica capacitors and have a higher stability and tolerance than those made of foil or film.

1.3.4 Paper Dielectric Capacitor

Paper capacitors are typically constructed of either paper, foil and film, or metallized film. The foil and film capacitor is made by interleaving alternate layers of metal foil and impregnated paper and winding these together. This type of capacitor is used in high-voltage and high-current applications.

In the metallized film construction, the impregnated paper dielectric is coated with a thin layer of aluminum to form the metal plate, and several layers are then wound. Metallized film capacitors have a smaller physical size than a comparable foil and film paper capacitor. However, a paper film capacitor will have higher current rating than a comparable metallized film paper capacitor, and a metal foil capacitor will have a better pulse rating than a comparable metallized capacitor.

Paper/oil-filled capacitors consist of alternate layers of aluminum and layers of paper in ribbon form that are rolled together. The paper may be saturated with an oil and the assembly mounted in an oil-filled, hermetically sealed metal case. The additional insulation oil increases the capacitor’s insulation resistance, temperature range, and primarily the working voltage. The oil fills the air gaps and thus limits the production of corona in the capacitor. Applications involving high-voltage dc filtering, high current at power line frequencies, and high-energy discharges use oil-filled paper capacitors. Although similar in appearance, each oil-filled capacitor design is different and has different application parameters. The ac oil-filled capacitor is designed primarily to provide large capacitance for ac industrial applications such as power factor correction.

All paper or paper-plastic dielectric fixed capacitors are hermetically sealed in metal cases. All of these materials are high temperature plastics with continuous operating temperatures that range from 250°F (121°C) to 300°F (149°C).

Applied voltage and operating temperature are the two major stressors that affect the life of an oil-filled capacitor in an ac application. Determining the applied voltage for ac oil-filled capacitors has led to a convenient rating system. The volt-ampere (VA) rating provides a basis for configuration and design and for determining the surface area of the container required to efficiently dissipate heat. The VA rating can be determined by the following equation:

$$VA = 2\pi fCE^2 x10^{-6}$$

where,

f = frequency in Hz

C = capacitance in F

E = rated voltage

1.3.5 Plastic Dielectric Capacitor

Plastic dielectric capacitors are constructed using foil and film and metallized processes. These capacitors are usually wound flat into a rectangular shape. Metallized plastic capacitors have almost replaced paper capacitors for low-voltage applications because of their smaller size and their superior electrical capabilities. Plastic film, however, is not saturable and is, therefore, a dry construction. This limits the peak ac and dc voltage ratings of these types of capacitors.

The following materials are typically used in plastic dielectric capacitors:

- Polystyrene
- Polyethylene terephthalate (PET) (Polyester)
- Polycarbonate (PC)
- Polypropylene
- Paper and polyethylene terephthalate

All plastic or paper-plastic dielectric fixed capacitors are hermetically sealed in an encapsulant, a plastic sleeve, or a metal case.

The electrical characteristics of a plastic capacitor vary, based on the type of dielectric material used in the capacitor. As with most capacitors, these characteristics are greatly affected by temperature. These behavioral variations are provided in manufacturers’ data for a particular type or family of capacitors.

1.3.6 Electrolytic Dielectric Capacitors

Electrolytic capacitors have the highest capacitance to voltage (CV) product for a given physical size and the largest absolute capacitance value. The large capacitance is obtained by the use of very thin dielectric film formed by oxidizing a metal. Tantalum and aluminum are the two metals that are typically used for electrolytic capacitors. These capacitors are produced in polarized, semipolarized, and nonpolarized designs.

1.3.6.1 Tantalum Capacitors

There are three basic types of tantalum capacitors:

- Tantalum foil
- Solid tantalum
- Wet-slug tantalum

Tantalum foil capacitors are made by oxidizing an anode tantalum foil to form the dielectric oxide and then winding it with a second tantalum foil and porous-paper spacers to provide separation and hold the electrolyte. The electrolyte used is usually sulfuric acid.

Solid tantalum capacitors are constructed of sintered tantalum powder packed around a tantalum anode to form a rigid ring. The porous anode pellet obtained after sintering is impregnated with manganese nitrate and heated to form manganese dioxide. This oxide forms a solid electrolyte negative electrode and makes contact with 90–98% of the surface of the dielectric. Control of this contact area during production is very important because it affects capacitance value. The solid manganese dioxide electrolyte has several advantages over conventional liquid electrolytes such as no dry out or leakage. The conduction in a solid tantalum capacitor is accomplished by electron flow rather than ion flow, thus resulting in lower specific resistance and better frequency performance. The manganese dioxide is coated with a layer of graphite and silver and encapsulated in the cathode system, which can be of many types. The coating is often dipped in an epoxy resin, placed in a metal case, and sealed with a resin seal.

Wet-slug tantalum capacitors use a porous anode or slug immersed in a liquid electrolyte. The electrolyte can be either a mixture of sulfuric acid and deionzied water or a gel electrolyte made of sulfuric acid and silica.

The cathode system used in tantalum capacitors can be silver, platinized silver, or sintered tantalum cathode. The silver cathode is used only occasionally; however, there is a disadvantage in that the silver can dissolve and collect in the electrolyte or deposit onto the anode so that the cathode surface is disrupted, the capacitance value is reduced, and the leakage current is increased, which might ultimately lead to a short circuit. These issues are overcome by the use of platinized silver cathodes and treating the internal surface of the silver case with black platinizing. This also increases the capacitance per unit area of the cathode by a factor of 10 to 15. The sintered tantalum cathode capacitor has the highest CV product per volume of any tantalum capacitor. The cathode material is similar to that used for the anode, and the capacitor can withstand about 3 volts in the reverse direction. In all types of tantalum capacitors, an over-voltage in the forward direction will cause the dielectric to grow in thickness, reducing the capacitance value. Ultimately, dielectric breakdown will occur.

The solid tantalum capacitor has a linear temperature characteristic but the foil and wet-slug types demonstrate a rapid fall in the mobility of the electrolyte ions. The performance of the capacitors is also dependent on electrolyte conduction, and since the ion mobility in liquid systems is low, the capacitor's high-frequency performance is reduced. Solid tantalums have long life because there is no wear-out mechanism such as the loss of electrolyte; however, it is very difficult to make solid tantalum capacitors in large capacitance values.

Although wet tantalum capacitors have a high CV product, it is not practical to make them in small physical sizes due to the space needed by seals and other materials.

1.3.6.2 Aluminum Electrolytic

Aluminum electrolytic capacitors are the most widely used electrolytic capacitors in the electronics industry. Their high CV product and large capacitance value make them indispensable in many electronic applications.

The aluminum electrolytic capacitor is made up of two electrically conductive material layers that are separated by a dielectric layer. The anode is formed by using an aluminum foil with an enlarged surface area. The foil is oxidized to give a thin coating of aluminum oxide, which acts as a dielectric. The other electrode of the capacitor is formed by an electrolyte. This electrolyte is usually an aqueous solution composed of glycol, conductive salts, and water. For some low ESR capacitors, non-aqueous electrolytes are used; however, to improve ripple characteristics and temperature ratings, ethylene glycol is preferred.

The cathode is in contact with a second aluminum foil called the cathode plate. This plate provides a broad surface area for the transfer of current to the electrolyte. These plates are also separated by a thin porous paper that is impregnated with the electrolyte. The foils and paper are wound together and placed in a metal can.

In order to increase the capacitance value for a given size capacitor, the aluminum foil may be etched. This increases the relative permittivity from about 7 to 10. The etched surfaces must remain free of the dielectric oxide, thus, there is a limiting thickness of oxide that can be grown and still preserve the surface gain obtained by etching. This limits the maximum operating voltage of the capacitor.

The electrolyte, however, fits well into the etched anode surface. The electrolyte serves another vital purpose in healing any weakness that might arise in the oxide film during operation. The dielectric is slightly attacked by the electrolyte when de-energized, but the lost oxide is regrown when the capacitor is in use. In an electrolytic capacitor, the cathode foil is usually highly etched and only lightly anodized. This gives the cathode a very high capacitance compared to the anode.

Typically, electrolytic capacitors are suited only for dc operation and are known as polar capacitors. The positive voltage must always be applied to the anode. However, bipolar aluminum electrolytic capacitors are available. In a bipolar capacitor, the anode and cathode foils are anodized. The cathode foil has the same capacitance rating as the anode foil. This construction allows for operation at direct voltage of either polarity, as well as operation at purely alternating voltages. Because it causes internal heating, the applied alternating voltage must be kept considerably below the direct voltage rating.

Due to the series connection of the two capacitor elements, the total capacitance amounts to only half the individual capacitance value. In comparison to a polar capacitor, a bipolar electrolytic capacitor of similar construction requires up to twice the volume for the same amount of capacitance and has twice the leakage current.

1.3.7 Capacitor Life

Capacitors are either electrostatic or electrochemical devices that are made up of various materials that will exhibit certain electrical behavior when exposed to external stimuli. The combination of materials that make up some capacitors might not be stable over time. Capacitor characteristics can change during storage as well as during operation. The behavior of a capacitor over time or its anticipated life is dependent upon the materials of composition, storage conditions, and its operating parameters. The manufacturer supplies a capacitor with a rated life based upon specific parameters. Because the life of a capacitor depends upon various conditions, the shelf life or storage life, the service life, and their relationships should be understood by the user.

1.3.7.1 Rated Life

The rated life of a capacitor is the anticipated period of time that a capacitor has been designed to operate, based upon application and operating conditions. The manufacturer will typically quote this life based on accelerated testing or field experience, depending upon available data.

Typically, the manufacturer will supply a device with a certain expected life based upon placing it in service soon after manufacture (that is, within two years of manufacture) and operating it within specified limits. The rated life will be different for different types of capacitors and applications. Although the manufacturer provides the rated life, it is the responsibility of the user to understand the effects of the application on the rated life. The rated life provides a reference point when no other data are available regarding capacitor behavior.

The rated life of a capacitor also depends on the quality of the construction and the materials used to make up the capacitor. There are two quality levels typically assigned to capacitors: general purpose and premium. Typically, the rated life of a premium capacitor is greater than that of a general purpose capacitor.

1.3.7.2 Shelf Life

Because capacitors degrade, there will be a change in their characteristics over time. The change in capacitor characteristics is primarily due to dielectric breakdown. The dielectric breakdown in electrolytic capacitors is entirely different from electrostatic capacitors [A.5.7].

When an electrolytic capacitor is stored for an extended period of time, the internal resistance tends to drop to a level where the dc leakage current might exceed the rated value. This change in leakage current is due to breakdown of the oxide layer that provides the dielectric strength for the capacitor. Because capacitors are made with different dielectric materials, the shelf life for each capacitor type varies.

Many manufacturers specify a typical shelf life for a capacitor or an assembly containing capacitors. The manufacturer’s stated shelf life for an aluminum electrolytic capacitor can range from 2 to 10 years, depending on the quality of the component. This shelf life is usually provided with a caveat related to storage without being powered. If the capacitor has been stored for a period of time without voltage, it should be reformed following reforming procedures. If an assembly has been de-energized for a period of time, it should be energized or “burned in” for about an hour before being placed in service.

From plant experience and limited studies, it appears that even the shelf life of aluminum electrolytic capacitors may not be as limited as stated by some manufacturers. Some aluminum electrolytic capacitors have been stored for more than 20 years and when characteristics are measured, some capacitor characteristics have had acceptable values. EPRI plans further studies and observations in order to monitor the performance of aged capacitors.

1.3.7.3 Service Life

Service life is the anticipated life that a component should provide before significant deterioration in operational characteristics or total failure occurs in proportion to rated life. This term is often referred to as “useful life.” The useful life of a component, however, is more akin to characteristic variations than to total failure of a component. Depending upon operability requirements, characteristic variations do not necessarily indicate equipment failure or loss of operability.

The anticipated service life of a capacitor must be based on several factors such as date of manufacture, storage conditions, operating parameters, and environment. The service life of a capacitor can be prolonged by operating it below its specified ratings. The three key characteristics that affect capacitor service life are:

- Applied voltage
- Ripple current
- Ambient temperature

The service life of a capacitor is typically provided by the capacitor manufacturer or can be calculated based on the circuit application requirements (for example, voltage rating).

The useful life of a capacitor should be related to the change in performance characteristics. The change in capacitor characteristics is primarily due to dielectric breakdown.

A useful life can be assigned to a capacitor by establishing levels at which maintenance actions will be taken, based upon measurable characteristics. These actions will also depend upon whether one is concerned with discrete components (for example, single capacitors) or assemblies (for example, power supplies or circuit cards).

1.4 Applications

Capacitors are used as energy-storage devices. The energy can be dissipated over a short or long period of time depending upon the application. For instance, a capacitor in parallel combination with a resistor to form a resistor capacitor (RC) circuit can be used as a filter circuit for smoothing dc ripple. Capacitors are used to prevent the flow of dc current while allowing ac current to pass and to block (attenuate) low-frequency currents while passing higher-frequency current.

Capacitors are selected to perform particular functions in a circuit. Depending on capacitor characteristics, various capacitor types will function in a circuit, but there are specific types that will provide better service, based on the application requirements.

When selecting a capacitor type for an application, there are numerous factors that must be considered. The general characteristics for a capacitor were presented in Section 1.2; however, the choice of a capacitor includes compromise between characteristics, cost, and anticipated capacitor life.

Capacitor circuit functions can be placed in the following general categories: filtering, energy storage, power correction, electric motor starting, and timing circuits.

1.4.1 Filtering

The term “filtering” used in this discussion describes several general capacitor circuit functions such as blocking, coupling, bypassing, tuning, and suppressing voltage.

A capacitor is said to block dc current and pass ac current. With this capability, a capacitor can be used to isolate a circuit component from a dc supply. However, it must be kept in mind that a capacitor will have a certain amount of leakage current that will pass through the capacitor to the component as a result of random electron movement in the dielectric. Thus, it becomes important to select a capacitor type with leakage current levels that will not cause the component or remainder of the circuit to malfunction.

Another aspect of filtering is coupling. The capacitor allows or appears to allow ac current to pass through the circuit. The capacitor is really charging in one direction and discharging in the opposite direction at each half-cycle as the ac signal changes in polarity. With this capability, a capacitor can be used to couple one portion of a circuit to another portion or even to another circuit. In this application, the dissipation factor of the capacitor type should be the chief consideration, especially if the heating effect of the ac voltage is substantial.

Bypassing is the combination of blocking and coupling in that a capacitor can be used to separate the dc and ac portions of a signal. In this application, a capacitor is used in parallel with a circuit element where the ac portion of the signal does not appear on the element or is blocked while the dc portion appears on the element. The ac signal sees a low impedance path through the capacitor while the dc signal sees a low impedance path through the other portion of the ciruit. In this application, both leakage current and dissipation factor parameters have to be considered in any application where these factors are important.

Because a capacitor’s behavior is frequency dependent, it is possible to select a capacitor that will discriminate between ac signals of different frequencies. Typically, the ability of a capacitor to pass current is related to its capacitance. Also, for a given capacitance, the higher the frequency, the more current the capacitor will pass up to its resonant frequency. In this application, the dissipation factor can be a critical consideration.

Voltage variations will occur on unregulated power supplies due to transient voltages. Capacitors can be used to stabilize or otherwise suppress voltage surge levels and prevent damage or malfunctions due to transient voltage peaks. This capacitor capability is used to reduce ac ripple voltages in rectified power supplies. This application can tolerate parametric changes in capacitor characteristics.

1.4.2 Energy Storage

The chief function of a capacitor is to store a charge and hold that charge until the capacitor is discharged. A capacitor can hold a charge for quite some time and then be discharged rapidly or slowly depending on circuit requirements. By discharging a capacitor over a short time, high currents can be developed. This capacitor capability has been used for applications such as medical equipment, lasers, masers, welders, and photographic flashes. The primary capacitor characteristic of concern in this application is the dissipation factor because of heating effects. However, the current carrying ability of the capacitor leads and other connections is the most critical consideration.

1.4.3 Power Correction

In an ac power system, part of the power supplied to the system is used to energize or excite certain components within the system. The power is somewhat absorbed by these components and is not available for use in the circuit. These components tend to be inductive, such as transformers and motors. With a large inductive load, the power factor tends to be less than unity because the current lags the voltage. By using capacitors, the amount of power that is required to energize these components can be reduced, thus, the power required to operate the system is used more efficiently. This effect also allows more power to be used throughout the system or by a particular component. Because of the high voltage and current requirements, oil-filled capacitors are typically used for these applications.

1.4.4 Motor Start and Operation

In the area of control service, capacitors are used to assist with motor starting and timing circuits. This area could be considered as part of the power correction portion but has been separated for clarity. In applications that use relaying and or other circuit interrupting devices, a capacitor circuit (in association with a resistor and/or an inductor) can be used to absorb the voltage pulses and to suppress the arc that is formed when contacts are opened.

Capacitors are used for motor starting and running. Motors that use capacitors in their operating circuit are usually single phase and low horsepower (typically less than 10 hp). There are two typical arrangements for motors that use capacitors: capacitor start and permanent split capacitor. There is a variation of these two motor arrangements that is called a capacitor start/capacitor run motor,which is built in sizes from ½ to 25 hp.

The capacitor start motor has a capacitor, an auxiliary winding (start winding), and a centrifugal switch that are all connected in parallel with the main motor winding. The capacitor start motor uses the capacitor to assist with starting and accelerating the motor. After the motor reaches operating speed, the centrifugal switch opens and removes the capacitor and the auxiliary windings from the circuit. This type of motor uses electrolytic capacitors with a fairly substantial microfarad rating (for example, as much as 1200 μF). A capacitor for this type of application is not designed for continuous duty.

The permanent-split-capacitor motor is built in the same fashion as the capacitor start motor with the exception of the centrifugal switch. The capacitor and auxiliary winding remain in the circuit at all times—both starting and operating. This motor utilizes an oil-filled capacitor of a few microfarads (for example, as much as 75 μF).

The capacitor start/capacitor run motor uses an additional capacitor and centrifugal switch in parallel with the auxiliary winding and capacitor.

1.4.5 Timing and Control

The rate at which the charges flow into and out of a capacitor can be directly controlled by capacitance and resistance in a circuit. Timing circuits make use of a capacitors charge and discharge capability in order to produce response times in circuits. In this application, the change in capacitance is an important consideration. Capacitance can change over time as well as be affected by temperature changes.

1.5 Summary

In power plants, capacitors are used in a variety of applications including, but not limited to, the following:

- Instrument power supplies
- Computer power supplies
- Inverters
- Battery chargers
- Circuit boards
- Controllers
- Motors

Inverter and battery charger capacitors generally have periodic replacement intervals specified by the manufacturer. In other applications, where a service life is not stated or established by the manufacturer, it is the responsibility of the user to understand the application's effects and consequences on capacitor performance and life.

Usually, the capacitors that are the concern of and can be maintained by plant personnel have been selected and installed by original equipment manufacturers (OEMs). The designer has made certain decisions in order to obtain a certain level of equipment operation for a reasonable time period. The operational history of a piece of equipment and its environment should be reviewed along with the specifications used by the designer (if available) to ensure that the capacitor has the desired operational life before it has to be maintained or replaced. This review will give some relative assurance that the component can be replaced with a suitable replacement.

Table 1-3 summarizes typical applications of each capacitor type.

Table 1-3
Capacitor Applications [A.3.1]

Type Of Capacitor	Typical Application Or Design Requirement	Comments
Aluminum electrolytic	Filtering Low-frequency bypass Relatively high leakage current Typically polarized	Low cost Wide variety of ratings and life characteristics High capacitance value High C/V ratio
Tantalum electrolytic	Filtering Low-frequency bypass Low leakage Available nonpolarized	High cost Variety of ratings and fairly stable life characteristics Limited in capacitance level Good temperature response
Mica	High stability Counting Timing Filtering at high frequency	Low C/V ratio
Ceramic	Bypass Coupling Filtering at medium frequency Timing Low leakage	Moderate stability Moderate C/V ratio High-voltage general purpose Wide variety of ratings Multi-layer available for higher C/V ratio
Plastic film	Power applications at medium frequency Alternating current applications	Replacing paper types
Paper	Power factor correction Motor starting and/or running Coupling Bypass	Being replaced by plastic for low-power and low-frequency applications
Oil-filled (paper)	Phase splitting Voltage regulation Power factor correction Stabilizing transformer circuit Motor starting and/or running Energy storage	Used at power line frequencies to provide large capacitance for industrial ac applications Used in high current applications

2 CAPACITOR STORAGE AND IN-SERVICE DEGRADATION MECHANISMS

A capacitor’s ability to store electrical energy is dependent upon its materials of construction, but chiefly its dielectric material. Many substances have been used as dielectric material for capacitors. These materials have their own electrical (permittivity), chemical, and physical properties that make it possible to build capacitors with different performance characteristics.

The properties of some materials or combination of materials used in the fabrication of capacitors change over time. The changes in properties will affect the characteristics of a capacitor. This section provides discussion on the changes that occur in capacitor characteristics during storage and in service.

2.1 Storage Degradation (Inherent Aging Factors) by Capacitor Type

Various dielectric materials have been used in capacitor construction. Examples of some popular dielectric materials are ceramic, glass, mica, paper, film (plastics), oil, and certain metal oxides. Some of these materials are inert and thus inherently stable, whereas others are chemically active and somewhat unstable. The changes in material properties over time affect capacitor characteristics and its ability to meet performance requirements. Some of the changes are reversible to some extent, whereas others are not reversible but can be tolerated within limits.

2.1.1 Ceramic

Ceramic capacitors do experience the effects of aging. The aging effects can be detected by a decrease in both the capacitance and the dissipation factor. Ceramic capacitor aging is due to the realignment of the ceramic crystalline structure. The realignment is a gradual process and occurs in a logarithmic fashion. The crystalline structure experiences very little change after the first 1000 hours of service. Ceramic capacitors are supplied as Class 1 and Class 2 (depending on the amount of dielectric material used in the construction). Class 1 ceramic capacitors are very stable and exhibit very little change in characteristic values over time; however, Class 2 ceramic capacitors are less stable and in time can exhibit significant characteristic changes.

Data compiled in MIL-STD-198E confirms that these types of ceramic capacitors do not appear to age over their operating range of -55°C (-67°F) to 125°C (257°F) [A.1.21]. Therefore, in storage, with no voltage applied and at typical storage temperatures, these capacitors are insensitive to aging. This is most applicable to Class 1 ceramic capacitors.

Documented accelerated aging and production tests performed by manufacturers have validated lifetimes equivalent to thousands of years. Other tests have shown no correlation between aging and seismic stress for accelerated lives equivalent to 53 years [A.3.3].

The test artificially aged the ceramic capacitors to an equivalent of 53 years and then subjected them to seismic tests. The capacitors survived the artificial aging and seismic tests, thus, ceramic capacitor should not have significant degradation in storage under class B storage conditions or better).

2.1.2 Glass Capacitor Aging

Glass capacitors are stable and durable because of their design. Layers of flexible ribbon (usually aluminum) and glass are interleaved to form the capacitor. Leads are attached to the assembly, and the assembly is fused to form a monolithic structure of great physical strength. This combination of materials and construction makes the glass capacitor fairly resistant to temperature, voltage, frequency, vibration, and moisture. This type of capacitor is immune to most aging effects that will change normal capacitor operating characteristics. Glass capacitors are even more stable than mica capacitors.

All of the materials used in the construction of glass dielectric capacitors are age insensitive; therefore, typical storage temperatures have no effect on capacitor characteristics.

2.1.3 Mica Capacitor Aging

Mica capacitors are among the most stable capacitor types because of the materials of construction and the manner in which they are fabricated. Film and foil or metallized mica sheets are two chief types of mica capacitors. The metallized mica capacitor has the highest stability of the mica capacitors. The metallized mica capacitor uses silver paste that is screened on the mica dielectric and is then heat bonded to the mica. This process forms individual capacitors, and these capacitors are then stacked (series and/or parallel) to provide the required capacitance value.

All of the materials used in the construction of button-style mica dielectric capacitors are age insensitive; thus, typical storage temperatures have no effect on capacitor characteristics.

These capacitors have a life expectancy of 50,000 hours (5.7 years) at rated conditions (125°C or 257°F) [A.1.21]. Most manufactures ascribe to the “10°C rule” which states, double the lifetime can be expected per 10°C temperature decrease. This principle, derived from the well-known law of Arrhenius that describes acceleration of reaction processes, is discussed later in this guide. Since life increases for every 10°C decrease in temperature and typical average storage temperatures are less then 40°C (104°F), the theoretical capacitor storage life is $2^{(8.5)} * 5.7$ years or 2,063 years. Essentially, these capacitors are insensitive to aging under storage conditions.

2.1.4 Paper Capacitor Aging

Paper dielectric capacitors use a special paper that is impregnated with a wax or fluid (for example, mineral oil) in order to enhance the dielectric properties of the paper. Metal foil is used in high-current and high-voltage paper capacitors. These materials are typically placed in a container and sealed in order to prevent moisture intrusion.

Paper dielectric capacitors are hermetically sealed in metal cases. The operating temperatures can be in the range of 121°C (250°F) to 149°C (300°F) [A.5.4]. The container seal is of great importance to the completed capacitor. If a seal fails, moisture absorption into the paper can occur, and in the case of metallized paper capacitor, oxidation of the metal at the paper-to-metal interface can occur. The chief degradation mechanism for the paper and oil is oxidation. These capacitors are fairly insensitive to degradation at storage temperatures.

2.1.5 Film (Plastic) Capacitor Aging

Plastic films are fairly stable under normal storage temperature conditions. Plastic films have been developed that are extremely resistant to moisture absorption, have fairly uniform structure, and are very thin. The following materials are used as dielectric materials in film capacitors:

- Polycarbonate (PC)
- Polyethylene terepthalate (polyester)
- Paper and polyethylene terepthalate
- Plastic or metallized plastic (typically PC or PET)
- Metallized polycarbonate
- Metallized paper and polyethylene terepthalate

Various film-type capacitors have been tested [A.3.2]. The capacitors were aged for the equivalent of 50 years and then subjected to a seismic test. No correlation was found between aging and seismic performance of the capacitors, that is, all types performed properly during seismic testing. Essentially, these capacitors are insensitive to aging under storage conditions.

2.1.6 Electrolytic Capacitor Aging

When a capacitor is in storage, there is no voltage applied and, therefore, no ripple current-induced internal temperature rise. The only aging parameter of consequence is the ambient temperature. With the exception of electrolytic capacitors, aging in storage is a question of materials used in the construction of the capacitors and whether there is a significant aging mechanism associated with individual materials. Since electrolytic capacitors use a liquid solution as the dielectric, the aging process while in storage is different from other types of capacitors and is discussed separately.

2.1.6.1 Tantalum Electrolytic Capacitor Aging

- Tantalum (solid)
- Tantalum (solid) chip
- Tantalum (nonsolid)

MIL-STD-198E states that tantalum and tantalum chip electrolytic capacitors have a "…substantially indefinite shelf life …" [A.1.21]. Their constructions and materials differ substantially from aluminum electrolytic capacitors and, therefore, do not age in storage conditions.

Dielectric tantalum oxide films, being less soluble than aluminum oxide dielectric films in the surrounding electrolyte, achieve longer shelf lives. Solubility is affected by the storage temperature to a significant degree. Solubility is excellent at temperatures from -55°C (-67°F) to +25°C (77°F); good at +65°C (149°F) and relatively poor at +85°C (185°F). Typical storage temperatures at three nuclear sites averaged 79°F (26.1°C) over the calendar year [A.5.9]. The most common failure mode, electrolyte leakage due to seal failure, is primarily due to the application of reverse voltage. Since no voltage is applied during storage, this common failure mode is of little concern. These capacitors should not exhibit significant aging in storage.

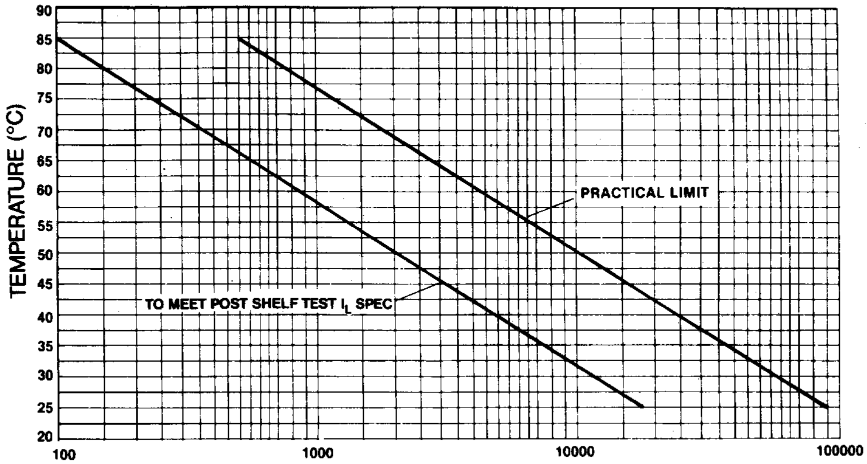
2.1.6.2 Aluminum Electrolytic Capacitor Aging

The aluminum electrolytic capacitor is an electrochemical device. The actual cathode of this type of capacitor is the liquid electrolyte, and the foil is only an electron transfer media. The characteristics of an aluminum electrolytic capacitor tend to change with time even during storage.

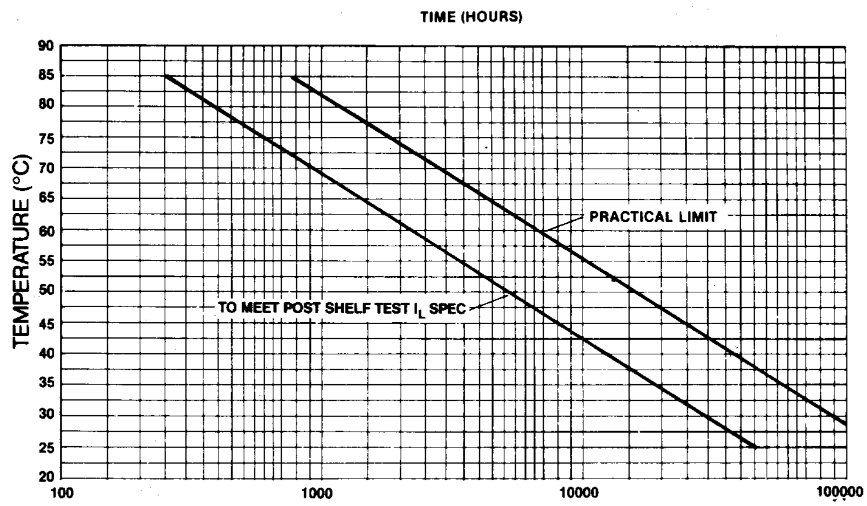
The oxide layer of an aluminum electrolytic capacitor tends to disintegrate during storage. Elevated temperatures worsen this condition. During operation, leakage current tends to transport oxygen ions to the anode, which helps to regenerate the oxide layer.

Aluminum electrolytic capacitors should be stored at or below the manufacturer's recommended temperature (about 40°C or 104°F). For prolonged storage stability and limiting the impact on useful life, the storage temperature should be at or below 25°C (77°F).

Figure 2-1 shows the shelf characteristics of several aluminum electrolytic capacitors used for power supplies.



3186, 3191, 3487 Shelf characteristics



3188, 3488 Shelf characteristics

Figure 2-1
Vendor Shelf Life Estimations [A.4.9]

One point is clearly illustrated by Figure 2-1, as the storage temperature decreases, the storage time increases. For a storage temperature of 25°C (77°F), the approximate storage time approaches 100,000 hours (approximately 11 years).

The configuration of the capacitor container and the lead arrangement will have some effect on the storage stability of an aluminum electrolytic capacitor. There is a distinction between the “axial and radial lead” type and the “can” type aluminum capacitors.

The sealing mechanism of the axial and radial lead-type aluminum electrolytic capacitor is also different (surface area and material) from the can electrolytic capacitor and prevents evaporation of the electrolyte, which is the major cause of shelf degradation of can-type capacitors.

Can aluminum electrolytic capacitors used in power supplies, converters, and inverters typically have high capacitance and diameters greater than 1 inch.

The limiting factor for can electrolytic capacitors is the evaporation of the electrolyte through the capacitor seal. Temperature is the only storage parameter that can cause evaporation.

Typical shelf life of can capacitors, according to the manufacturers, is 10 years at 40°C (104°F). Most manufactures ascribe to the “10°C rule”; therefore, at 30°C (86°F) storage temperature, a shelf life of 20 years would be expected.

2.2 Conclusions Regarding Shelf Life

If capacitors have been stored under the recommended conditions, the following statements can be made regarding shelf life when ambient temperature is the primary stressor. Before placing any capacitor in service, it would be prudent to perform testing to confirm the capacitor’s characteristics. The dc leakage current, capacitance, and ESR should be measured. Electrolytic capacitors can be reformed if the leakage current exceeds the manufacturer’s limits. As long as the leakage current and other characteristics are within specifications (based on measurements), a capacitor is assumed to be suitable for service.

Glass, mica, paper-plastic and ceramic capacitors are insensitive to aging when in storage and, therefore, should have an indefinite shelf life.

Tantalum electrolytic capacitors also are insensitive to aging when stored and, likewise, should have an indefinite shelf life.

Can electrolytic capacitors, typically greater than 1 inch in length and diameter and used in power supplies, converters, and inverters, should have a shelf life of about 20 years, based on storage temperatures.

Radial and axial lead electrolytic capacitors of the type used on printed circuit boards should have a shelf life greater than the can electrolytic capacitor. Radial and axial lead capacitors tend to have smaller volumes and better sealing mechanisms.

It should also be noted that equipment used in nuclear plants is thoroughly tested/checked out according to the manufacturer’s recommendations before being placed in service. Any significant degradation of components should be detected during the check-out period.

The effect that shelf life has on service life (useful life) is not fully understood. EPRI is considering a study to determine the effect that aging has on capacitor service life and to develop condition monitoring techniques that can be used to detect capacitor degradation.

2.3 Inservice Degradation Mechanisms

2.3.1 Failure Mechanisms

Dielectric breakdown, terminal lead trouble, and seal or container failure are some of the chief failure mechanisms for capacitors. Temperature (ambient and operational) is the principal stressor that prompts changes in capacitor operating parameters. These changes can be gradual or catastrophic depending on temperature levels.

The rated life or design life of a capacitor is specified by the manufacturer. The service life can differ from the rated life due to degradation during storage or due to degradation caused by misapplication.

Capacitors are grouped according to their dielectric material and mechanical configuration and can have substantially different rated lives. Such differences arise from environmental and electrical effects on the chemical reactivity and mechanical strengths of materials used in their construction. Environmental factors include temperature, humidity, atmospheric pressure, and vibration. Electrical factors include operating voltage, ripple current, and charge-discharge duty cycle. Among these factors, temperature (ambient temperature and internal heating due to ripple current) is the most critical to the life of capacitors. Conditions such as vibration, shock, and humidity have less effect on capacitor life.

The effective selection, application, storage, maintenance, and replacement of instrument power supply capacitors is predicated on a sound understanding of their natural and induced causes of failure. The type of age-related failure that a particular capacitor exhibits, as well as the time it takes for a failure to occur, depends on its design, application, and environment. Under ideal conditions, the failure rate of electrolytic capacitors tends to follow some form of a traditional bathtub curve.

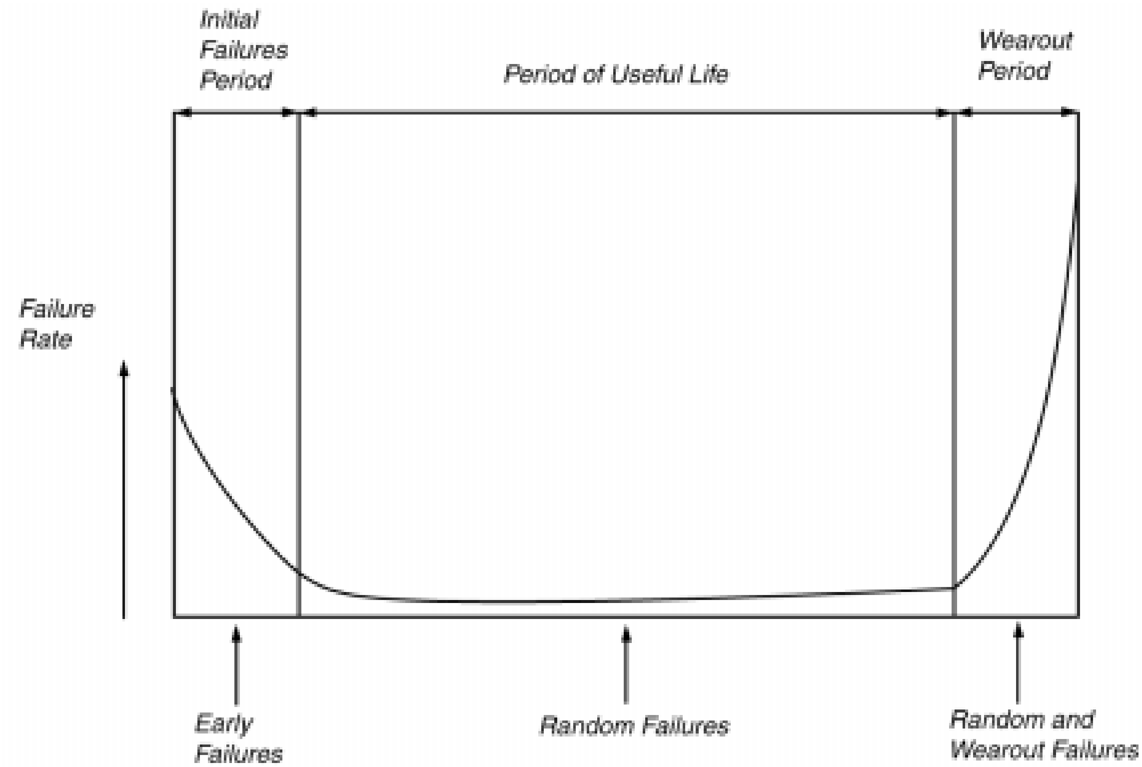


Figure 2-2
Typical Failure Rate Curve

2.3.1.1 Initial Failure Period

Early failures are typically caused by deficiencies in design, structure, manufacturing processes, or severe misapplication. Typical failure modes attributable to manufacturing include:

- Short circuits caused by foil impurities
- Defects, such as burrs
- Breaks or tears in the foil
- Breaks or tears in the separator paper

The manufacturing process has improved considerably, and new electrolytic capacitors have probably been screened and tested as part of production, with defective capacitors rejected prior to shipment. For this reason, most early failures are more likely to be caused by misapplication. Typical misapplication examples include extreme ambient conditions, exceeding rated voltage, reverse voltage, or excessive ripple current.

2.3.1.2 Period of Useful Life

After a capacitor is installed and operating within its rated parameters, the failure rate tends to be low for several years. Random failures should rarely occur for many years of operation, unless application conditions are severe.

Text books and manufacturers typically state that short circuits are the most common failure mode during the period of useful life, caused by random breakdown of the dielectric materials under operating stress. Short circuits can also be caused by excessive stress in which voltage, temperature, or ripple current exceed specified ratings. Excessive temperature, high voltage, or reverse voltage can also promote dielectric breakdown.

Some users have noted that open circuits are more common than short circuits in their power supply applications. Open circuits can be caused by failure of the internal circuits joining capacitor terminals to the foil. Mechanical connections can develop an oxide film at the contact interface, increasing contact resistance and eventually causing an open circuit. Defective weld connections can also fail. Excessive mechanical stress, such as high vibration, can accelerate this type of failure. The failure of a capacitor can be defined as either total failure (that is, short circuit or open circuit) or significant changes in parametric values that significantly affect circuit operation.

Capacitor degradation and failure are related to changes in capacitor characteristics. The operating life of a capacitor is determined by its operating voltage, ripple current, and operating temperature.

Manufacturers have used various methods such as tables, equations, charts, and combinations of all three to predict capacitor operating life.

Figure 2-3 shows a life-time nomogram that is often used to predict operating life. The information displayed in the figure is for axial and radial electrolytic capacitors rated for 85°C (185°F) and a life of 2000 hours [A.5.9]. The ripple current is generally related to a particular frequency (typically 120 hertz) and particular temperature (such as 85°C or 185°F). Appendix E provides examples of predicting capacitor life using tables.

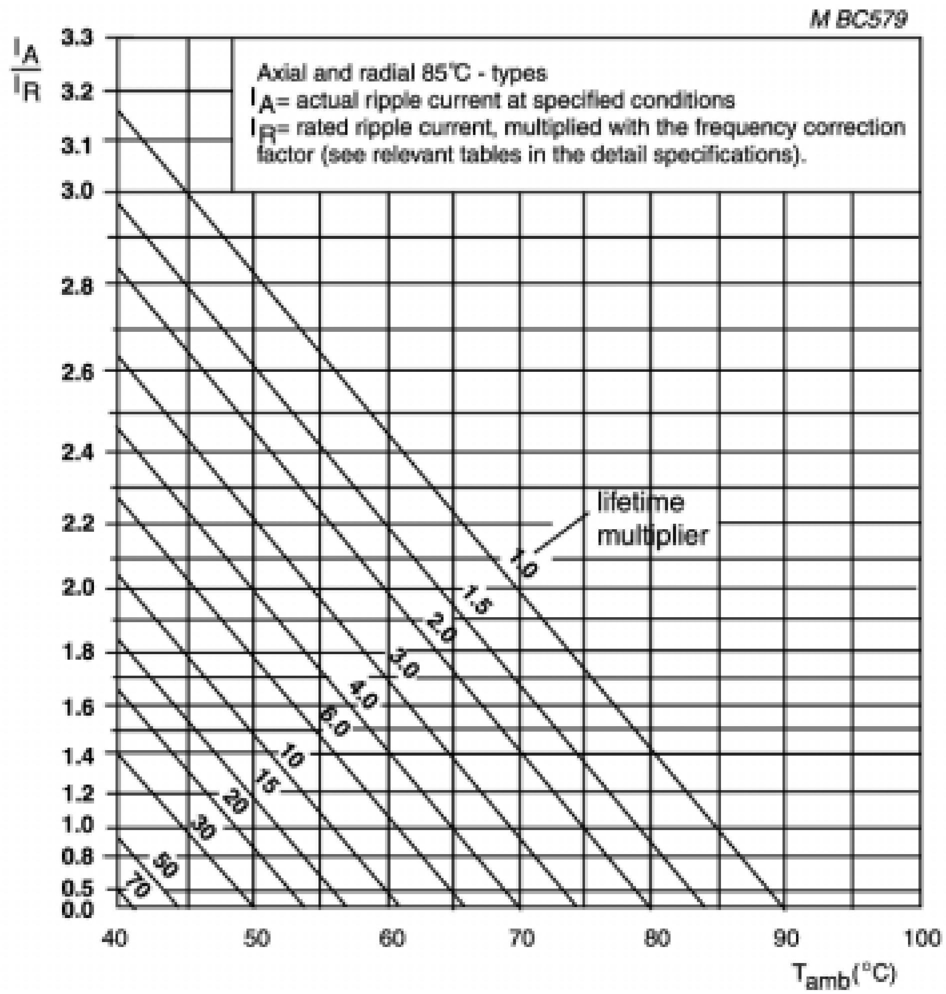


Figure 2-3
Typical Example of a Life-Time Nomogram: Useful Life As a Function of Ambient Temperature and Ripple Current Load [A.4.6]

A commonly observed failure mode is corrosive attack of the foil and terminal tabs by halogenated hydrocarbon cleaning agents absorbed through the capacitor end seal. Only cleaning agents recommended by the manufacturer should be used.

2.3.2 Stress-Induced Degradation

Stress-induced failures are not related to operating time but to application conditions that stress the capacitor. The effect of these stresses depends on characteristics inherent to capacitors, their design, and their manufacturing processes and can be evaluated relative to the capacitors' specifications.

Electrolytic capacitors, for instance, are manufactured by an electrochemical formation of an oxide on a metal surface. The metal on which the oxide film is formed serves as the anode or positive terminal of the capacitor; the oxide film is the dielectric; and the cathode or negative terminal is either a conducting liquid or a gel.

The shunt resistance (R_p in Figure 1-2) is the insulation resistance and accounts for the dc leakage current. Heat is generated in the ESR by ripple current and in the shunt resistance by voltage. The ESR is due to the spacer-electrolyte-oxide system and varies only slightly except at low temperature, where it increases greatly.

The impedance of a capacitor (Fig.2-4) is frequency dependent. The initial downward slope is caused by the capacitive reactance X_C. The trough (lowest impedance) is almost totally resistive, and the upward slope is due to the capacitor's self-inductance X_L. An ESR plot would show an ESR decrease to about 5–10 kHz, remaining relatively constant thereafter.

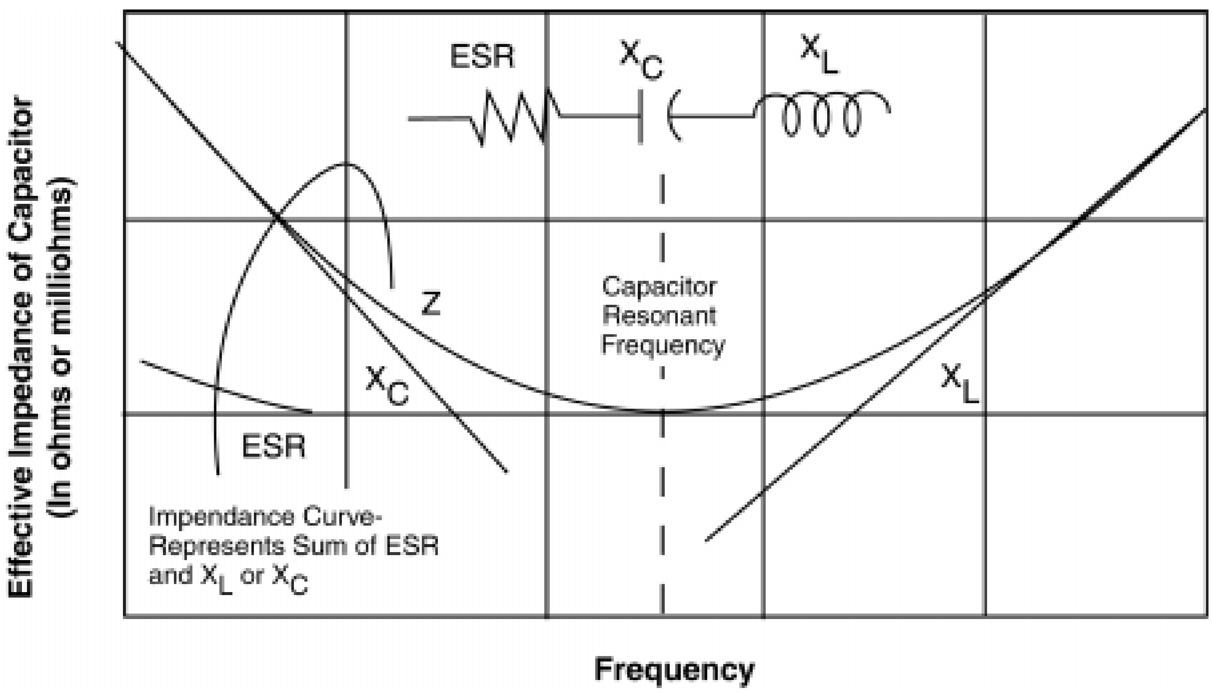


Figure 2-4
Impedance Characteristics of a Capacitor [A.5.2]

The leakage current that passes through an electrolytic capacitor is the direct current caused to flow when a correctly polarized dc voltage is applied to its terminals. It is proportional to temperature, becoming increasingly important at elevated ambient temperatures. Leakage current increases slowly after voltage is applied, reaching steady-state conditions in about 10 minutes.

The surge voltage specification of a capacitor determines its ability to withstand high transient voltages that generally occur during the start-up period of the equipment. Standard tests generally specify a short on and long off period for an interval of 24 hours or more, and the allowable surge voltage levels are generally 105% above the rated voltage of the capacitor.

Table 2-1 illustrates how temperature, applied voltage, reverse voltage, and ripple current affect measurable performance parameters of electrolytic capacitors. The following subsections discuss the effect of these stresses and the relevancy of measurable parameters to expected operating life. While each subsection focuses on a particular parameter, the degraded parameters and stresses causing the degradation are interactive from the standpoint that a change in one parameter induced by a stress may accelerate changes in others. For instance, a loss in electrolyte (weight loss) may increase ESR, creating an increase in operating temperature, which subsequently reduces capacitance and shortens the period of useful life.

Table 2-1
Effect of Application Stress on Measurable Performance

Measurable Parameters

Stressors	Drop In Capacitance	Leakage Current	Weight Loss	Increased ESR	Dielectric Absorption
Operating Temperature	X	X	X	X	X
Voltage	X	X	X		X
Reverse Voltage	X	X	X	X	X
Ripple Current	X		X	X	X

Note: Time increases the effect of the stressors listed in this table (the longer these conditions persist, the more degradation takes place).

2.3.2.1 Drop in Capacitance

Drop in capacitance is a typical sign of capacitor wear out. This change in capacitance is usually brought on by a degradation of the dielectric material within the capacitor. For aluminum electrolytics, the change in capacitance is often associated with the loss of electrolyte.

- **Drop in Capacitance vs. Temperature**

  A change in capacitance is usually due to degradation of a capacitor’s dielectric material. The degradation is gradual under normal operating conditions and is accelerated by high operating temperatures.

  In service, the electrolyte gradually evaporates through the seal, resulting in a drop in capacitance. High ambient and operating temperatures accelerate electrolyte loss. These changes are most prominent during the wear-out failure period.

- **Drop in Capacitance vs. Voltage**

  In service, if a capacitor is not exposed to voltages above its rated voltage, the life of the capacitor should not be greatly affected. However, if a capacitor is exposed to a momentary (in the microsecond range) surge voltage beyond the working voltage for that capacitor, permanent damage and drop in capacitance and other characteristics will occur.

- **Drop in Capacitance vs. Reverse Polarity**

  If a capacitor is connected with reverse polarity, the oxide film is forward-biased, offering very little resistance to current flow. This causes internal heating and oxidation of the cathode foil generating gas, which leads to venting and to possible self-destruction of the capacitor. The total heat generated in a capacitor is the sum of the heat created by the product $(I_{leakage})(V_{applied})$ and the I^2R losses in the ESR. Aluminum electrolytic capacitors can withstand up to 1.5 volts of reverse voltage without detriment. Higher reverse voltages, when applied over extended periods, lead to loss of capacitance and increased electrical losses ($\tan\delta$) as illustrated in Figure 2-5.

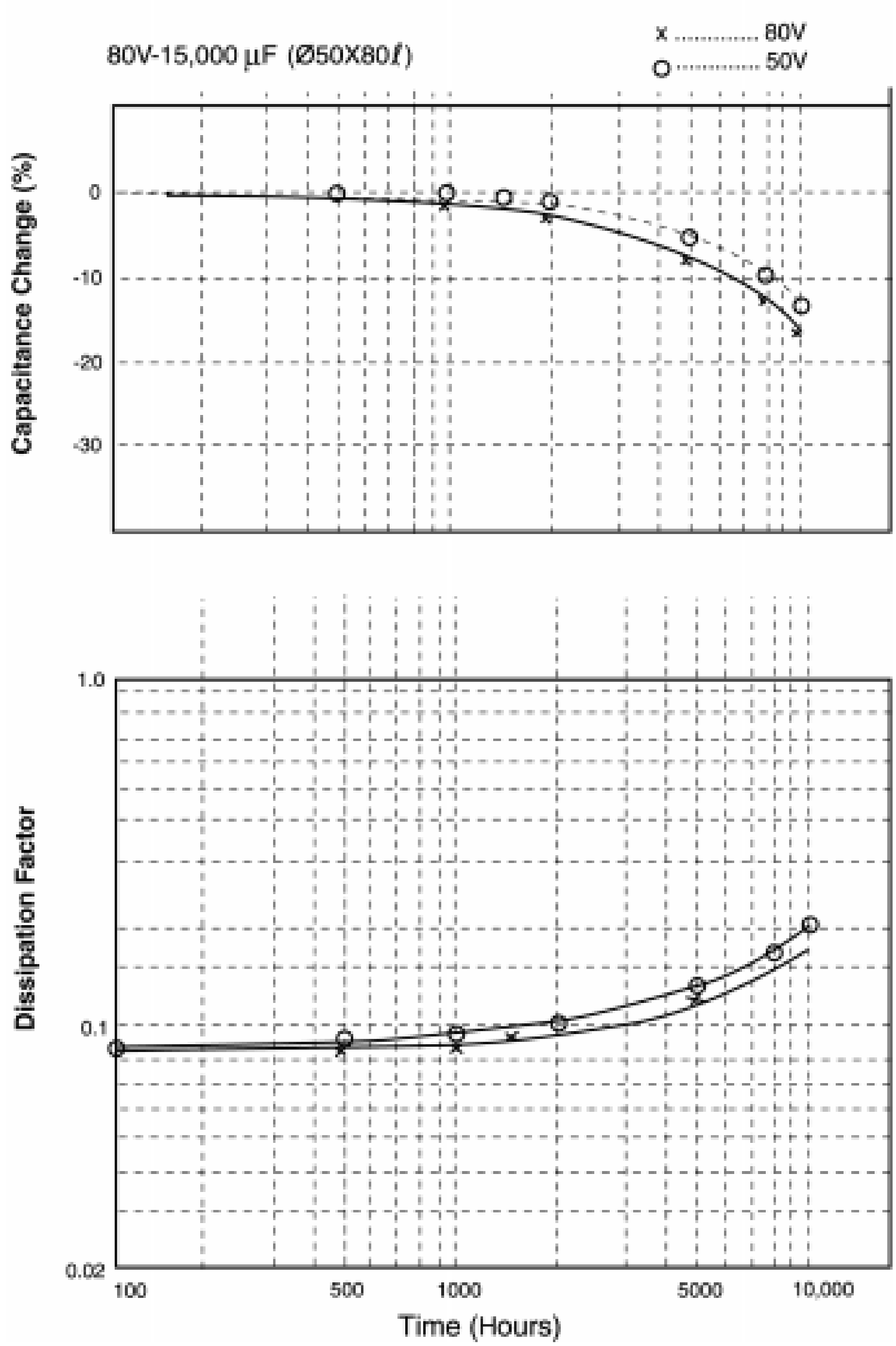


Figure 2-5
Reverse Voltage at 85°C (185°F) [A.4.7]

- **Drop in Capacitance vs. Ripple Current**

  Ripple is one of the principle considerations when selecting a capacitor for an application. Excess ripple current causes increased internal heating in the capacitor and, in turn, degrade the dielectric material of a capacitor.

For an electrolytic capacitor in service, the electrolyte gradually evaporates through the seal, resulting in a drop in capacitance. These changes are accelerated by high ambient temperatures and ripple current. This is one of the predominant failure mechanisms during the wear-out period.

2.3.2.2 Leakage Current

The dielectric of a capacitor has a very high resistance that prevents a flow of dc current. However, there are some areas in the dielectric that allow a small amount of current to pass, and this current is called the leakage current. The areas allowing current flow are due to very small impurity sites that are not homogeneous, and the dielectric formed over these impurities does not create a strong bond.

- **Leakage Current vs. Operating Temperature**

  When the capacitor is exposed to high temperatures, the bonds within the dielectric break down and the leakage current increases.

- **Leakage Current vs. Voltage**

  Under voltage-free conditions, the leakage current may increase. This increase in leakage current is due to the breakdown of the oxide layer on the anode of the capacitor. When there is no voltage applied, the oxide layer does not regenerate as it would under voltage conditions.

  The leakage current is proportional to the capacitance and increases with the applied voltage. Continuous application of excessive operating voltage rapidly increases the leakage current as illustrated by Figures 2-5 and 2-6. Internal heating and gas generation caused by increased leakage current can destroy the capacitor.

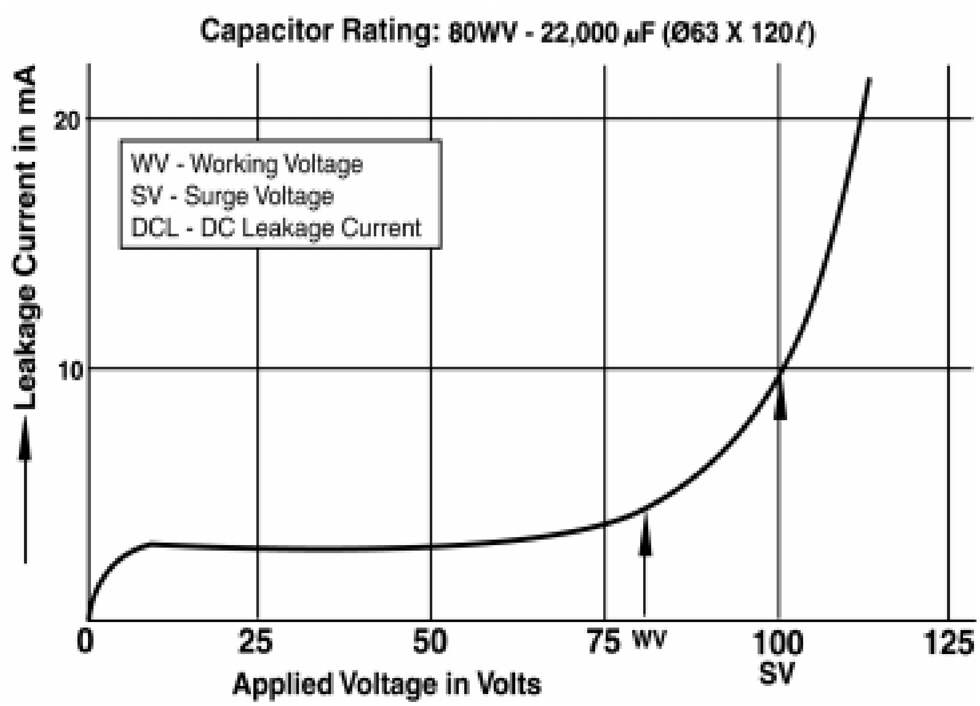


Figure 2-6
Voltage and I_{DCL} Characteristics [A.4.7]

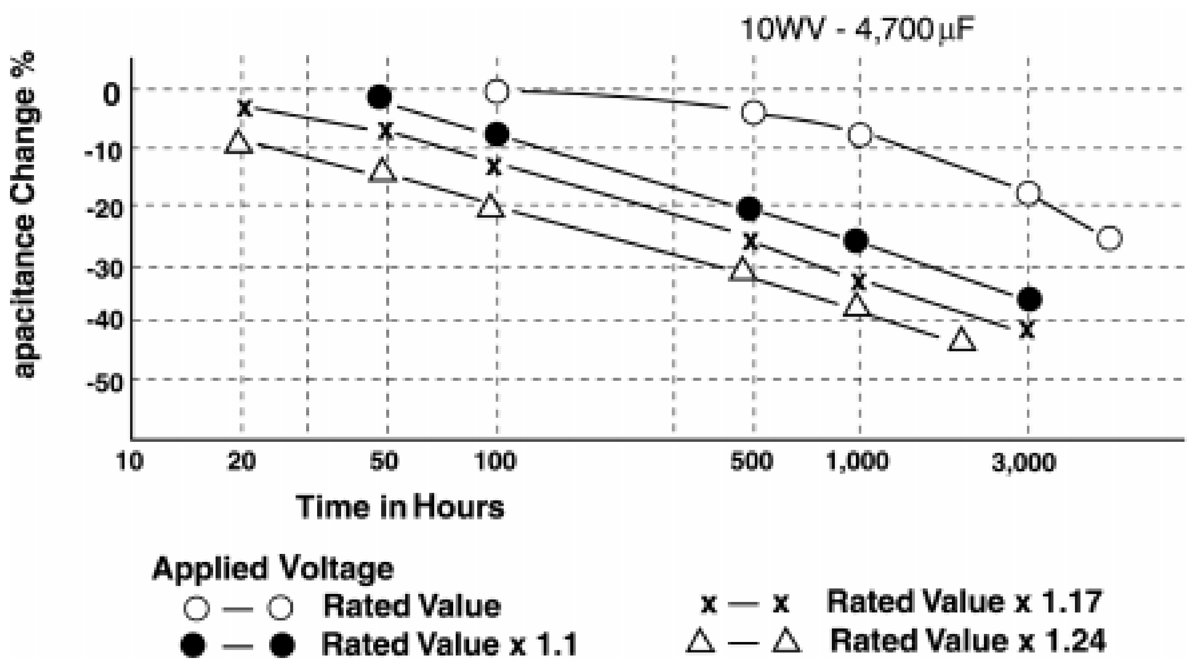


Figure 2-7
Excessive Operating Voltage at 85°C [A.4.7]

- **Leakage Current vs. Reverse Voltage**

  Unless a capacitor is designed for reverse voltage, even a small amount of reverse voltage will destroy a capacitor. A capacitor that is designed for reverse voltage has a limit to the amount of voltage that it can tolerate. As the voltage increases, the leakage current increases.

2.3.2.3 Weight Loss

Gradually, during storage and/or operation, the electrolyte in an aluminum electrolytic capacitor is lost by means of vapor transmission through the end seal. The rate of loss is directly dependent on the composition of the electrolyte, the effectiveness of the end seal, and the operating and/or storage temperatures. The expected life of the capacitor is a direct function of the rate of loss of the electrolyte. Electrolyte loss can be measured as weight loss. Capacitors in normal service should be free from electrolyte leakage. Electrolyte leakage is caused by mechanical factors such as lead stress or chemical deterioration of the seal. Electrical factors such as excessive operating voltage, excessive ripple current, reverse voltage, and ac current, which cause internal heat rise and pressure increases, can also cause electrolyte leakage. Since all stressors contribute to internal heat rise, only the operating temperature is addressed in this section.

The capacitor tends to maintain capability until 40% of the weight of the electolyte is lost. At this point, the capacitor characteristics began to change rapidly, and the capacitor is near the end of its life.

- **Weight Loss vs. Operating Temperature**

  Extensive testing shows that weight loss is linearly related to temperature throughout the useful life of each capacitor type. Figure 2-8 shows a typical life test run for 10,000 hours with weight loss plotted at five different temperatures.

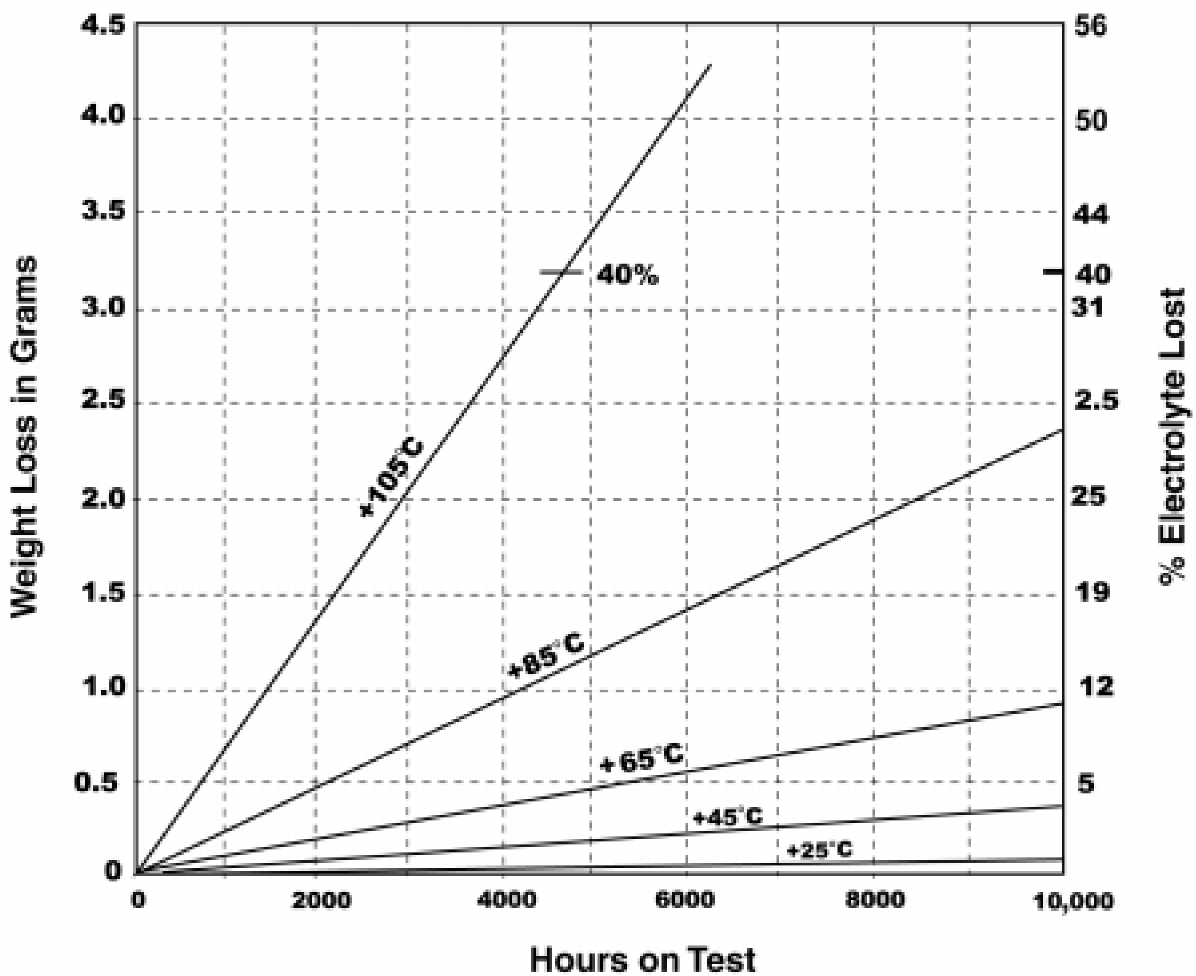


Figure 2-8
Type 604D – 85 µF, 200 VDC Weight Loss on Life Test [A.5.6]

The weight loss initially had little effect on the electrical performance of the capacitors. However, after about 40% of the electrolyte had been lost, at about 4,600 hours on the +105°C (221°F) test, the ESR increased rapidly, the capacitance decreased, and finally the capacitors appeared open.

When the capacitance drops sharply and the ESR increase accelerates, useful life ends. The electrical parameters will soon exceed the limits specified in the life test sections of the manufacturer's applicable engineering bulletins. The end of useful life corresponds to the point when 40% (by weight) of the electrolyte is lost through evaporation.

It has been a common practice to estimate that weight loss doubles for a 10°C temperature increase and halves for a 10°C decrease. Actual test data show that this is a very close approximation at normal use temperatures from +30°C (86°F) to +60°C (140°F). However, this system does not follow observed weight loss at higher temperatures. A more accurate model can be devised using Arrhenius' theory of chemical activity. Developed in 1889, the theory defines the level of chemical activity as a function of the base of the natural logarithm to the negative power of E, over temperature in degrees Kelvin.

$$K = Ae^{-E/RT}$$

where,

K = chemical reaction rate

A = intercept of activity line (a constant for a given system)

e = natural Log base (2.7183)

E = activation energy

R = gas constant (ergs/ K) (g/mole)

T = temperature in Kelvin

E/R = slope of activity line(a constant for a given system)

Figure 2-9 shows the weight loss for four typical capacitors at various temperatures.

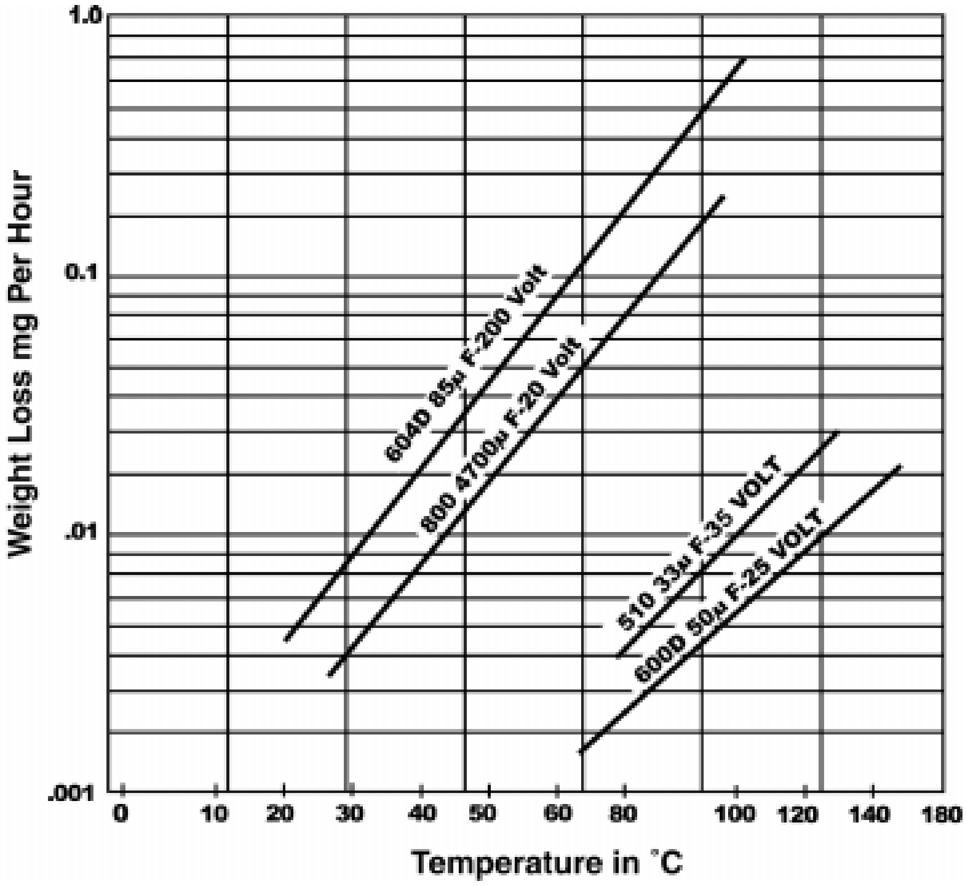


Figure 2-9
Weight Loss for Four Typical Capacitors at Various Temperatures [A.5.6]

The straight line fit shows that the Arrhenius model can be used to determine weight loss as follows:

$$W = Ae^{-B/T}$$

where,

W = weight loss in mg/hour

A = magnitude constant

e = natural Log (2.7183)

B = slope constant

T = temperature in Kelvin

Note that the model verifies the initial estimate of double weight loss for a 10°C temperature rise from +30°C (86°F) to +60°C (140°F) and follows the observed data at higher temperatures. For example, the Sprague Type 604D capacitor plotted in Figure 2-8 shows a doubling with a 14°C temperature rise near +100°C (212°F).

Additional factors affecting weight loss are the relative vapor pressure of the electrolyte and the effectiveness of the capacitor seal. However, the slope of the model varies only slightly for different capacitor ratings and styles depending on variations in the slope of the vapor pressure curves of the electrolytes.

- **Weight Loss vs. Voltage**

  Excessive voltage applied to a capacitor increases the leakage current and promotes internal heating. Internal heating promotes gas generation, electrolyte evaporation, and thus capacitor weight loss.

- **Weight Loss vs. Ripple Current**

  As the ripple current increases, the amount of heat dissipated in a capacitor increases. The heat generated is due to the current passing through the ESR of the capacitor. The temperature rise causes the loss of electrolyte, which in turn is weight loss for the capacitor.

Effect of the Capacitor Seal

The capacitor seal can have significant impact on limiting electrolyte weight loss and extending capacitor life. In particular, the size of the seal has a definite effect on weight loss. Double-ended capacitors have one-half the expected useful life of the same size single-ended capacitors.

Epoxy end seals added to standard rubber end seals prevent the absorption of halogenated hydrocarbons into the capacitor during cleaning operations. However, the epoxy end seal has only a limited long-term effect on electrolyte loss by vapor transmission.

2.3.2.4 ESR

The equivalent series resistance (ESR) is due primarily to the spacer-electrolyte-oxide system. Examination of a simplified equivalent circuit of an electrolytic capacitor (Figure 1-2) reveals two resistances. The shunt resistance represents dc leakage current. The series resistance (ESR) is responsible for the energy loss and heating effects within the unit.

- **ESR vs. Operating Temperature**

  The ESR varies inversely with the capacitor operating temperature. The effects of temperature on operational life at full rated voltage and variations related to product series are illustrated by Figure 2-10 [A.5.6]. Notice that some capacitors have an expected life of 20 years at 45°C (113°F), while others have an expected operating life of only 7 years at the same temperature. The differences in expected operating life depend on capacitor size, configuration, and quality. Premium quality capacitors generally have a longer life than standard quality capacitors.

Notice also in Figure 2-10 that all capacitors tend to fail quickly at high temperatures. Above the rated operating temperature, other failure modes can be introduced, and the failure rate increases rapidly with temperature.

The capacitor operating temperature is defined as the actual capacitor temperature, not the nearby ambient temperature, and includes any internal temperature rise caused by ripple current.

$$T_{(Operating)} = T_{(Ambient)} + \Delta T_{(Rise)}$$

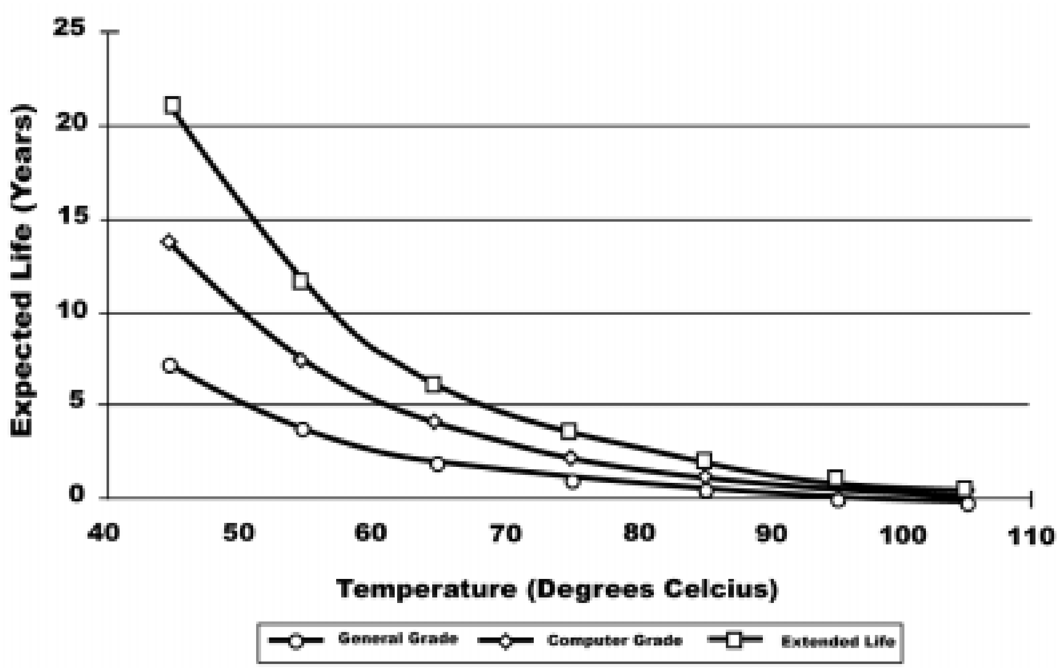


Figure 2-10
Different Capacitors – Life as a Function of Operating Temperature [A.3.1]

- **ESR vs. Ripple Current**

When ripple current flows through the capacitor, heat is generated by the power dissipated in the capacitor accompanied by a temperature increase. The increase in temperature as a function of ripple current is [A.3.1]:

$$\Delta T = I_{RMS}^{2}R/\beta\ A$$

where,

ΔT = Temperature rise produced by internal heating

I_{RMS} = Ripple current (amperes)

R = ESR (ohm)

β = Heat transfer constant (depending on can size: 0.0007 to .0013watts/in^2/°C)

A = Surface area of can

2.3.2.5 Dielectric Absorption

Dielectric absorption is the tendency of a capacitor to retain a “permanent charge” that is released to the plates after the capacitor has been discharged, causing the voltage to build up again. It contributes to the power loss in a capacitor. The apparent capacitance of a capacitor can be strongly affected by absorption effects. A capacitor measured at low frequencies might appear to have a much greater capacitance than at high frequencies. It also is associated with a component of leakage current that varies inversely with time, that is, I x t = constant.

If the discharge current is monitored under short circuit conditions, it is found to be approximately equal to the same component of leakage current. It can influence useful life in timing circuits, sample and hold circuits, A/D converters, or other analog circuits where precise waveforms must be maintained.

2.3.3 Ceramic Capacitor Degradation

Voltage, temperature, and frequency variations affect ceramic materials. Temperature will have a non-linear effect on capacitance values in a ceramic capacitor. Most manufacturers will supply data that show how the capacitance varies with temperature.

Dc voltage tends to depolarize the cells within the ceramic material, which can be manifested as a reduction in capacitance. Ac voltage tends to have the opposite effect on the polarization domains, and the capacitance increases.

An increase in frequency causes an increase in capacitance. The level of increase is dependent upon the type of ceramic capacitor. For Class 1 ceramics, the change is negligible; however, for Class 2, the change could be large.

The dissipation factor of Class 1 ceramic capacitors is stable, although for Class 2, it decreases with temperature and dc voltage and increases with frequency and ac voltage.

2.3.4 Glass Capacitor Degradation

Glass capacitors are the most stable capacitor type. Some early failures in service can be contributed to handling during installation. Improper preheat or postheat during circuit installation could cause a breach in the casing integrity of a glass capacitor.

Temperature effects are minimal for glass capacitors over their useful operating range. There is minimal deviation of capacitance over the recommended temperature range.

2.3.5 Mica Capacitor Degradation

Mica capacitors are a very stable capacitor type when manufactured and handled properly. The casing should be well sealed in order to prevent moisture intrusion. Moisture lowers insulation resistance and increases power factor and capacitance.

Operating voltage for mica capacitors should be held below the voltage rating. Ripple current (a result of the applied voltage) can contribute to the internal heating of the capacitor and limit operating life.

2.3.6 Paper Capacitor Degradation

The operating life of paper capacitors can be affected by humidity and moisture. Typically, the paper used in capacitor construction is impregnated with a liquid to increase its moisture resistance. In addition, enclosures are used to limit the transfer of moisture into the paper, but over time, the paper will absorb some moisture. For certain applications, paper capacitors are supplied in hermetically sealed containers to prevent moisture intrusion. These capacitors have high capacitance, but the dissipation factor varies widely with temperature changes. As long as the container integrity is not breached, paper capacitors provide reasonable service.

Operating temperature is one of the two major factors that determine the life of an oil-filled capacitor. Operating temperature is a combination of ambient temperature and the rise due to the power dissipated by the current passing through the capacitor.

A capacitor will have a designed voltage that should be applied to the capacitor. The combination of operating voltage and ripple voltage should not exceed the designed or what has been referred to as the “rated” voltage for the capacitor. Oil-filled capacitors should not exceed their volt-ampere rating for ac applications.

2.3.7 Film Capacitor Degradation

Dielectrics used in film capacitors are fairly resistant to moisture; however, the leads and connections should be protected from prolonged exposure to humidity. Exposure to high temperatures changes capacitor characteristics and promotes terminal failure. Elevated temperatures can be caused by high ambient, as well as operating, conditions. Operating any capacitor near its rated voltage increases the internally generated heat and contributes to dielectric breakdown.

2.3.8 Electrolytic Capacitor Degradation

Electrolytic capacitors provide a high level of capacitance with regard to size; however, temperature has some unique effects on liquid electrolytes and oxide films. Proper voltage polarity must be observed for most electrolytic capacitors. These types of capacitors are highly sensitive to reverse voltage.

2.3.8.1 Tantalum Electrolytic Capacitor Degradation

Tantalum capacitors are the most stable of the electrolytic capacitors. The are typically supplied it the following forms:

- Tantalum (solid) foil
- Tantalum (solid) chip
- Tantalum (wet)

Typical tantalum capacitors have an operating temperature range of –55°C (-67°F) to +125°C (257°F). The wet sintered tantalum is also produced in a model that can operate up to +200°C (392°F). The solid tantalum capacitor has a fairly linear capacitance vs. temperature behavior; however, the capacitance drops off rapidly for other types of tantalum capacitors because of the ion mobility in the electrolyte. Solid tantalum capacitors are limited in their ability to dissipate heat due to their small physical size.

Voltage stress increases the heat generated internally and thus contributes to the overall operating temperature. Electron mobility also affects the frequency response for foil and wet tantalum capacitors. Solid tantalum capacitors provide long life because they are not subject to loss of electrolyte as in wet and foil types. The solid tantalum fails due to oxide crystallization. As these capacitors begin to fail, the capacitance tends to decrease and the dissipation factor to increase.

The principal failure mechanism for tantalum capacitors is caused by loss of electrolyte and dielectric breakdown due to operating voltage and current.

2.3.8.2 Aluminum Electrolytic Capacitor Inservice Degradation

Aluminum and aluminum oxide electrolytic capacitors are essentially the same except for the electrolyte used. In aluminum capacitors, the electrolyte is usually an aqueous solution of ammonium borate, boric acid, and glycol. Aluminum oxide capacitors typically have a non-aqueous base electrolyte.

There is a distinction between axial and radial lead-type and can-type aluminum capacitors. They are discussed separately below.

2.3.8.2.1 Axial and Radial Lead Aluminum Electrolytic Capacitors

Axial and radial lead-type aluminum electrolytic capacitors are those typically used on printed circuits boards where space is at a premium. Due to design limitations, as the working voltage increases for these types of capacitors, the capacitance of the capacitor decreases. For example, a

Sprague 516D aluminum capacitor has a high end capacitance of 10,000 μF at 6.3 VDC but only has a high end capacitance of 33 μF at 450 VDC.

The sealing mechanism of the axial and radial lead-type aluminum electrolytic capacitor is also different (surface area and material) from the can electrolytic capacitor and prevents evaporation of the electrolyte. Evaporation is the major cause of degradation for can-type capacitors in storage.

Manufacturers have also performed many tests to demonstrate the shelf life capabilities of axial and radial lead-type aluminum electrolytic capacitors [A.4.5]. Many users of aluminum electrolytic capacitors have the misconception that an aluminum electrolytic capacitor will “deform” its oxide film if it is used at voltages under the rated voltage. Manufacturer’s data indicate that the oxide film is quite stable at the no load condition and that electrolytic capacitors do not “deform.” This stability is credited to good anodizing techniques that result in a superior oxide film, electrolyte systems most compatible with all materials used inside the capacitor, and proper derating.

2.3.8.2.2 Can Aluminum Electrolytic Capacitors

Can-type aluminum electrolytic capacitors used in power supplies, converters, and inverters are typically of high capacitance and have diameters greater than 1 inch.

The limiting factor for can electrolytic capacitors is the evaporation of the electrolyte through the capacitor seal.

As electrolytic capacitors approach the end of their life, their failure rate increases due to gradual deterioration of electrical properties, for example, leakage current. Failures are manifested by changes in the capacitor’s measurable parameters from those specified during the design of a circuit for a specific application. They can be instantaneous (catastrophic), resulting in short circuits or open circuits, or take place over time, causing a gradual deterioration in performance (wear out).

Electrolytic vapor transmission occurs through the end seal on a continuous basis throughout a capacitor’s useful life. Electrolyte loss has no significant effect on operation or reliability until the loss approaches approximately 40% of the capacitor’s initial electrolyte content (see Figure 2-8). After this amount of electrolyte has been lost, the electrical parameters deteriorate, and the capacitor is considered worn out or at end of useful life.

2.4 Summary

Capacitors should meet or exceed the rated life provided by the manufacturer. This is also true with regard to shelf life. There is limited evidence that shows that most capacitors, barring manufacturing defects, have been assigned a fairly conservative estimate of their overall capability (shelf life and service life).

Controlling the stressors that affect the life and performance of a capacitor is highly important when discussing shelf life or service life. The following list of stressors has been compiled to make the users aware of the conditions that affect capacitors in their plants.

Table 2-2
Stressors and Effect on Capacitor

Stressor	Effect
High ambient temperature	Thermal fatigue Change in operating parameters
Ohmic heating	Thermal fatigue Change in operating parameters
Temperature variations	Change in operating parameters
Voltage Overvoltage Transients (surges, sags) Ripple	Thermal fatigue Change in operating parameters Component damage Short circuit
Current Overcurrent Ripple	Thermal fatigue Change in operating parameters Component damage
Vibration	Fatigue Component damage Open circuit Electrolyte leakage
Chemical attack	Open circuit Electrolyte leakage Component damage

Some of these stressors can be brought on by both external and internal causes. The conditions that are internal to the component are related to application and/or manufacturing issues. Stressors caused by external conditions can be readily determined, such as high ambient or high operating temperature.

Routine observation should provide some insight into the onset of stressors; however, many times a thorough root cause investigation using insight from operating data must be conducted when component failures occur.

3
CAPACITOR MAINTENANCE

Capacitor maintenance generally falls into two categories: "in-service" maintenance and "in-storage" maintenance. Additionally, maintenance can be performed on either a discrete component or assembly. To focus resources, decisions must be made as to which components or assemblies require maintenance and what kind of maintenance is needed. Figure 3-1 is an example of capacitor maintenance decision guidelines.

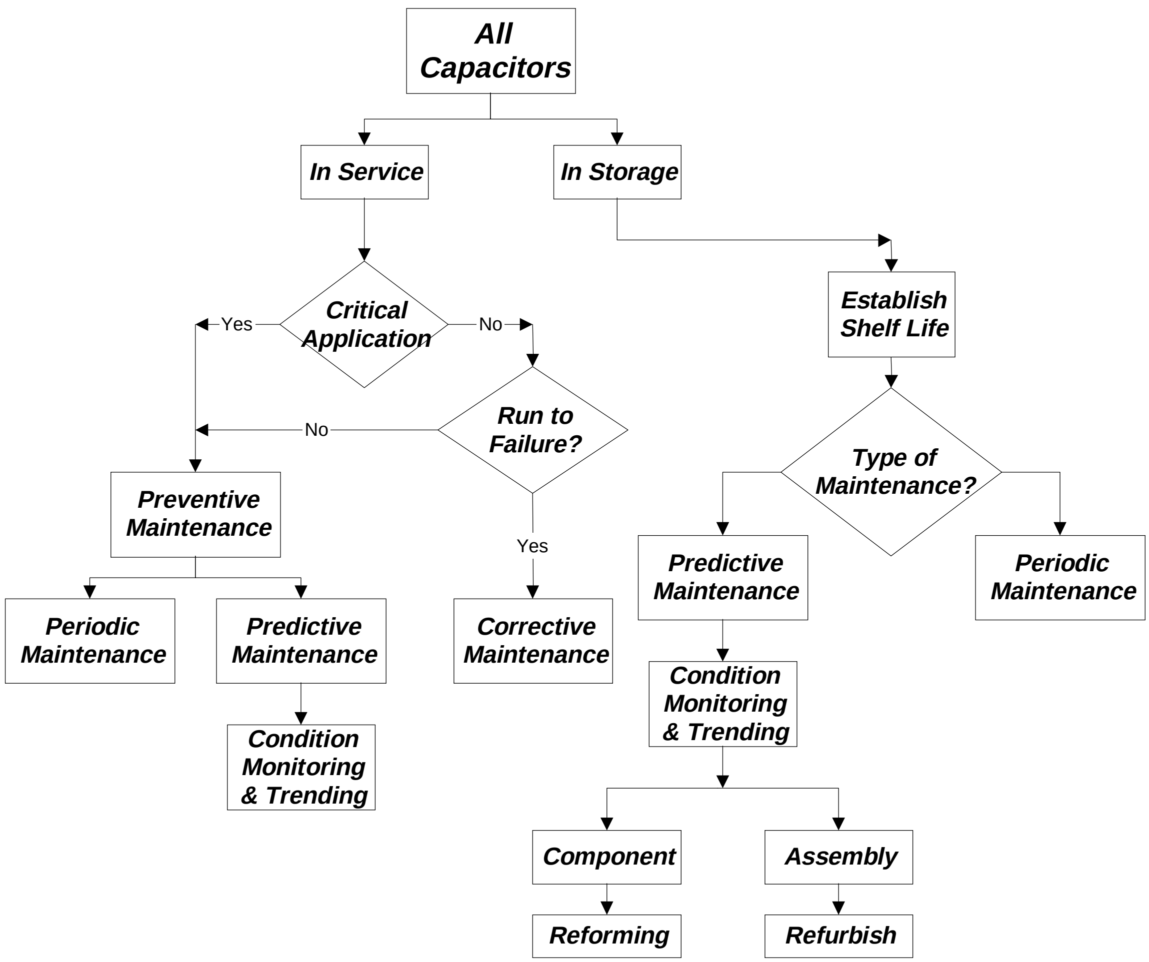


Figure 3-1
Maintenance Decision Guidelines

Three distinctly different types of maintenance tasks are typically performed on components and assemblies: periodic, predictive, and corrective. It should be noted that periodic and predictive are subsets of preventive maintenance. Descriptions of and information relevant to performing these maintenance tasks follow.

3.1 Preventive Maintenance

Most often capacitors either remain in storage for extended periods before they degrade to a level of unacceptability or must operate for many hours before they degrade to the point at which a power supply ceases to perform to specification. The identification of a life prognosis, that is, a failure prediction approach, allows scheduling of preventive maintenance in a timely manner and increases both maintenance personnel efficiency and system availability. However, these gains must be weighed against the cost of more frequent electrical measurements.

The measurements are compared to predetermined limits to validate acceptable power supply operation. Acceptance criteria can be based on vendor specifications that identify tolerances for a capacitor such as capacitance, dissipation factor, leakage current, and ripple current. Mechanisms responsible for capacitor degradation and drift in parameters that are associated with wear out have been described elsewhere in this document.

There are two types of preventive maintenance: periodic and predictive. Periodic maintenance involves establishing a service life and replacing the component or assembly at the end of its life. Predictive maintenance typically involves measuring parameters in order to determine degradation and determining appropriate action.

3.1.1 Periodic Maintenance

Service life is the anticipated life that a component should provide before significant variations in operational characteristics or total failure occurs. This is often referred to as “useful life.”

The service life of a capacitor is established based on several factors such as storage conditions, operating parameters, and operating environment. Appendix E provides manufacturer guidelines for life prediction of capacitors and example calculations. After the service life is established, the component or assembly is replaced at the end of its service life. Capacitors are typically the most age-sensitive components in an assembly and should be replaced when refurbishment of an assembly is an option. In refurbishment, careful consideration must be given to identifying other degraded components and the cost of replacing those parts.

3.1.2 Predictive Maintenance

Predictive maintenance is performed to prevent downtime by detecting imminent capacitor failures before they occur. Imminent failures are predicted through condition monitoring, that is, measurement of capacitor parameters that degrade slowly before the end of the capacitor’s life. A sound foundation for a predictive maintenance program is based on the accumulation of component life data through condition monitoring over long periods for varying applications. Through analysis of these data, trends in capacitor parameter change with time become evident, providing a basis for predicting imminent failures and remaining life. Prediction of remaining life can be used to reschedule periodicity of maintenance in real time.

3.1.2.1 Condition Monitoring

By accumulating component life data, preventive maintenance activities can be refined. The data collected should provide a basis for adjusting PM intervals. This activity should consist of taking measurements to determine equipment condition. Data should be collected over time.

3.1.2.2 Trending

Through analysis of these condition monitoring data, trends in capacitor parameter changes become evident with time, providing a basis for predicting imminent failures and remaining life. Prediction of remaining life can be used to reschedule periodicity of maintenance in real time.

3.1.3 Corrective Maintenance

Corrective maintenance encompasses removal of a failed or failing capacitor and identification of the cause of failure, for example, end of life, malfunction elsewhere in the circuit, or capacitor failure due to an overload condition exceeding its rating. Corrective action is taken to repair the malfunction, and the capacitor is replaced with an identical component or acceptable substitute.

3.2 Off-Line Monitoring for Components

Electrolytic capacitors have a limited shelf life and should be periodically tested to determine their acceptability as replacements when corrective maintenance is performed. Measurements should be made of capacitance, leakage current, dielectric absorption, and ESR. The following test approaches are recommended. If leakage current exceeds recommended values, an electrolytic capacitor should be reformed before being placed in service.

- **Capacitance**

  Two methods of measuring capacitance that are commonly used are a balanced bridge (or phase method) and an impedance meter (sometimes called a Z Meter, such as a Sencore meter). The balanced bridge performs the measurement using an ac signal and the measured value is accurate only for the frequency of measurement. Since most manufacturers test electrolytic capacitors with a 120 Hz or 1 kHz bridge, these capacitors are often marked with a value lower than would be achieved by a dc measurement. A Z Meter measurement provides a higher value than would be produced in an ac circuit.

  The Z Meter measures capacitance by measuring the time to charge the unknown capacitor through a precision resistor. The capacitance is then determined from the time constant. If the reading does not fall within the manufacturer’s tolerance, the capacitor is bad.

An open capacitor gives the same reading on the meter as an open pair of meter leads. Other capacitor defects give inconsistent readings when capacitance is measured.

- **Leakage Current**

  When measuring leakage current with a Z Meter, the rated voltage of the capacitor must be input. The meter applies the rated voltage and the leakage current through the capacitor is displayed. The maximum leakage current allowed is determined by the type of capacitor, the capacitance value, and the voltage rating of the capacitor. Maximum allowable leakage currents have been identified by the EIA (Electronic Industry Association) or have been extrapolated from other existing standards or manufacturer's data. As long as the leakage reading is less than the specified values, the capacitor is good.

- **Dielectric Absorption**

  Two methods can be applied to measure dielectric absorption. The charge-discharge method measures the capacitance before and after the leakage current test to determine the degree of capacitor discharge. The larger the difference in the two capacitance readings, the worse the dielectric absorption. In the second method, the capacitor is charged to a preset level and is then discharged. The remaining voltage on the capacitor after discharge is then measured and the percentage of voltage recovery is calculated. For example, the allowable dielectric absorption is 15% for aluminum and tantalum electrolytic capacitors.

- **ESR**

  A theoretically perfect capacitor, having no ESR, has zero voltage drop across it when voltage is initially applied. In a real capacitor, voltage rises instantaneously to a value depending on the magnitude of the ESR. A Z Meter simply charges the capacitor while measuring the rise in voltage during the first microsecond after applying the voltage. The instantaneous voltage step is used to calculate resistance using simple voltage dividing formulas.

  The maximum ESR allowed is determined by the type of capacitor, the capacitance, and the voltage rating. Maximum ESRs allowed have been identified by the EIA (Electronic Industry Association) or have been extrapolated from existing standards or manufacturer's. data. As long as the ESR measured is less than specified values, the capacitor is good.

3.3 Corrective Maintenance of Off-Line Components

If off-line monitoring of on-the-shelf components indicates measured parameters are close to exceeding maximum allowable values, reconditioning (reforming) may be in order. Aluminum electrolytic capacitors often decrease in value and develop leakage if they are stored de-energized for a long period of time. These symptoms are caused by loss of some of the aluminum oxide dielectric layer, a natural deterioration with time. If the electrolyte has not dried up, the oxide coating can be reformed by applying a dc voltage to the capacitor for a period of time. If the reforming process does not reduce the leakage current to an acceptable level, the capacitor is defective and should be discarded.

Guidance for reforming procedures can be found in the following:

- MIL-STD-1131B [A.1.22]
- EPRI TR-107044 [A.3.1]

3.4 Monitoring Frequency for Off-Line Components

Guidance to frequency of tests for stored capacitors can be found in the following:

- **MIL-STD 1131B**

  MIL-C-62 (dc aluminum, dry electrolyte, polarized) and non-military grade capacitors stored at 35°C (95°F) or less, 60 ± 15% relative humidity (RH) and air pressure of 725 ± 75 mm of Hg should be tested within six years from the date of manufacture. If they are not stored at the above conditions, they should be tested within four years of the date of manufacture or within three years of the last test. They should be disposed of after a total of 12 years [A.1.22].

- **MIL-PRF C-39018**

  Aluminum oxide capacitors stored at 40°C (104°F) or less, 50 ± 20% RH and air pressure of 725 ± 75 mm of Hg should be tested within 10 years from the date of manufacture. If they are not stored at the above conditions, they should be tested within five years of the date of manufacture or within four years from the last test. The capacitors should be disposed of after a total of 15 years [A.1.27].

3.5 Preventive Maintenance Adjustment of Off-Line Components

Both of the military specifications/standards provide a finite amount of time (in years) that capacitors are good for. Figure 2-10 refers to three grades of capacitors, some of which have expected operating lifetimes in excess of 20 years. Some extension of the life of a capacitor may be given if the capacitor continues to meet the specifications of capacitance, leakage current, dielectric absorption, and ESR. If this method is used, an increase in the testing frequency specified by the Mil Spec might be warranted (that is, every two years) if a capacitor will be used past its anticipated shelf life.

3.6 Condition Monitoring for Off-Line Electronic Assemblies

Condition monitoring is performed by making conventional voltage and current measurements. If power supplies have been on the shelf unpowered for extended periods, a soft-start method may be recommended to allow electrolytic capacitors time to reform as voltage is applied. A soft start might not be appropriate for all power supply types. Refer to the manufacturer’s data or the power supply type before energizing the power supply.

For the soft-start process, the voltage is slowly increased until the power supply reaches its rated voltage. This can be achieved as follows:

1. Connect a voltage source to the power supply's input.
2. Starting from the minimum voltage, increase the voltage source's output slowly, in increments of 10 volts/minute until the rated voltage of the power supply has been reached.
3. After 24 hours of applied voltage, verify that the output voltage is as specified by the manufacturer.

Only external measurements are made on the power supply. The following characteristics should be checked:

- DC output voltage
- DC output current (measured with an ammeter or voltmeter across a current shunt)
- Ripple voltage amplitude at the output (measured with either an oscilloscope or with a digital volt meter)
- Load regulation from no-load to full-load operation
- Line regulation with rated input voltage variation

Acceptance criteria are typically provided in the manufacturer's operating manual.

3.6.1 Rated Load Check

The dc output voltage should be measured at full-load conditions. The voltage should then be slowly decreased until the current in the load reaches a maximum value; there should be little change in output voltage for a regulated power supply. The power supply should now be delivering rated maximum current at the rated output voltage. Be careful not to short-circuit the power supply by adjusting the variable resistance to zero ohms.

3.6.2 Ripple

The peak-to-peak ripple amplitude can be measured using an oscilloscope or with an ac voltmeter. However, since the voltage waveform is not truly sinusoidal in shape, the voltmeter generally indicates a lower ripple than the oscilloscope. Unless the normal load is known, the power supply should be fully loaded while measuring the ripple. The peak-to-peak amplitude depends on the type of power supply and the filter circuit, and should typically be less than 100 mV or as specified by the manufacturer. To determine if the ripple is within the manufacturer's tolerance, measure the nominal dc level (V_{out}), as shown in Figure 3.1. The dc component associated with the ripple can be calculated from a measurement of the peak ripple voltage ($V_{dc} = 2/\pi\ V_p$). V_{dc} can then be compared to the manufacturer's ripple tolerance.

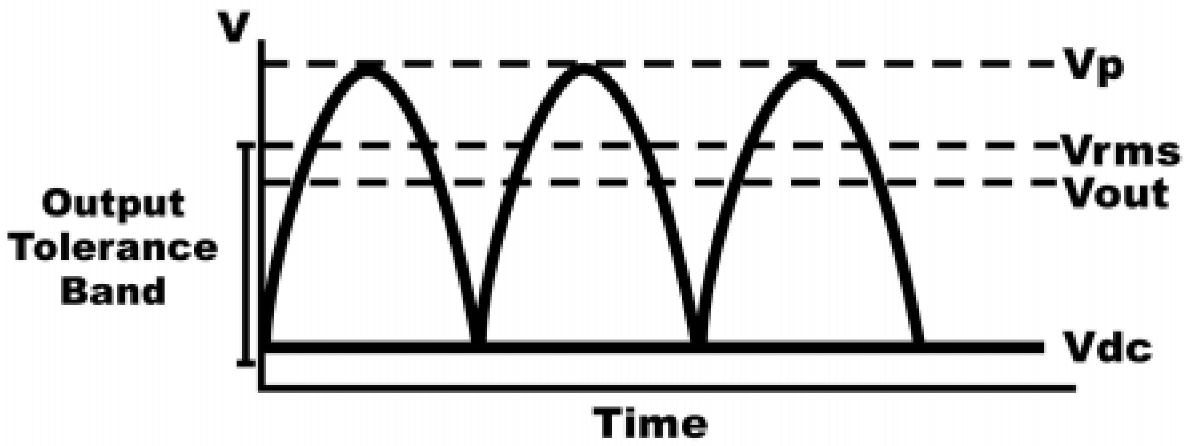


Figure 3-2
Ripple Voltage Tolerance

3.6.3 Load Regulation

The manufacturer's specification should be consulted to determine the acceptable load regulation. Since a change in voltage of less than 1% is expected, a high accuracy voltmeter should be used to measure regulation. To determine load regulation, measure the power supply output characteristic during no-load (or minimum rated load) and full-load operation while maintaining the input voltage constant at its normal value. The regulation is calculated as follows.

$$\textit{Percent Regulation} = 100\ (V_{NL} - V_{FL})/V_{FL}$$

3.6.4 Line Regulation

Line regulation (input voltage variation) varies from 2% to over 10% depending on the make and model. The regulation is checked by measuring the dc output voltage variation as the ac input voltage is changed. The measurement can be made by connecting a variac to the input of the power supply and varying the input voltage over the full range of the supply while monitoring the dc output voltage at full load. The regulation can be expressed as a ratio of the percent change in output to a given percent change in input.

3.7 Corrective Maintenance of Off-Line Electronic Assemblies

Ideally, faulty power supplies should be replaced with new ones when it is determined that the power supply does not meet the manufacturer's specifications. However, due to budgetary (or procurement) reasons, a faulty power supply might need to be repaired. Since electrolytic capacitors are considered to be the weak link in most power supplies, replacement of the electrolytic capacitors and subsequent testing might be sufficient to enable the power supply to meet the manufacturer's specifications.

3.8 Monitoring Frequency for Off-Line Electronic Assemblies

Electrolytic capacitors installed inside spare, non-energized electronic assemblies (typically kept in warehouse stock) would benefit greatly from periodic energization. Power supply vendors typically specify periodic energization of spare power supplies anywhere from once a year while in storage to once every few years. The recommended energization period varies from 1 to 24 hours. Most manufacturers suggest monitoring the parameters mentioned in Section 3.6 and comparing them to the nameplate ratings.

All power supplies are not the same. Power supplies are used in a variety of applications and are manufactured to varying quality and reliability levels. When maintenance recommendations are used to establish monitoring frequency, consideration must be given to the criticality of the expected application, the failure history of a particular power supply type, and the power supply design.

3.9 Condition Monitoring for On-Line Electronic Assemblies

Approaches to on-line condition monitoring are constrained by reluctance to disrupt operation of the power supply. Therefore, it is crucial to identify a parameter that can be measured from a readily accessible point, preferably without breaking the circuit.

3.9.1 ESR

The ESR of an electrolytic capacitor has been found to increase as the capacitor approaches the end of its life, a phenomenon related to the capacitor's loss of electrolyte. Thus, measuring the equivalent series resistance and identifying a threshold beyond which failure is imminent can provide the desired monitoring scheme. However, the direct measurement of ESR requires a circuit interruption. There is some evidence that the change in ESR is accompanied by a change in power supply output voltage. If this correlation can be established, a viable technique for accumulating trend data and establishing a threshold for failure may be available.

3.9.2 Temperature

An approach that has been considered is detection of temperature rise of the capacitor associated with an increase in ESR. Tests have been performed indicating that the temperature rise and imminent capacitor failure can be detected using infrared thermography and/or the use of remote temperature data-loggers. Its implementation requires periodically examining circuit boards of a power supply with an infrared camera or other non-contact infrared thermometer having a calibrated artificial color code. The usefulness of this technique clearly depends on the accessibility of the circuit boards or capacitors for viewing.

The data-loggers, however, may provide a more direct method of acquiring the temperature rise at a capacitor. The remote sensor option allows its placement directly on the capacitor with no interruption of the circuit and the ability to download the temperature data. With temperature rise data and ambient temperature data, the operating temperature of an output filter capacitor of an electronic assembly can be determined and then applied to the expected life of that assembly.

3.9.3 Input Voltage (and Frequency)

These parameters are measured as more of a go/no-go test and for information comparison. These measurements ensure that the input voltage and frequency are within the manufacturer's specifications for proper operation of the power supply. In some cases, a malfunctioning power supply can be attributed to the input voltage and/or frequency being outside of the manufacturer's specifications for that power supply.

3.9.4 Output Voltage

Output voltage is measured to ensure that the power supply is functioning within allowable tolerances. This is usually a manufacturer's specification and is unique to each power supply. A majority of these power supplies require adjustments over time as the power supply ages to maintain this value within allowable tolerances. However, if drastic adjustments over several consecutive intervals are required, this can be an indication of an impending failure.

3.9.5 Output Ripple Voltage

This is also a manufacturer's specification unique to each power supply and for full load of the power supply. If the application of the power supply is something less than full load, an interpretation of its value might be necessary to use it for predictive analysis.

A number of things must be considered when measuring the output ripple voltage. An excessive ripple might be due to the downstream modules, supplied by the power supply, producing a "loop effect" or "loop product." In most cases, the frequency can be quantified and is usually the frequency of the 120 VAC (60 Hz) or one of its harmonics (120 Hz, 180 Hz, etc). This would be visible when viewed with an oscilloscope or frequency meter.

An increase in ripple voltage that looks more like random noise is indicative of a failing output filter capacitor. This increase could be seen as slow and steady over many intervals or a step increase between two intervals. Be aware that a possible cause for a step increase could be caused by a fault in a downstream module or a downstream connection.

3.10 Summary

From discussions with plant personnel and survey responses, it appears that the maintenance applied to capacitors varies depending on plant experience (for example, number of failures) and equipment type.

Thermography has become an accepted method for monitoring plant components including some capacitors (chargers/rectifiers, UPS). Due to the difficulty of taking accurate camera shots for small equipment, thermography has not been widely applied to small power supplies or circuit cards.

The safety-related equipment such as chargers/rectifiers and inverters has well-established preventive maintenance programs. Capacitor change outs are done somewhere between 7 to 15 years depending on vendor recommendations and plant operating experience.

Equipment that is covered by plant technical specifications or the maintenance rule has prescribed surveillance and/or inspection intervals. Also, capacitors that are part of a larger system can be tested or inspected during system maintenance.

The following recommendations are made for equipment that might not be covered by other plant practices or plant practices that might not have been effective in preventing failures. These recommendations all hinge on the idea of good storage and handling practices. Also, devices should receive a good receipt inspection and testing before being accepted for storage. If all the proper storage and handling is done, there should be only a limited need for routine testing.

Capacitors in proper storage should not require routine testing or surveillance. A visual inspection should be sufficient to ensure that the devices have not experienced damage during storage. Periodic testing to assure component capability is a slightly different concern. However, based on limited studies, it appears that no significant changes should occur for capacitors in storage. For relative assurance, a five-year interval for checking, on a sample basis, replacement capacitors should be sufficient. If the capacitor characteristic values are within limits specified by the vendor or other industry standards, then the capacitors should be considered acceptable for service. This means that shelf life is over only when the capacitor characteristic values are outside of specifications. All capacitors should be tested prior to circuit installation; electrolytic capacitors should be reformed before being placed in service.

Assemblies containing capacitors in storage should be treated in the same manner (some type of periodic testing). These units should have requirements to inspect and test (soft-start or other power-up methods) before being placed in service.

EPRI has planned a study to establish some reasonable testing intervals for capacitors using naturally aged and artificially aged capacitors to compare their capabilities. Some of the capacitors will be placed in power supplies and operated, and certain parameters will be measured to determine if capacitor deterioration can be detected. The aging and testing will continue until the capacitor or device fails to operate. It is hoped that this will provide the user with a solid basis for what is now observed behavior for capacitors and other assemblies that use capacitors.

4 PROCUREMENT

Securing replacement capacitors for nuclear plant applications requires information that might not be readily available from equipment suppliers or capacitor vendors. During an EPRI issues meeting held in December of 1996, several capacitor suppliers stated that many of the capacitors used in typical assembled units (that is, power supplies) are not the same capacitors that are listed as available in their catalogs. This practice makes the substitution of individual (discrete components) less straight forward.

This section provides some considerations for making substitutions for components when vendor information is not readily available. There are several general considerations that can be made regarding part substitutions, but discussions with the original equipment supplier are always advisable. In light of equipment obsolescence, some vendors might not provide the same equipment or support the equipment that might be in a particular plant. In those cases, the user is left with the decision to repair the current equipment or secure a replacement unit.

There have been several EPRI documents developed to assist the user when dealing with procurement of replacement parts, such as CGICA01, NP-5652, NP-6406, and NP-6895 [A.3.14, A.3.15, A.3.16, A.3.17]. These documents provide guidance for performing a technical evaluation, determining critical characteristics, and so forth.

4.1 Discrete Components

Capacitors have wide ranges for certain characteristics (for example, capacitance), depending on the required circuit operating parameters. Generally, capacitor characteristics are specified at a given temperature and frequency. When considering the repair option for an assembly, the user must be familiar with key characteristics for the capacitor that is to be replaced and also be given some information about the environment and operating history.

Having the knowledge of general capacitor characteristics for certain applications should prove helpful when securing a replacement or making a part substitution. The user should have some knowledge of the design considerations (if possible) and general function of the equipment that is being repaired. If this limited evaluation is not done, a selected replacement part might not provide the expected performance or life.

Electrical characteristics such as capacitance and voltage ratings are usually dictated by circuit requirements; however, capacitor type, location, and mounting might be less restrictive, and the user may have more latitude in these choices. Also, as capacitor size decreases to a point, capacitor cost increases. The difficulty in manufacturing and assuring proper characteristics becomes more difficult with smaller, more compact designs.

Some general considerations that should be taken into account when a capacitor needs to be replaced are the following:

Environmental conditions: Are there any conditions in the operating environment that would adversely affect the performance of the capacitor (for example., high temperature)? Will the conditions in the environment affect the dielectric material over time or temporarily under certain conditions? Will the case material, seals, or terminal leads be affected by moisture, temperature, or pressure?

Physical arrangements: Will a new capacitor "fit" into the space provided? Are there any special brackets or modifications required to secure the capacitor in place? Will there be space limitations if the terminal arrangement is changed? Can a plug-in capacitor be replaced with a soldered-in capacitor or vice-versa? Can the capacitor be relocated on the circuit board or cabinet?

Maintenance issues: Why is this capacitor being replaced? What has been its operating history? How often does this capacitor require replacement? How much effort does it take to remove and install the capacitor? Should a different fixture be considered (plug-in arrangement) for a capacitor that has to be routinely replaced? What type of failure modes are introduced if a new type of fixture is used? Should a different type of capacitor be considered (for example, a higher working voltage or higher temperature)?

4.1.1 Method of Identifying Replacements

When a replacement capacitor is selected, the characteristics of the original capacitor should be known. If this information is not readily available, an evaluation should be done to determine at least the type and physical size of an appropriate replacement. Of course, the OEM should be the most logical source for information relating to securing a replacement component. Some considerations are provided to aid with the replacement part evaluation process.

- **Precision Capacitors**

  Capacitors falling into the precision category are generally those having exceptional capacitance stability with respect to temperature, voltage, frequency, and life. They are available in close capacitance tolerances and have low-loss (high-Q) dielectric properties. These capacitors are generally used at radio frequencies in tuner, rf filter, coupling, bypass, and temperature compensation applications. Typical capacitor types in this category are mica, ceramic, glass, and polystyrene.

- **Semi-Precision Capacitors**

  Paper and plastic film capacitors and foil or metallized dielectric constitute a large portion of general applications. These capacitors are non-polar and generally fall between the low-capacitance precision types, such as mica and ceramic, and the high-capacitance electrolytics.

- **General-Purpose Capacitors**

  Electrolytic (aluminum and tantalum) capacitors and large usage general-purpose (high dielectric constant) ceramic capacitors are grouped together because they have broad capacitance tolerances, are temperature sensitive, and have high volumetric efficiencies (capacitance-volume ratio). They are primarily used as bypass and filter capacitors where high capacitance is needed in small volumes and with guaranteed minimum values. These applications do not require the low dissipation factors, stability, or high insulation resistance found in precision and semi-precision capacitors. On a performance vs. cost basis, the general-purpose capacitors are the least expensive of the groups. High-capacitance aluminum electrolytic capacitors have been designed for computer applications featuring low equivalent series resistance and long life.

- **Suppression Capacitors**

  Feed-through capacitors are three-terminal devices designed to minimize effective inductance and to suppress rf interference over a wide frequency range. For heavy feed-through current applications (60–400 Hz power supplies), paper or film dielectrics are normally used.

- **Capacitors for Microelectronic Circuits**

  Discrete miniature capacitors are electrically suitable for microelectronic circuit use (filtering, coupling, tuning bypass, etc.). The chip capacitor, widely used in hybrid circuits, is available in single wafer or multi-layer (monolithic) ceramic construction or in tantalum construction, both offering reliable performance, very high volumetric efficiency, and a wide variety of capacitance ranges at moderate cost. Temperature-compensating ceramic chips are used where maximum capacitance stability or predictable changes in capacitance with temperature are required.

4.1.1.1 Meets Original Design

Capacitors are usually selected according to certain key characteristics. The characteristics are discussed in Section 1 of this guide. When seeking a replacement part, typically an exact replacement is sought from the original equipment manufacturer. However, products will be slightly modified over time and the user might or might not be aware of a modification, but the product may retain the same part number.

If an exact replacement cannot be obtained, a “like for like” replacement is usually the next option. “Like for like” replacement suggests that a manufacturer supplies a component that is equal in fit, form, and function to the part that it is replacing. A user should perform some confirmation testing to check component characteristics.

When a direct replacement part is not available, the user must make use of an equivalency evaluation or a part substitution to secure a suitable replacement part.

4.1.1.2 Equivalency

An equivalency evaluation would be required to ensure that a replacement capacitor meets or exceeds the original requirements. If the specifications of the original capacitor are not available (for example, may only have a capacitance value), the engineer can find a suitable replacement based on the application and using available industry standards (for example, EIA RS-395) to determine minimum performance characteristics for the type and grade of capacitor in question. Care should be used to account for any unique application requirements.

Manufacturers tend to make modifications to their products over time, and this holds true for capacitors. Capacitors with the same characteristics can be physically different and have improved ratings. This most often presents a challenge to physically fitting the capacitor in the original space; however, it can also present other problems (such as environmental).

4.1.1.3 Substitution

Guidance similar to equivalence should be used when a substitute part must be selected. The part must meet the fit, form, and function requirement to be a suitable substitute. However, with capacitors, over time the size, capability, and materials have changed even for capacitors of similar type (that is, electrolytic). Before a capacitor is chosen as a substitute, the original capacitor's cause of failure should be known. It might be possible to avoid a similar failure by securing a capacitor with different characteristics and/or a different type that can limit the effects of the previous failure causes.

- **Capacitor Derating**

  Capacitor derating involves application of electrical stresses below the component rating [A.5.10]. The objective of derating is to increase the reliability of a given part, but the degree to which derating is implemented is a compromise between an improvement in reliability and the increase in cost, size, and weight.

  Derating is accomplished in one of two ways, either by reducing the stress on the part (for example, by connecting two capacitors in parallel to halve the inrush current in each), or by increasing the part strength (for example, by using a capacitor rated at 500 volts instead of 250 volts). Failure rates normally decrease as applied stress ratios decrease. A possible exception is when stress rates are so low that power dissipation is inadequate to dispel moisture from packages, which can occur when devices are in storage.

  It is imperative that derating be cost effective. If derating is excessively conservative (that is, part ratings are much higher than necessary), costs can rise considerably. At optimum derating, a rapid decrease in failure rate is noted for small decreases in stress. There is usually a practical limit to derating. Below some stress level, capacitor size can increase drastically per unit capacitance, offsetting any reliability gain achieved by further derating.

  Some of the better known derating guidelines that give specific directions for derating of parts include the following:

- TE000-AB-GTP-010 [A.1.28]
- ESD-TR-85-148, ASD-A153-299 [A.1.16]
- MIL-STD-975K, Notice 2 [A.1.26]

Guidelines frequently used by the Department of Defense to derate aluminum electrolytic capacitor dc voltage to 80% of maximum and derate temperature by 20°C (36°F) from the maximum limit. For electrolytic tantalum capacitors, the dc voltage is derated by 50% to 60% of the maximum level and temperature is derated by 20°C. For solid tantalum capacitors, the dc voltage is derated by 50% to 60% with a maximum operating temperature of 85°C (185°F).

4.1.2 Procurement Methods

In order to find a replacement, the procurement engineer should determine the original specifications of the existing capacitor. This can be accomplished by obtaining the original manufacturer's part number, specifications, vendor manuals, bill of materials, etc. Capacitors are also physically marked by their manufacturer's logo, ratings, and/ or part number. Illustrations of this information can be found in Appendix F of this document. When this information is available, the engineer should obtain the same capacitor (if possible) or find an equivalent replacement by comparing design characteristics, application, and environment.

4.1.2.1 10CFR50 Appendix B

Capacitors could be purchased directly from a 10CFR50 Appendix B approved supplier. Appendix B to 10CFR50 establishes the quality assurance (QA) criteria for safety-related SSCs in nuclear power plants in the United States. The supplier takes the responsibility to assure that the product being purchased is equal to or better than the original part, based on original equipment information supplied at purchase.

4.1.2.2 Commercial Grade Items

Many components in the nuclear industry have become obsolete and are no longer supported or supplied by the original equipment manufacturer. These products have to be purchased commercial grade and dedicated for use in safety-related applications. EPRI report NP-5652 provides methods for dedicating commercial grade items for nuclear power plant applications [A.3.15]. Products can also be bought commercial grade and dedicated through a third party. The third-party vendor typically furnishes the quality assurance portion for securing replacement parts by providing testing and certification that a part meets the requirements of the user and/or meets the claims of the manufacturer.

4.1.3 Shelf Life Evaluation

Shelf life should be considered for capacitors that will be procured and stored for any length of time. Section 2 of this document provides some insight into the effects of time on capacitor capability. Most capacitor types (such as ceramic, glass, mica, paper, and film) are not significantly affected by normal storage conditions. In a Class A storage environment, most capacitors do not experience much change in their characteristics.

Humidity may have more effect on the material condition of a capacitor and subsequently, its capability; thus, if the terminals, seals, and other components are degraded, then the capacitor will fail prematurely.

Electrolytic capacitors (especially aluminum) have a tendency to increase in leakage current over time due to impurities and the manufacturing process. Even with these concerns, most electrolytic capacitors are given fairly conservative shelf lives by the manufacturer.

4.1.3.1 Date Codes

Date codes and manufacturer's logos are usually stamped directly on the capacitor case when size permits. The manufacturing date is used to determine the age of a capacitor. The date code usually consist of four numbers such as 9722. The first two numbers typically indicate the year and the last two represent the week of manufacture such as the 22^{nd} week of the year. There are industry standards that prescribe the manner in which dates codes should be displayed; however, some manufacturers use their own methods. Interpretation of the date code for a particular capacitor should be in the manufacturer's literature.

The manufacturing date can be used together with the receipt date to give an idea of the time that a capacitor might have been in storage at a particular site before use.

4.1.3.2 Manufacturers Lot Date

This designation is more applicable to mass produced and/or small sized capacitors (can be <1µF) that might not be easy to label directly. A manufacturer can use a lot date to designate a period during which certain capacitors might have been manufactured.

4.1.3.3 Receipt Date

Receipt date for a capacitor becomes important for making an estimate of the amount of time that a capacitor has been in possession of a user. This does not necessarily tell the user the real age of the capacitor, but it does give the user a basis for establishing a program to check the capacitor characteristics and reestablishing or setting shelf life. This information can also be used to establish PM (testing during storage) intervals for capacitors that might be selected to be periodically replaced.

4.1.3.4 Recommended Shelf Life

Vendor manuals and military specifications provide shelf life guidance for capacitor types. Also EPRI report NP-6408 [A.3.10] uses three methods to arrive at shelf life estimations for certain components including capacitors. There is a certain amount of conservatism in these numbers. If the stressors that promote material changes are controlled, the capability and component life should not be drastically altered. Electrolytics are a slight exception in that they rely on chemical reactions that are not ever completely stable. Some tantalum electrolytics use sulfuric acid, which is a corrosive compound, as an electrolyte.

Vendors typically provide shelf life guidance for their capacitors, especially for electrolytic products. Manufacturers recommend a shelf life for general-purpose aluminum electrolytic capacitors is one to two years without applied voltage. After this period of time, most manufacturers recommend reforming a capacitor before it is placed into service.

Certain premium quality aluminum electrolytic capacitors are provided with a 10-year shelf life from the manufacturer. This recommendation assumes that the component has been stored within specified temperature limits and protected from extreme humidity and moisture.

Capacitors are typically supplied with an anticipated service life. This life is typically based on the component being placed in service soon after its manufacture. However, some capacitors are not usually placed into service soon after manufacture and are stored as replacement parts.

Limited testing has been done to determine the effect that storage would have on capacitor characteristics [A.5.5]. The findings, although not altogether conclusive, demonstrated by experiment that capacitors do not "lose all capability" while on the shelf. The paper also challenges the findings for assigned shelf lives for various components including capacitors. The assertions in the paper are based on experiments conducted with naturally aged capacitors and compared to findings from other work that used artificial aging. The artificially aged capacitors appeared to have a high level of conservatism when compared to the data from the naturally aged component experiments.

4.2 Assemblies Using Capacitors

If a replacement unit is secured, the considerations for selecting particular components are still important. Although the unit might be new, there will be failures during the operating life of the unit. If on-site repair is to be an option, knowledge of the capacitor's characteristics essential for that equipment is necessary (for example, low leakage current vs. high insulation resistance).

4.2.1 Method of Identifying Replacements

Power Supply Capacitors

As can be surmised from Table 1-1, electrolytic capacitors generally have the largest value of capacitance and are often used for power supply filtering applications. Instrument power supplies routinely use electrolytic capacitors in the capacitance range of 1 to 1,500 μF, well above the capability of other capacitor types. While plastic film, mica, and ceramic capacitors are used in power supplies, the required capacitance values are substantially lower than electrolytics.

A commercial quality capacitor model developed by the Reliability Analysis Center (RAC) to predict failure rates incorporates a capacitance factor based on statistical analysis of collected failure data, that is, regression analysis and goodness-of-fit testing [A.5.10]. The premise applied is that failure rate is proportional to capacitance because capacitance is proportional to the dielectric area and as a result, the probability of a capacitor containing defects is proportional to the dielectric area [A.5.11]. Through regression analysis, the capacitance factor was found to be significantly different for electrolytic and non-electrolytic capacitor types. The relative failure rates as a function of capacitance were determined to be:

Electrolytic: $\lambda \alpha C^{.23}$

All Others: $\lambda \alpha C^{.09}$

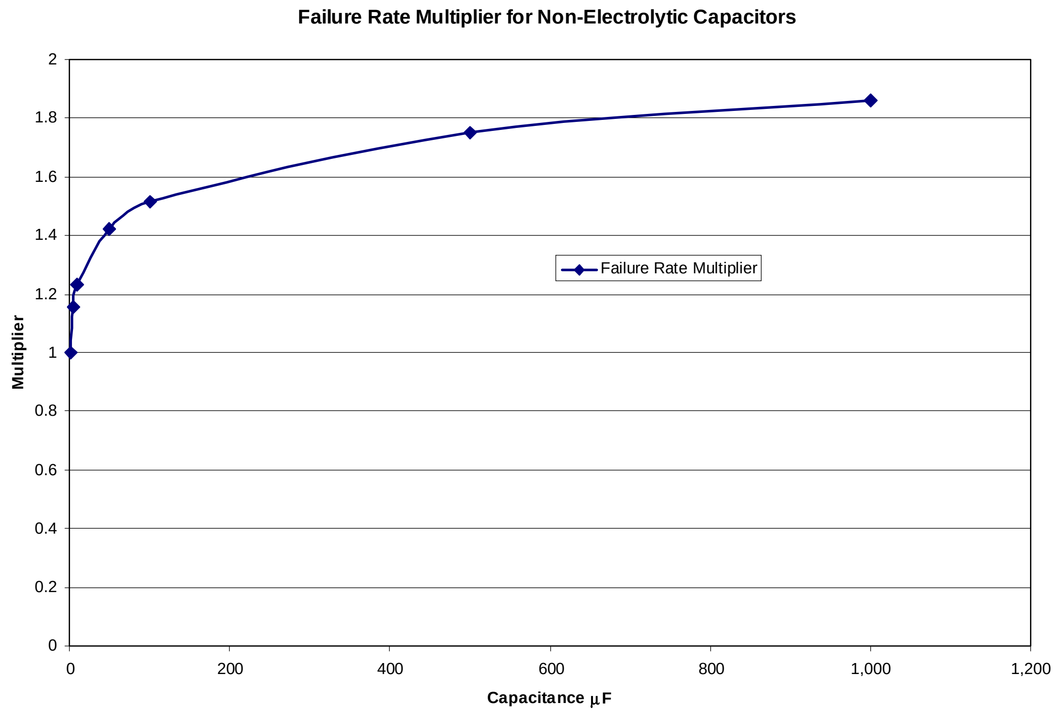
where:

λ is the failure rate

C is the capacitance in microfarads

α is "proportional to"

Clearly from the above relation, for a given capacitance value, electrolytic capacitors have a significantly higher failure rate than other capacitor types, and for capacitances less than 1 μF, lower failure rates are predicted for any type of capacitor (see Figure 4-1). Therefore, electrolytic capacitors, as opposed to other types, have more limited operational lives and are the primary concern of this document.



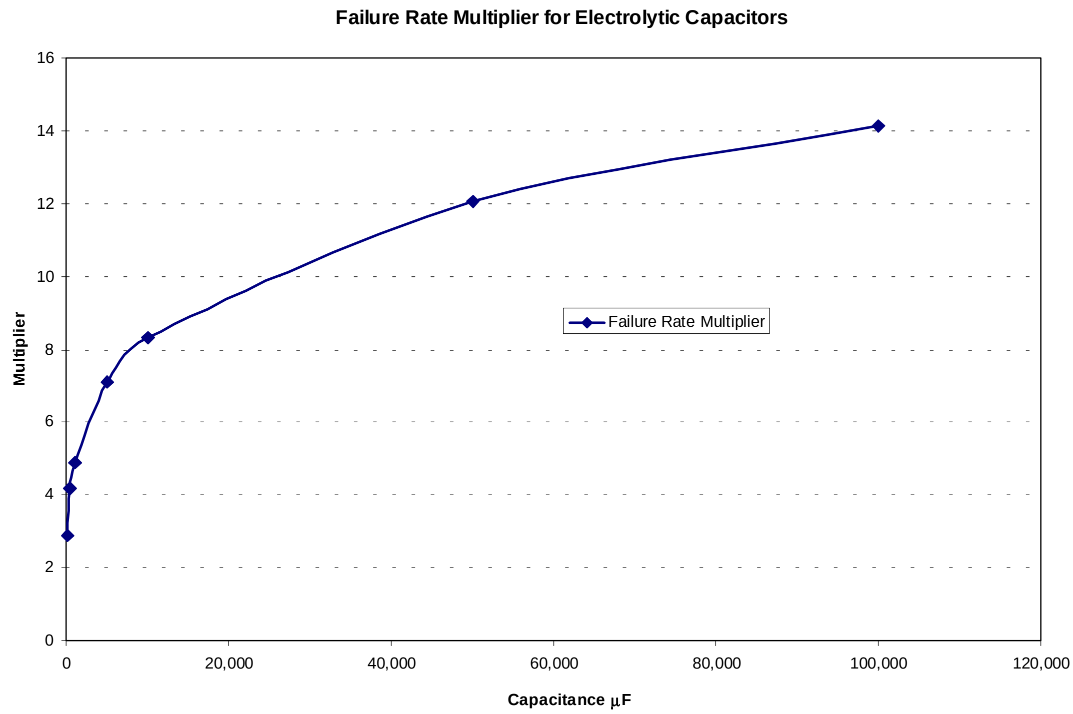


Figure 4-1
Failure Rate Multipliers

MIL-HDBK-217F provides another model for establishing capacitor failure rates based on operating conditions [A.1.20].

4.2.2 Power Supply Procurement

Power supplies were originally available from qualified suppliers. For most safety-related power supplies (especially instrument), they were supplied by OEMs or as a package from a vendor. As discussed in the discrete component section, when available, a qualified supplier (Appendix B) should be sought to supply a replacement unit.

Since many suppliers have discontinued their Appendix B programs, commercial grade items have been used as replacements after the items have undergone a dedication process.

4.2.2.1 Shelf Life Based on Age Sensitive Components

Shelf life for an assembly should be based on the most age-sensitive component in the assembly. Electrolytic capacitors appear to be the limiting component for many power supplies. There should be some discussion with the equipment vendor regarding type of component and the expected behavior over time of a specific component.

Based on the expected changes in characteristics over time, the testing and monitoring that are required to ensure assembly capability should be discussed with the supplier.

4.2.2.2 In-Storage Maintenance

Based on shelf life for age-sensitive components, the vendor should supply directions regarding testing (both type of test and test periodicity) in order to ensure that the assembly will perform reliably when placed in service.

There are not many tests currently recommended for assemblies. Reforming of aluminum electrolytic capacitors is achieved by powering up an assembly and allowing the assembly to operate for a specified period of time is the typical recommendation.

Operability testing can be done for power supplies if there is a bench set or a test instrument loop. This allows the power supply to be loaded and operated to determine its capabilities.

Usually, complete assemblies should be soft started (see Section 3.6). This allows any capacitor that might have weak places to “heal” and reduces the amount of leakage current that would flow if the capacitor were to be placed directly into service. This is typically true for assemblies that contain electrolytic capacitors.

A
REFERENCES

A.1 Industry Standards

A.1.1 EIA-153-B (ANSI/EIA-153-B-72) Molded and Dipped Mica Capacitors (Wire Lead Styles)

A.1.2 EIA 198 (ANSI/EIA-198-E-91) Individual Specifications for Ceramic Dielectric Capacitors Classes I, II, III, and IV

A.1.3 EIA-376 (ANSI/EIA-376-71) Fixed Film Dielectric Capacitors in Metallic and Non-Metallic Cases for DC Applications

A.1.4 EIA-377 (ANSI/EIA-377-71) Metallized Dielectric Capacitors in Metallic and Non-Metallic Cases for Direct Current Application

A.1.5 EIA-395 (ANSI/EIA-395-72) Polarized Aluminum Electrolytic Capacitors for Long Life (Type 1) and for General Purpose Application (Type 2)

A.1.6 EIA-401 (ANSI/EIA-401-73) Paper, Paper/Film, Film Dielectric Capacitors for Power Semiconductor Applications

A.1.7 EIA-454 (ANSI/EIA-454-78) Fixed Paper and Film-Paper Dielectric Capacitors with Non-PCB Impregnants for Alternating Current Applications

A.1.8 EIA-456-A (ANSI/EIA-456-A-89) Metallized Film Dielectric Capacitors for Alternating Current Application

A.1.9 EIA-RS-463 (ANSI/EIA-463-79) Fixed Aluminum Electrolytic Capacitors for Alternating Current Motor Starting, Heavy Duty (Type 1) and Light Duty (Type2)

A.1.10 EIA-479-A (ANSI/EIA-479-A-93) Film-Paper, Film Dielectric Capacitors for 50/60 Hz Voltage Doubler Power Supplies

A.1.11 EIA-495-A (ANSI/EIA-495-A-89) Film Dielectric Capacitors with Metallized Paper Electrodes for Alternating Current Applications

A.1.12	EIA-521	Application Guide for Multilayer Ceramic Capacitors - Electrical
A.1.13	EIA-535 Series	Fixed Tantalum Capacitors
A.1.14	EIA-580 Series	Specification for Fixed Metallized Polyethylene-Terephthalate Dielectric Capacitors
A.1.15	EIA-595	Visual and Mechanical Inspection Multilayer Ceramic Chip Capacitors
A.1.16	ESD-TR-85-148, ASD-A153-299	Derating Applications of Parts for ESD System Development
A.1.17	IEC 68 (IEC 60068-1 (1988-06)	Environmental Testing. Part 1: General and Guidance
A.1.18	IEC 384 (IEC 60384-1) (1999-03)	Fixed Capacitors for Use in Electronic Equipment - Part 1: Generic Specification
A.1.19	IEEE 1205-1993	Guide for Assessing, Monitoring, and Mitigating Aging Effects on Class IE Equipment in Nuclear Power Generating Stations
A.1.20	MIL-HDBK-217F	Reliability Prediction of Electronic Equipment
A.1.21	MIL-STD-198E	Military Standard, Capacitors, Selection and Use Of," May 29,1984, p. 602.1. Superseded by MIL-HDBK-198, Selection and Use of Capacitors, Revision, 7/14/99.
A.1.22	MIL-STD-1131B	Storage Shelf Life and Reforming Procedures for Aluminum Electrolytic Fixed Capacitors. Superseded by MIL-HDBK-1131.
A.1.23	MIL-A-A-55089A	"Capacitors, Fixed, Ceramic Dielectric"
A.1.24	MIL-C-5/8G	"Capacitors, Fixed, Mica Dielectric, Style CM50"
A.1.25	MIL-STD C-62	"General Specification for Capacitors, Fixed, Electrolytic, (DC, Aluminum, Dry Electrolyte Polarized)" *Note: Inactive for new designs, only used for replacements*
A.1.26	MIL-STD-975K, Notice 2	NASA Standard Parts Derating, 1993

A.1.27	MIL-PRF C-39018	"General Specifications for Capacitors Fixed, Electrolytic (Aluminum Oxide) Established Reliability and Non-Established Reliability"
A.1.28	TE000-AB-GTP-010, 1991	Parts Application and Reliability Information Manual for Navy Electronic Equipment

A.2 Regulatory Documents

A.2.1	NUREG/CR-4564	Operating Experience and Aging-Seismic Assessment of Battery Chargers and Inverters, Brookhaven National Laboratory, June 1986
A.2.2	NUREG/CR-5051	Detecting and Mitigating Battery Charger and Inverter Aging, Brookhaven National Laboratory, August 1988
A.2.3	NUREG/CR-5192	Testing of a Naturally Age Nuclear Power Plant Inverter and Battery Charger, Brookhaven National Laboratory, September 1988
A.2.4	Information Notice 87-24	Operational Experience Involving Losses of Electrical Inverters
A.2.5	Information Notice 94-24	Inadequate Maintenance of Uninterruptible Power Supplies and Inverters
A.2.6	Information Notice 94-33	Capacitor Failures in Westinghouse Eagle 21 Plant Protection Systems

A.3 EPRI Documents

A.3.1 *Instrument Power Supply Tech Note*. TR-107044. Palo Alto, CA: Electric Power Research Institute, December 1996.

A.3.2 *Seismic Ruggedness of Aged Electrical Components*. NP-5024. Palo Alto, CA: Electric Power Research Institute, January 1987.

A.3.3 *Correlation Between Aging and Seismic Qualification for Nuclear Plant Electrical Components.* NP-3326. Palo Alto, CA: Electric Power Research Institute, December 1983.

A.3.4 *A Review of Equipment Aging Theory and Technology*. NP-1558. Palo Alto, CA: Electric Power Research Institute, September 1980.

A.3.5 EPRI NP-4483, *Improved Reliability for Analog Instrument and Control Systems, Volume 1; Failure Analysis Guidelines for Component Selection and Replacement, Volume 2*. Palo Alto, CA: Electric Power Research Institute, May 1986.

A.3.6 *UPS Maintenance and Application Guide.* TR-100491. Palo Alto, CA: Electric Power Research Institute, August 1994.

A.3.7 Investigation of Failures in I&C Power Supply Hardware. NSAC 44. Palo Alto, CA: Electric Power Research Institute.

A.3.8 Workshop on Vital DC Power. NSAC 48. Palo Alto, CA: Electric Power Research Institute.

A.3.9 Instrument and Control Strategies for Power Plants, Volume 1; Notes on the Instrument and Control Workshop, Volume 2. NSAC 153. Palo Alto, CA: Electric Power Research Institute.

A.3.10 *Guidelines for Establishing, Maintaining, and Extending the Shelf Life Capability of Limited Life Items.* NP-6408 (NCIG-13). Palo Alto, CA: Electric Power Research Institute, May 1992.

A.3.11 *Guidelines for Determining In-Storage Maintenance for Items for Nuclear Facilities*. NP-6896 (NCIG-18). Palo Alto, CA: Electric Power Research Institute, February 1991.

A.3.12 *Guideline for Using Items Manufactured to Other Industry Standards in Nuclear* Safety-Related Applications. TR-101752. Palo Alto, CA: Electric Power Research Institute, March 1993.

A.3.13 *Application of a Cost-Benefit Analysis Methodology for Nuclear I&C System Upgrades.* TR-101984. Palo Alto, CA: Electric Power Research Institute, December 1992.

A.3.14 EPRI CGICA01, Commercial Grade Item Evaluation of Fixed Capacitors.

A.3.15 *Guidelines for the Utilization of Commerical Grade Items in Nuclear Safety-Related Applications (NCIG-07).* NP-5652. Palo Alto, CA: Electric Power Research Institute, June 1988.

A.3.16 *Guidelines for the Technical Evaluation of Replacement Items in Nuclear Power Plants (NCIG-11)*. NP-6406. Palo Alto, CA: Electric Power Research Institute, December, 1989.

A.3.17 *Guidelines for the Safety Classification of Systems, Compenents, and Parts Used in Nuclear Power Plant Applications (NGIG-17)*. NP-6895. Palo Alto, CA: Electric Power Research Institute, February 1991.

A.4 Manufacturers' References

A.4.1 GE Nuclear, SIL No. 570, Shelf Life Validation for Analogic Model 4800 Modules

A.4.2 Sencore – Servicer’s Handbook of Component Analyzing (Form 4336).

A.4.3 Mallory, “Electronic Components Catalog,” 1995.

A.4.4 Philips Components, “1990-91 Resistor/Capacitor Data Book.”

A.4.5 Sprague Technical Paper No. 62-7, “Introduction to Electrolytic Capacitors”, Henry D. Hazzard, “Axial-Lead and Miniature Aluminum Electrolytic Capacitors,” Stanley W. Dubriski, “Cylindrical Aluminum Electrolytic Capacitors,” Joseph A. Moresi.

A.4.6 Phillips Components, “General Introduction to Electrolytic Capacitors.”

A.4.7 “Understanding Aluminum Electrolytic Capacitors,” United Chemi-Con Inc., Second Edition, U7002.

A.4.8 Capacitor Technology Products, Inc., Catalog, “Application Guidelines - Capacitor Life Prediction Guidelines,” pp. 39-40.

A.4.9. Phillips Components, "1994 Electrolytic Capacitors Data Handbook." PA01-A. p. 130.

A.5 Miscellaneous References

A.5.1 *Aging Management Guideline for Commercial Nuclear Power Plants- Battery Chargers, Inverters, and Uninterruptible Power Supplies*. SAND93-7046. Sandia National Laboratories, February 1994.

A.5.2 *The Electrical Engineering Handbook*. Editor-in-Chief, R.C. Dorf, Univ. of Calif., Davis, CRC Press, 1993.

A.5.3 *Electronic Engineers Handbook, Second Edition*. Editor-in-Chief, R.C. Dorf, Univ. of Calif., Davis, CRC Press, 1982.

A.5.4 Kenneth G. Budinski. *Engineering Materials Properties and Selection*. Prentice-Hall, Inc., 1992.

A.5.5 Salvador Polanco and Anup K. Behera. “Shelf Life of Electronic/Electrical Devices.”*IEEE Transactions on Nuclear Science*, Vol. 40, No. 4, August 1993.

A.5.6 J. A. Lauber. *Aluminum Electrolytic Capacitors – Reliability, Expected Life And Shelf Capability*. Sprague Technical Paper TP 83-9, December 1985.

A.5.7 Robert Smith. “Capacitor Shelf Life.” Memo NSD-0185. Duke Power Company, June 23, 1998.

A.5.8 H. D. Hazzard. “Introduction to Aluminum Electrolytic Capacitors,” Sprague Technical Paper No. 62-7, Symposium on Aluminum Electrolytic Capacitors.

A.5.9 Robert Smith. “Duke Power Company - Shelf Life and Storage.” DPC-1381.05-00-0006.

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A.5.11 W. K Denson. “VHSIC/VHSIC-Like Reliability Prediction Modeling.” RADC-TR-89-177, October 1989.

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A.5.13 M. Brotherton. *Capacitors—Their Use in Electronic Circuits*. D. Van Nostrand Co., Inc., New York. 1946.

A.5.14 Cletus J. Kaiser. *The Capacitor Handbook, Second Edition*. C. J. Publishing, Olathe, Kansas, 1995.

A.5.15 G. Ballou, *Handbook for Sound Engineers, The New Audio Cyclopedia*. Macmillan Computer Publishing Company, Carmel, Indiana, 1991.

B
GLOSSARY OF TERMS

Aluminum Electrolytic: A capacitor with two aluminum electrodes (one with an oxide film) separated by layers of absorbent paper and electrolyte, which acts as the cathode of the capacitor.

Anode: The positive electrode of a capacitor.

Blocking: The ability of a capacitor to limit the flow of current.

Bypass: The ability of a capacitor to provide a current path around circuit elements.

Capacitance: The property of a device to store electrical energy when voltage is applied. Capacitance is measured in farads, microfarads, or picofarads. See **Farad**.

Cathode: The negative electrode of a capacitor.

Dielectric: The insulating material between the conducting plates of a capacitor.

Dielectric Absorption: The property of a material whereby all electric charges caused by an electric field are not returned to the field. The measurement of dielectric absorption is an indication of the condition of the dielectric condition.

Dielectric Constant: The characteristics of a material that determines how much electrostatic energy can be stored per unit volume when a voltage is applied. The value is measured by comparing the capacitance of a material to the capacitance of a vacuum.

Dissipation Factor: The ratio of resistance to reactance, measured in percent. See also **Power Factor.**

Electrolyte: The current-conducting solution (liquid or solid) between two electrodes of a device. A medium used to transport charged particles (electrons or ions) between conductors. Can also function as an electrode.

Equivalent Series Resistance (ESR): The sum of the resistance of the oxide film, electrolyte, separator, conductors, and lead wires of a capacitor.

Farad: The unit of capacitance measured as the ratio of the charge that exists between two conductors to an applied voltage. See **Capacitance**.

Impedance: The opposition to current flow in an alternating current circuit. The unit of measurement is the ohm. Impedance is the vector sum of resistance, capacitive reactance, and inductive reactance.

Insulation Resistance: The direct current resistance measurement across the terminals of a device.

Leakage Current: The direct current that flows through the dielectric of a capacitor when voltage is impressed across its terminals.

Nonpolarized Capacitor: Capacitors that have equal thickness of oxide film formed on both the anode (positive) and the cathode (negative). These capacitors are designed to be used in circuits that will have dc applied in either direction or in ac applications.

Permittivity: See **Dielectric Constant**.

Polarized Capacitor: Capacitors that have only one electrode with an oxide film formed on the anode (positive terminal). These capacitors are designed to operate with current flow in one direction and are used only in dc applications.

Power Factor: The ratio of resistance to impedance, measured in percent. See **Dissipation Factor.**

Quality Factor: The ratio of reactance to resistance.

Rated Voltage: The sum of the dc voltage and the superimpoed ac voltage that can be continuously applied to a capacitor.

Ripple: The ac component of a unidirectional voltage or current, usually small in comparison to the dc component.

Semipolarized Capacitor: Capacitors designed in a similar fashion to polarized capacitors with the exception of having a thin oxide layer on the cathode to allow for a small amount of reverse voltage. These capacitors are designed for dc applications where reverse voltage (les than rated) may be applied for extended periods.

Surge: A transient variation (usually short lived) in the voltage or current of a magnitude larger than the normally operating voltage or current.

Working Voltage: See **Rated Voltage**.

C
OVERVIEW OF INDUSTRY STANDARDS

EIA-153-B (ANSI/EIA-153-B-72) Molded and Dipped Mica Capacitors (Wire Lead Styles)

This standard outlines electrical, mechanical, and environmental requirements for commercial capacitors that have natural mica dielectric and wire terminations. It is a graded specification covering a variety of case sizes, capacitance values, capacitance tolerances, voltage ratings, operating temperature ranges, and temperature coefficient characteristics.

EIA 198 (ANSI/EIA-198-E-91) Individual Specifications for Ceramic Dielectric Capacitors Classes I, II, III, and IV

This standard is a revision and update of EIA-198-D covering ceramic dielectric capacitors. Revision E has been modified to contain information on new products, specifically low voltage rated and small case size surface mount capacitors. Part I of this standard provides ways to characterize ceramic capacitors electrically and mechanically by use of type designations. In addition, this part outlines dielectric classifications, marking specifications, and test sequences.

EIA-376 (ANSI/EIA-376-71) Fixed Film Dielectric Capacitors in Metallic and Non-Metallic Cases for DC Applications

This standard covers the general requirements for direct current film dielectric, fixed capacitors in metallic and non-metallic cases. Capacitors listed are primarily in entertainment, commercial, and industrial equipment for filtering, bypass, coupling, and blocking purposes where dc voltages predominate.

EIA-377 (ANSI/EIA-377-71) Metallized Dielectric Capacitors in Metallic and Non-Metallic Cases for Direct Current Application

Capacitors listed in this standard are used primarily for filtering, bypass, coupling, and blocking purposes where the dc voltage is the predominate concern. They have a small physical size and are characterized by their ability to “clear,” or resume functioning within specification limits, following momentary overloads.

EIA-395 (ANSI/EIA-395-72) Polarized Aluminum Electrolytic Capacitors for Long Life (Type 1) and for General Purpose Application (Type 2)

This standard attempts to establish uniform requirements for judging the electrical, mechanical, and environmental properties of these two types of capacitors, to describe test methods, and to give recommendations for standard ratings and dimensions.

EIA-401 (ANSI/EIA-401-73)	Paper, Paper/Film, Film Dielectric Capacitors for Power Semiconductor Applictions

This standard covers the requirements for paper film and film dielectric, oil-impregnated external foil for electrode capacitors, hermetically sealed in metal cases, and capacitors for general-purpose applications in power semiconductor circuits.

EIA-454 (ANSI/EIA-454-78)	Fixed Paper and Film-Paper Dielectric Capacitors with Non-PCB Impregnants for Alternating Current Applications

This standard is a companion document to EIA-456 and EIA-495 and describes the requirements for paper and film-paper dielectric capacitors with other than polychlorinated biphenyl (PCB) impregnants, hermetically sealed in metal cases for general-purpose application on ac voltages. These capacitors are intended for use with motors, high intensity discharge (HID) lighting ballasts, ferro resonant transformer power factor corrections, and other applications.

EIA-456-A (ANSI/EIA-456-A-89)	Metallized Film Dielectric Capacitors for Alternating Current Application

This standard describes the requirements for metallized electrode film dielectric capacitors, dry or non-PCB liquid-filled capacitors that are sealed in metal cases or in non-metal cases made of self-extinguishing material. They are intended for use in lighting ballasts, ferroresonant transformer power supplies, some power factor corrections, with motors, and other general-purpose applications. The capacitors are rated for service in 50 Hz to 60 Hz circuits at case temperature.

EIA-RS-463 (ANSI/EIA-463-79)	Fixed Aluminum Electrolytic Capacitors for Alternating Current Motor Starting, Heavy Duty (Type 1), and Light Duty (Type2)

This standard covers the requirements for aluminum electrolytic capacitors, non-polarized, sealed in plastic or aluminum cases and that are for the intermittent service starting single-phase, alternating current induction motors. The capacitors are rated for service in 50 Hz and 60 Hz circuits and can be operated in ambient temperatures. This standard was adopted and approved for DoD use in November 24,1980.

EIA-479-A (ANSI/EIA-479-A-93)	Film-Paper, Film Dielectric Capacitors for 50/60 Hz Voltage Doubler Power Supplies

This standard describes the requirements for film-paper and film dielectric capacitors impregnated and/or filled with non-PCB oil. They are intended for use in half wave or full wave voltage doubler power supplies of microwave ovens or other equipment operated from 50–60 Hz power lines.

EIA-495-A (ANSI/EIA-495-A-89)	Film Dielectric Capacitors with Metallized Paper Electrodes for Alternating Current Applications

This standard describes some of the requirements for film dielectric capacitors, oil-filled or impregnated, made with two metallized paper electrodes or one metallized paper electrode and one aluminum foil electrode, and sealed in metal cases. They are intended for use in lighting ballasts, ferroresonant transformer power supplies, some power factor correction (with motors) and other general purpose applications. The capacitors are rated for service in 50 Hz to 60 Hz circuits with case temperature range as specified within the document.

EIA-521	Application Guide for Multilayer Ceramic Capacitors - Electrical

This document covers capacitor classes I-IV. Definition of important terms are included. Factors influencing performance as temperature, voltage (ac and dc), temperature-voltage, aging, and frequency are discussed in detail. Other topics as piezoelectric properties, corona, dielectric absorption, reliability, and applications are described extensively.

EIA-535 Series	Fixed Tantalum Capacitors

This series of standards covers the various arrangements and designs for tantalum electrolytic capacitors.

EIA-580 (ANSI/EIA-580A000-91)	Specification for Fixed Chip with Metallized Electrodes and Polyethylene-Terephthalate Dielectric for use in Electronic Equipment

This standard provides preferred ratings and characteristics and select information from IEC Publication 384-1 (1982), the appropriate quality assessment procedures, tests, and measuring methods and gives general performance requirements for this type of capacitor. Test severities and requirements prescribed in detail specifications referring to this sectional specification shall be of equal or higher performance level, because lower performance levels are not permitted.

EIA-595	Visual and Mechanical Inspection Mutilayer Ceramic Chip Capacitors

This document covers the general industry inspection requirements for multilayer ceramic chip capacitors.

IEC 68 (IEC 60068-1 (1988-06)	Environmental Testing - Part 1: General and Guidance

This document enumerates a series of environmental tests and appropriate severities, and prescribes various atmospheric conditions for measurements for the ability of specimens to perform under normal conditions of transportation, storage, and operational use.

IEC 384 (IEC 60384-1) (1999-03)	Fixed capacitors for use in electronic equipment - Part 1: Generic specification

This document is applicable to fixed capacitors for use in electronic equipment. It establishes standard terms, inspection procedures, and methods of test for use in sectional and detail specifications for qualification approval and for quality assessment systems.

D
OVERVIEW OF INDUSTRY AND REGULATORY DOCUMENTS

NUREG/CR-4564	Operating Experience and Aging-Seismic Assessment of Battery Chargers and Inverters, Brookhaven National Laboratory, June 1986
NUREG/CR-5051	Detecting and Mitigating Battery Charger and Inverter Aging, Brookhaven National Laboratory, August 1988
NUREG/CR-5192	Testing of a Naturally Aged Nuclear Power Plant Inverter and Battery Charger, Brookhaven National Laboratory, September 1988

Information Notice 87-24 — Operational Experience Involving Losses of Electrical Inverters

This notice provides a case study report that highlights the failure mechanisms related to service condition parameters (for example, ambient temperature and/or humidity and voltage spikes and perturbations) that have common-cause implications.

The dominant cause of inverter losses was attributed to component failure such as diodes, fuses, silicon controlled rectifiers, capacitors, transistors, resistors, printed circuit boards, transformers, and inductors. It also appears that major contributing factors for the occurrence of component failure events are high ambient temperature and/or humidity within inverter enclosures and electrical disturbances at the inverter input/output terminals.

Information Notice 94-24 — Inadequate Maintenance of Uninterruptible Power Supplies and Inverters

The notice documents the failures of a UPS because of battery problems. It also highlights other maintenance-related issues including replacement of components.

Information Notice 94-33 — Capacitor Failures in Westinghouse Eagle 21 Plant Protection Systems

This information notice alerts the industry to two different types of capacitor failures that can cause loss of power to portions of Eagle 21 reactor protection systems manufactured by Westinghouse Electric Corporation.

E
ELECTROLYTIC CAPACITOR LIFE PREDICTION GUIDELINES

The purpose of this appendix is to examine different life prediction methodologies used by capacitor manufacturers in order to arrive at a conservative guideline that is applicable to all electrolytic capacitors.

Three manufacturers' methodologies were examined: GE/Capacitor Technology Products, United Chemi-Con, and Philips Components. Excerpts from each manufacturer's product catalogs applicable to life prediction are contained at the end of this appendix. Basically, electrolytic capacitor life is dependent on ambient temperature and temperature rise. Temperature rise is dependent on or related to ripple current. An additional life stressor is applied voltage vs. rated voltage. All manufacturers' guides use the same mathematics/derivations to arrive at a life; they just present it differently.

GE/Capacitor Technology Products, Inc.

Capacitor Technology Products has established a lifetime prediction method based upon allowable worst-case operating conditions [A.4.8]. The methodology is similar to the United Chemi-Con except for an additional term that considers the voltage stress.

SECTION I:

To calculate the predicted life expectancy at 100% duty-cycle for a given electrolytic capacitor, a number of parameters must first be determined:

1. $\mathbf{V_a}$: The applied dc voltage (worst-case) that the capacitor will experience during operation (in volts).

2. $\mathbf{V_r}$: The maximum rated dc working voltage of the capacitor intended for use in this application. This value is shown on the specification sheet or in the catalog (in volts).

3. **ESR**: The rated equivalent series resistance of the capacitor, obtained from the specification sheet or the catalog (in ohms).

4. $\mathbf{T_a}$: The highest ambient temperature in the immediate vicinity of the capacitor (in °C).

5. $\mathbf{I_a}$: The 120 hertz RMS value of the applied ripple current the capacitor will experience during operation (in amps).

6. **I_r**: The maximum 120 hertz RMS value of ripple current for which the capacitor is rated for the value of ambient temperature (T_a). This maximum value can be obtained by multiplying the 85°C current by the ripple current temperature multiplier (RCTM) for the series of capacitor and ambient temperature of interest.

   I_r = (rated current at 85°C) x (RCTM)

7. **RCTM**: The ripple current temperature multiplier. This value converts the 85°C maximum ripple current rating to a maximum rating at any other desired temperature. This value can be obtained as follows:

$$RCTM = \sqrt{\frac{(\max.\,core\ temp.) - (desired\ temp.)}{(\max.\,core\ temp.) - (85)}}$$

   The value for maximum core temperature (in °C) for the series of interest can be obtained from the (GE) Capacitor Technology Products Guidelines [A.4.8].

8. **AREA**: The surface area of the aluminum case (square inches).

9. **L_b**: The base life in hours of the series of capacitor intended for use in this application can be obtained from the (GE) Capacitor Technology Products Guidelines [A.4.8].

10. **K_t**: The thermal conductance [Watts/(C) X (sq. inch)] of the case of the capacitor to be used can be obtained from the (GE) Capacitor Technology Products Guidelines [A.4.8].

11. **T_c**: The projected core temperature that will result from the applied ripple current and determined as follows (in °C).

$$T_c = \frac{(I_a)^2 (ESR)}{(K_t)(AREA)} + T_a$$

12. **T_m**: The maximum allowable core temperature for the device of interest can be obtained from the (GE) Capacitor Technology Products Guidelines [A.4.8].

<u>SECTION II</u>:

13. **L_t**: The life extension factor due to the derating of the core temperature is obtained as follows:

$$L_t = 2^{\left[\frac{(T_m - T_c)}{10}\right]}$$

SECTION III:

Due to the heating effects generated by the product of V_a (the applied voltage) and I_a (the applied ripple current) on high-voltage capacitors and the electrical stress being placed on the anode foil, the capacitor life can be extended by reducing the ratio of the applied voltage (V_a) to the rated voltage (V_r). It is generally recommended that the level of derating be near 15%.

14. **L_v**: The extended life of the capacitor due to voltage derating can be determined as follows:

$$L_v = 2^{\left[\frac{(V_r - V_a)}{V_r} \times 6.66\right]}$$

SECTION IV:

The complete life extension factor is a product of the voltage derating factor (L_v), as well as the core temperature derating factor (L_t).

15. **L_c**: The combined factor for both voltage and core temperature derating of the capacitor can be obtained from the product of L_t and L_v as follows:

$$L_c = (L_v) \times (L_t)$$

SECTION V:

The value for the expected life of the capacitor under the given set of operating parameters can be obtained by finding the product of the base life value (L_b) and the combined derating factor (L_c)

16. **L_e**: The total extended life (in hours) due to combined derating of temperature and voltage.

$$L_e = (L_c) \times (L_b)$$

United Chemi-Con

United Chemi-Con provides the following formula that combines life approximations based on operating temperature and ripple current/load [A.4.7]:

$$L_2 = L_1 A^{\frac{T_1 - T_2}{10}} \times A^{\frac{\Delta T_1 - \Delta T_2}{k}}$$

Where:

L_1 = Significant life at temperature T_1

L_2 = Significant life at temperature T_2

T_1 = Maximum rated operating temperature (°C)

T_2 = Ambient temperature (°C)

A = Acceleration coefficient due to ambient. A ≅ 2 when T_2 is less than T_1

ΔT_1 = Allowed change in core temperature due to ripple current at rated temperature

ΔT_2 = Actual change in core temperature due to ripple current at operating conditions

k = Acceleration factor, varied from 5 to 10 by product and conditions

The ΔT's can be calculated using a derivation of the following equation:

$$I_{RMS} = \sqrt{\frac{\beta \times A \times \Delta T}{R}}$$

Where:

I_{RMS} = Ripple current (amps)

R = ESR (ohms)

β = Heat transfer constant

A = Surface area of can

ΔT = Temperature rise produced by internal heating (T_{max} - T_a)

Where:

T_{max} = Temperature of capacitor center

T_a = Ambient temperature

Re-arranging:

$$\frac{I_{RMS}{}^2 R}{\beta \times A} = \Delta T$$

ΔT represents the internal temperature rise of the capacitor due to ripple current.

United Chem-Con states, “If the applied voltage exceeds the rated voltage of the capacitor, the capacitor may be damaged from an increase in leakage current.” Additionally, United Chemi-Con cautions that the peak ac ripple voltage plus the applied dc voltage should not exceed the rated voltage of the capacitor. They do not consider applied voltage vs. rated voltage to be a significant stressor except in cases where the rated voltage is exceeded.

Philips Components

Philips Components provides capacitor life prediction guidelines in their catalog [A.4.4]. The guidelines include tables that indicate a “life multiplier” for a given core temperature vs. % of rated voltage. Core temperature can be calculated by the following equation:

$$CoreTemp = AmbientTemp + \frac{I^2 \times ESR}{\mathrm{K_t} \times Area}$$

Where:

K_t = Thermal conductivity of the case (.006 watts/sq. inch/°C)

I = Ripple current (amps)

ESR = Equivalent series resistance (ohms)

After calculating the core temperature for a particular application, the life of the capacitor can be determined. Table 1, reproduced below as Table E-1, is used to determine which life multiplier table to use:

Table E-1
Table Base Life [A.4.4]

Type	Load Life Hours	Ambient Temp. °C	Design Core Temp. °C	Life Multiplier Table
3120	3000	85	105	2
3186	1000	85	95	1
3188	2000	85	105	3
3191	1500	85	100	4
3487	1000	85	95	1
3488	2000	85	105	3
3489	1000	85	95	1

The appropriate life multiplier is multiplied by the load life listed in Table E-3 to arrive at the life of the capacitor.

Capacitor Life Prediction Examples

The following capacitor life prediction examples are presented using the three methods discussed.

The capacitor type used in the examples will be an 85°C Mallory with the following parameters [A.5.14.]:

Table E-2
Mallory Capacitor Parameters

Manufacturer	Rated Voltage	Capacitance	Catalog Part Number	Case Size DxL (in.)	ESR (Ω)	I_r (A rms)
Mallory	200	2200	CGS222T200V4C2A	2.0 X 4.125	.054	6.0

Assumptions:

T_{amb} = 45°C (40°C ambient + 5°C enclosure rise)

L_b = 1000 hours per the Mallory catalog

I_a = 3 amps

k = .006 watts/sq. in./°C (Heat transfer coefficient based on general agreement between manufacturers for this size can)

V_a = 150 volts or 75% of rated

Example #1 - Capacitor Technology Products

<u>**SECTION I**</u>:

1. $\mathbf{V_a}$: 150 volts
2. $\mathbf{V_r}$: 200 volts
3. **ESR**: 0.054 ohms
4. $\mathbf{T_a}$: 45°C
5. $\mathbf{I_a}$: 3 amps
6. $\mathbf{I_r}$: (rated current at 85°C) x (RCTM) = 6.0 X 2.2 = 13.2
7. **RCTM**: The ripple current temperature multiplier = 2.2 per Mallory catalog
8. **AREA**: 29.06 sq. in.

9. **L$_b$**: 1000 hours

10. **K$_t$**: 0.006 watts/(C) X (sq. inch)

11. **T$_c$**: The projected core temperature which will result from the applied ripple current:

$$T_c = \frac{(I_a)^2 (ESR)}{(K_t)(AREA)} + T_a = \frac{3^2 \bullet 0.054}{0.006 \bullet 29.06} + 45 = 47.79°C$$

12. **T$_m$**: 95°C (typical industry standard, rated plus 10°C hot spot allowance)

<u>SECTION II</u>:

13. **L$_t$**: The life extension factor due to the derating of the core temperature is obtained as follows:

$$L_t = 2^{\left[\frac{(T_m - T_c)}{10}\right]} = 2^{\frac{95-47.79}{10}} = 2^{4.72} = 26.37$$

<u>SECTION III</u>:

14. **L$_v$**: The extended life of the capacitor due to voltage derating can be determined as follows:

$$L_v = 2^{\left[\frac{(V_r - V_a)}{V_r} \times 6.66\right]} = 2^{\left[\frac{(200-150)}{200} \times 6.66\right]} = 2^{1.665} = 3.17$$

<u>SECTION IV</u>:

15. **L$_c$**: The combined factor for both voltage and core temperature derating of the capacitor may be obtained from the product of L$_t$ and L$_v$ as follows:

$$L_c = (L_v) \times (L_t) = 3.17 \times 26.37 = 83.5929$$

<u>SECTION V</u>:

16. **L$_e$**: The total extended life (in hours) due to combined derating of temperature and voltage.

$$L_e = (L_c) \times (L_b) = 83.5929 \times 1000 = 83{,}592\ Hours$$

Example #2 - United Chemi-Con

$$L_2 = L_1 \bullet 2^{\frac{T_1 - T_2}{10}} \bullet 2^{\frac{\Delta T_1 - \Delta T_2}{k}}$$

Where:

L_2 = ?

L_1 = 1000

T_1 = 95°C (85°C rated plus 10°C allowable heat rise at full rated ripple current)

T_2 = 45°C

Core temperature rise due to operating applied ripple current:

$$\frac{I^2 R}{\beta \times A} = \Delta T_2 = \frac{3^2 \bullet .054}{.006 \bullet 29.06} = 2.79° C$$

ΔT_2 = 2.79°C actual heat rise due to ripple current at 45°C ambient

Core temperature rise due to rated current is 10°C per manufacturer.

k = 5 (typical)

$$L_2 = L_1 \bullet 2^{\frac{T_1 - T_2}{10}} \bullet 2^{\frac{\Delta T_1 - \Delta T_2}{k}} = 1000 \bullet 2^{\frac{95-45}{10}} \bullet 2^{\frac{10-2.79}{5}} =$$

$$L_2 = 1000 \bullet 2^5 \bullet 2^{1.442} = 86{,}943\, Hours$$

Example #3 - Philips Components

Where:

K = Thermal conductivity of the case (.006 watts/sq. inch/°C)

I = Ripple current (amps) = 3 amps

ESR = Equivalent series resistance (ohms) = 0.054 ohms

Area = 29.06 sq. in.

$$CoreTemp = Ambient\ Temp + \frac{I^2 \times E.S.R.}{K \times Area} = 45 + \frac{3^2 \bullet .054}{.006 \bullet 29.06} = 47.79° C$$

After calculating the core temperature for a particular application, the life of the capacitor can be determined. Table E-1 is used to determine which life multiplier table to use. The Mallory is similar to Philips type 3186; therefore, life multiplier table (LMT) # 1 [A.4.4], shown here as Table E-3, is used.

Table E-3
Life Multiplier Table 1

CORE TEMP	% RATED VOLTAGE 75	80	85	90	95	100
95	2.6	2.2	1.8	1.5	1.2	1.0
94	2.7	2.2	1.8	1.6	1.3	1.1
93	2.9	2.4	2.0	1.6	1.3	1.2
92	3.3	2.8	2.4	1.9	1.5	1.2
91	3.6	2.9	2.4	2.0	1.6	1.3
90	3.8	3.2	2.6	2.2	1.8	1.4
89	4.2	3.4	2.8	2.3	1.9	1.5
88	4.2	3.5	3.0	2.4	1.9	1.6
87	4.6	3.9	3.2	2.6	2.1	1.7
86	5.0	4.2	3.4	2.9	2.4	1.9
85	5.3	4.4	3.6	3.0	2.4	2.0
84	5.8	4.9	4.0	3.2	2.6	2.1
83	6.2	5.2	4.2	3.5	2.8	2.3
82	6.6	5.5	4.4	3.7	3.0	2.5
81	7.3	6.1	5.0	4.1	3.3	2.6
80	7.9	6.5	5.4	4.4	3.5	2.8
79	8.3	6.8	5.6	4.5	3.7	3.0
78	9.1	7.5	6.1	5.0	4.0	3.3
77	9.6	7.9	6.4	5.3	4.2	3.5
76	10.5	8.6	7.1	5.7	4.7	3.7
75	11.3	9.2	7.5	6.1	5.0	4.0
74	12.2	10.0	8.1	6.6	5.3	4.3
73	12.9	10.6	8.8	7.0	5.6	4.6
72	14.1	11.4	9.4	7.6	6.1	4.9
71	15.1	12.4	10.0	8.1	6.6	5.3
70	16.3	13.3	10.6	8.8	7.1	5.7
69	17.9	14.2	11.6	9.3	7.5	6.1
68	18.8	15.4	12.4	10.1	8.1	6.5
67	20.0	16.3	13.2	10.7	8.6	7.0
66	21.7	17.6	14.3	11.8	9.3	7.5
65	23.3	18.9	15.3	12.4	10.0	8.0
64	25.2	20.4	16.5	13.3	10.7	8.6
63	27.0	21.9	17.6	14.2	11.4	9.2
62	29.1	23.5	19.0	15.3	12.4	9.8
61	31.2	25.3	20.4	16.4	13.2	10.6
60	33.4	26.9	21.7	17.5	14.1	11.3
59	35.9	29.0	23.3	18.7	15.1	12.1
58	38.8	31.3	25.2	20.3	16.2	13.0
57	41.5	33.5	26.9	21.6	17.3	13.9
56	44.7	36.0	28.9	23.2	18.6	14.9
55	48.0	38.6	31.0	24.9	19.9	16.0
54	51.5	41.4	33.4	26.6	21.3	17.2
53	55.6	44.6	35.8	28.7	23.0	18.4
52	59.6	47.9	38.4	30.7	24.6	19.7
51	64.1	51.3	41.1	32.9	26.4	21.1
50	68.8	55.2	44.2	35.4	28.3	22.6
49	74.0	59.2	47.4	37.9	30.3	24.2
48	79.6	63.7	51.0	40.7	32.5	26.0
47	85.6	68.9	54.6	43.7	34.9	27.9
46	91.8	73.3	58.5	46.8	37.4	29.9
45	98.5	78.6	62.8	50.2	40.0	32.0
44	105.9	84.4	67.3	53.8	42.9	34.3
43	113.9	90.6	72.4	57.7	46.1	36.8
42	122.3	97.4	77.6	61.9	49.4	39.4
41	131.3	104.5	83.3	66.3	52.9	42.2
40	141.1	112.2	89.3	71.2	56.8	45.3
39	151.3	120.4	95.7	76.3	60.8	48.5
38	162.7	129.2	102.8	81.9	65.2	52.0
37	174.7	138.7	110.3	87.8	69.9	55.7
36	187.6	148.9	118.3	94.1	75.0	59.7
35	201.4	159.7	126.8	100.9	80.3	64.0
34	216.2	171.4	136.1	100.2	86.1	68.6
33	232.5	184.2	146.1	116.1	92.4	73.5
32	249.4	197.5	156.7	124.4	99.0	78.8
31	267.9	212.0	168.1	133.5	106.1	84.5
30	287.5	227.4	180.2	143.1	113.8	90.5
29	308.6	244.0	193.3	153.4	121.9	97.0
28	331.3	261.8	207.3	164.5	130.7	104.0
27	355.6	280.8	222.3	176.3	140.1	111.4
26	382.0	301.6	238.6	189.2	150.3	119.4
25	409.9	323.4	255.8	202.8	161.0	128.0

The % of rated voltage is 150/200 or 75%.

From Table E-3, using a core temperature of 48°C and 75% of rated voltage, the life multiplier is 79.6. The life of the capacitor is:

$$L_e = L_b \times \mathit{Life\ Multiplier} = 1000 \times 79.6 = 79{,}600\,\mathit{Hours}$$

Evaluation/Recommendation

The lives calculated by the three different methods are:

GE/Capacitor Technology Products	83,597 hours or 9.5 years
United Chemi-Con	86,943 hours or 9.9 years
Philips Components	79,600 hours or 9.1 years

The 79,600 hours was arrived at using the life multiplier table E-3 provided by Philips. The core temperature was rounded up to 48°C to be conservative. The life multiplier at 47°C is 85.6 which would have yielded a life of 85,600 hours. The actual life is somewhere in between. Using a curve-fitting program, the multiplier was calculated to be 80.5 at 47.79°C. The Philips life, using interpolation, is 80,500 hours. It is also very difficult to determine how much conservatism is built into the life multiplier tables.

The United Chemi-Con estimate is the highest due to uncertainties in their formula. The most apparent being the value of “k”. United Chemi-Con states that the acceleration coefficient k varies with the change in temperature due to ripple current and the product series.

$$k \cong 5 \sim 10$$

Since the actual value of k for the Mallory capacitor used in the example is not known, 5, as used in the example, may be too low and, as a result, produces a higher life. The whole ripple current term in the United Chemi-Con equation is very sensitive to k; therefore, having an accurate value of k would produce a better-defined life by increasing the accuracy of the equation. The value of k can be obtained from United Chemi-Con for a particular capacitor.

The GE/Capacitor Technology Products method seems to arrive at a life using more and better defined parameters than the other two methods. Since none of the parameters are manufacturer specific, such as the value of k for United Chemi-Con, and available from a typical capacitor specification sheet, this method would be applicable to any electrolytic capacitor.

It is recommended that the GE/Capacitor Technology Product be used for capacitors whose manufacturer does not provide life prediction guidelines. In all other cases, the manufacturer’s guidelines should be followed unless technical justification can be provided to use other methodology.

F
IDENTIFICATION OF CAPACITORS

Manufacturing Date

Most capacitors have the manufacturing date printed on the case along with the label (see Figures F-1 and F-2) [A.4.2.]. This date is printed in the form of a four-digit number. The first two digits represent the year the capacitor was produced, and the last two numbers signify the week of the year it was produced. For example, a capacitor made in the 26th week would have a date code of 9726 stamped on its case. By checking this date, you can determine how long the capacitor has been manufactured and associate it with shelf life.

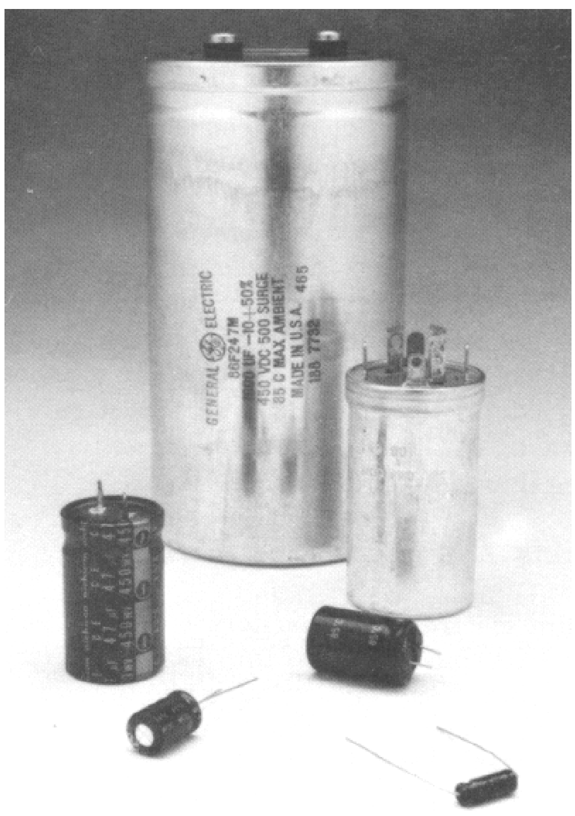


Figure F-1
Aluminum Electrolytics Package [A.4.2.]

Identifying Aluminum Capacitors

Aluminum electrolytic capacitors are the easiest capacitor types to identify. They are most commonly cylinder shaped and have screw terminals or solder lugs. The case of an aluminum electrolytic capacitor usually is rolled in or formed out near the lead in to hold the end cap and seal. All aluminum electrolytic capacitors have a seal that is soft and rubber-like to allow gases to vent. Depending on the physical size of the case, the soft seal might make up the entire end of the case, or it might be just the small section of a hard end cap.

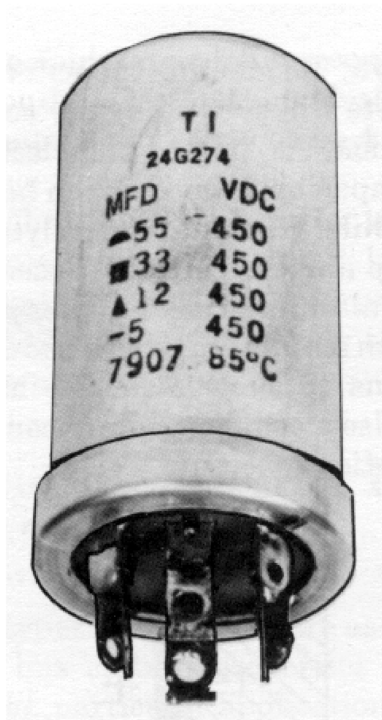


Figure F-2
Date Code and Other Markings on Aluminum Electrolytic Capacitors

Aluminum electrolytic capacitors have a large physical size to capacity ratio. These capacitors can also have several sections, with each section having a different capacitance value but sharing the same negative terminal, usually the case.

Because of their unique physical characteristics, most aluminum electrolytic capacitors are not easily confused with other capacitor types. Axial lead aluminum electrolytic capacitors, however, may possibly be mistaken for axial lead tantalum electrolytic capacitors. The lead weld is an identifying characteristic of the tantalum electrolytic and is a quick way to differentiate between an axial lead aluminum electrolytic and a tantalum electrolytic capacitor. Aluminum electrolytic capacitors do not have a lead weld on either terminal.

Identifying Tantalum Electrolytic Capacitors

Tantalum electrolytic capacitors are rapidly replacing aluminum electrolytic capacitors in many electronic circuits. Besides having less leakage and higher value tolerances than aluminum electrolytic capacitors, tantalum capacitors are about one half the size of a similar aluminum electrolytic capacitor of the same value and voltage rating.

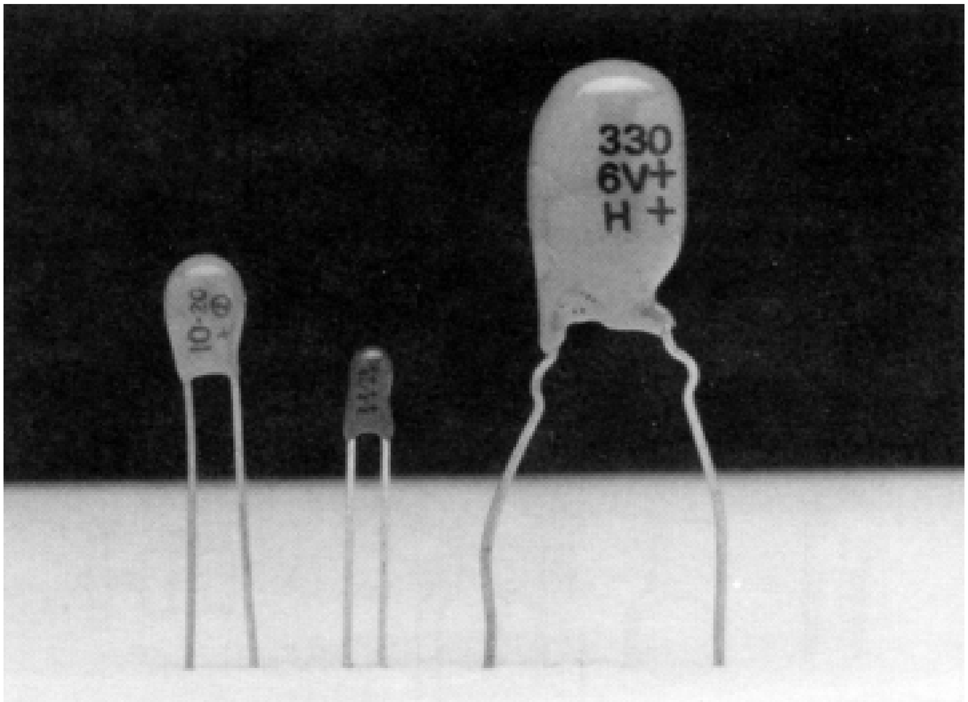


Figure F-3
Tantalum Electrolytic Capacitors

The most common shapes of tantalum capacitors are illustrated in Figures F-3 and F-4. While they may have many shapes, tantalum capacitors always have polarized leads. Lead polarization is often the only way to distinguish a tantalum electrolytic capacitor from another type of capacitor.

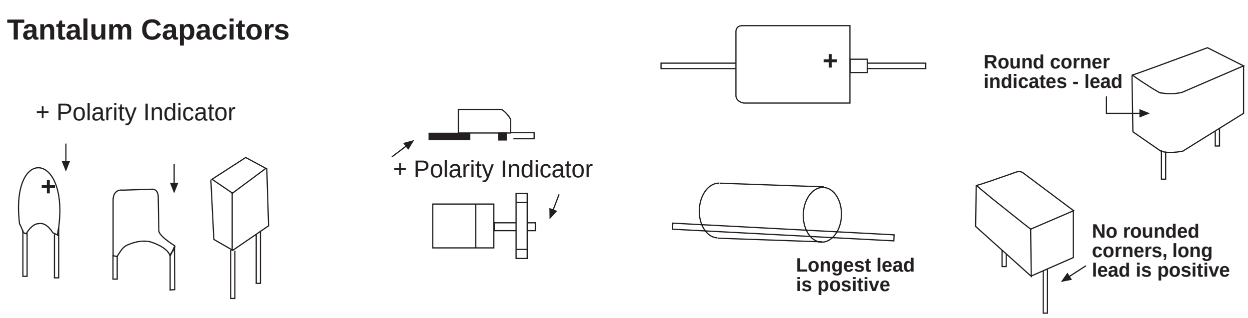


Figure F-4
Polarity Indicators for Tantalum Electrolytic Capacitors

After you become familiar with the polarity markings used, tantalum electrolytic capacitors are not difficult to identify. The polarity markings are not meant to be difficult to notice or understand, although if you are not aware of them, they might be overlooked. Pay careful attention so that you do not overlook the polarity indication and misidentify a tantalum capacitor as another type.

The simplest and most common polarity indicator is a “+”sign near one of the leads. This is often used along with a second type of indicator. Figure F-4 shows several examples of lead identification used in tantalum capacitors. In addition to the “+”sign, each capacitor shown has a second indication of the “+” lead: a lead weld, a tapered case, a rounded corner, a line, or an extra ridge near the “+” lead.

A “+” indicator is not printed on all tantalum capacitors. In many cases, the polarity indicator is simply the lead weld, a tapered case or rounded corner, a line or an extra ridge on the case. Several other polarity identifiers are also used. The end or side nearest the plus might be painted one color. Also at times, just a dot or a line on the side of the package is used.

Tantalum capacitors are also available in the small surface mount or “chip” type. Tantalum chip capacitors could be confused with the ceramic chip capacitors because they are similar in size and appearance at first glance. But as Figure F-5 shows, a tantalum capacitor is polarized and has an easily identifiable positive lead.

The polarity identification that might give you the most difficulty in identifying a tantalum capacitor is lead length. The only identification of the positive lead on some tantalum capacitors is that it is longer than the other lead. Of course, this presents no problem when the capacitor is new, but after it has been installed into a circuit board, the leads are cut off to the same length. In this situation, use the circuit as the clue to the capacitor’s type and polarity.

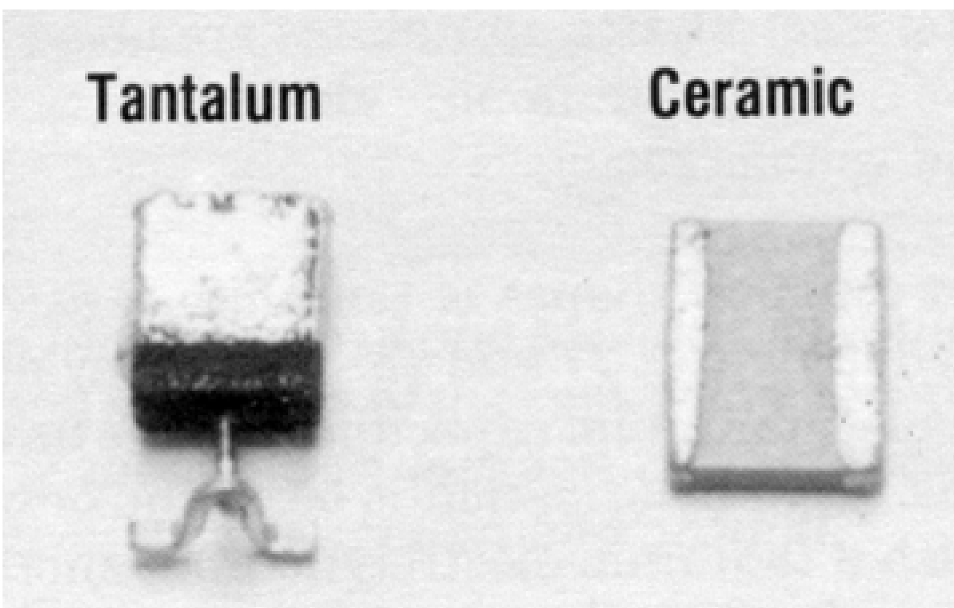


Figure F-5
A Tantalum Chip Capacitor and a Ceramic Chip Capacitor

Dipped Tantalum Capacitors

Color	Rated Voltage	Capacitance in Picofarads 1st Figure	2nd Figure	Multiplier
Black	4	0	0	–
Brown	6	1	1	–
Red	10	2	2	–
Orange	15	3	3	–
Yellow	20	4	4	10,000
Green	25	5	5	100,000
Blue	35	6	6	1,000,000
Violet	50	7	7	10,000,000
Gray	–	8	8	–
White	3	9	9	–

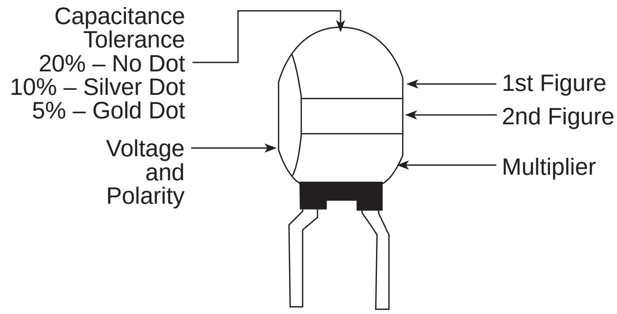


Figure F-6
Values Of Dipped Tantalum Capacitors [A.5.13]

Double-Layer Electrolytic Capacitors

Double-layer electrolytic capacitors are commonly known by trade names such as “Supercap” or “Gold Cap.” These capacitors have an extremely large capacitance value for their physical size. Double-layer electrolytic capacitors are usually marked in farads, rather than microfarads or picofarads. The polarity of a double-layer electrolytic capacitor is often printed on the case, although a longer lead might also be used to identify the positive terminal (see Figure F-7). Some double-layer electrolytic capacitors use a line next to one lead that can be either “+” or “-” (see Figure F-8). If there is no other marking, the terminal that is part of the metal case is the negative lead.

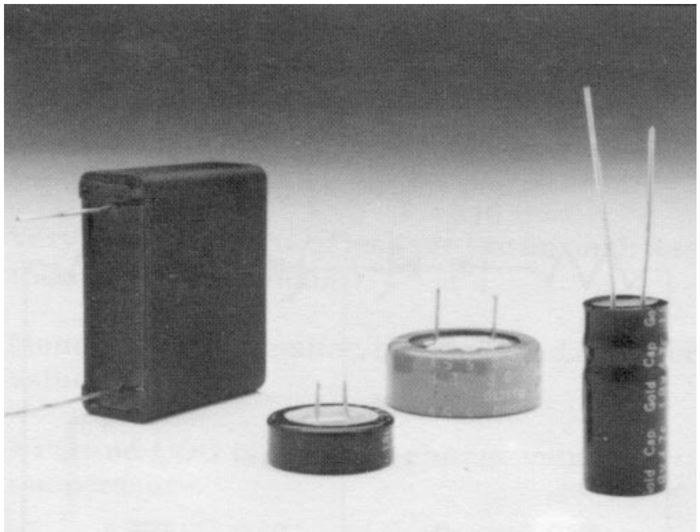


Figure F-7
Double-Layer Electrolytic Capacitor

Double Layer Electrolytic Capacitors
(Typically much smaller physically than similar value Aluminum Lytics.
Value usually marked in F.)

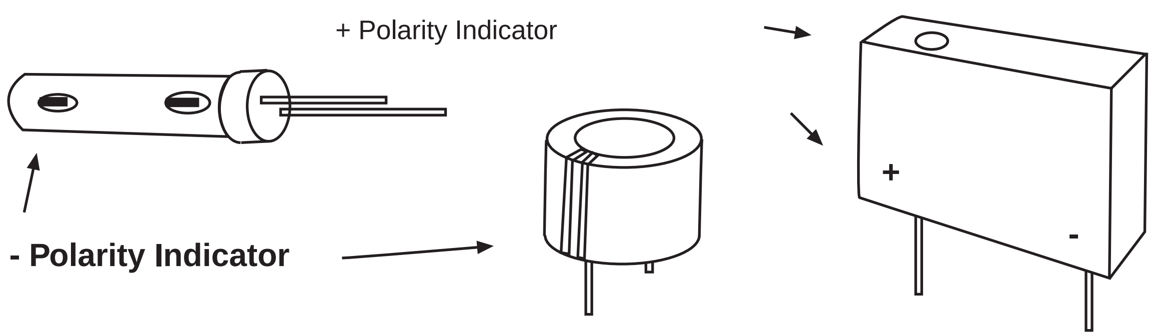


Figure F-8
Positive Leads of a Double-Layer Electrolytic Capacitor

Non-Polarized Electrolytic Capacitors

The non-polarized electrolytic capacitor can generally be identified by its shape and the lack of polarity markings (see Figure F-9). If you are not sure, refer to the schematic of the circuit that the capacitor is used in. The non-polarized capacitor is similar in appearance to a polarized electrolytic, but there are no polarity markings.

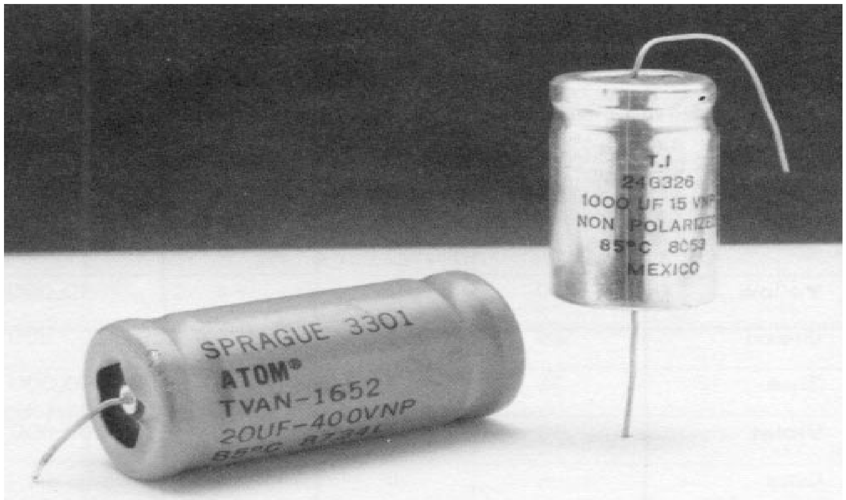


Figure F-9
Non-Polarized Electrolytic Capacitors

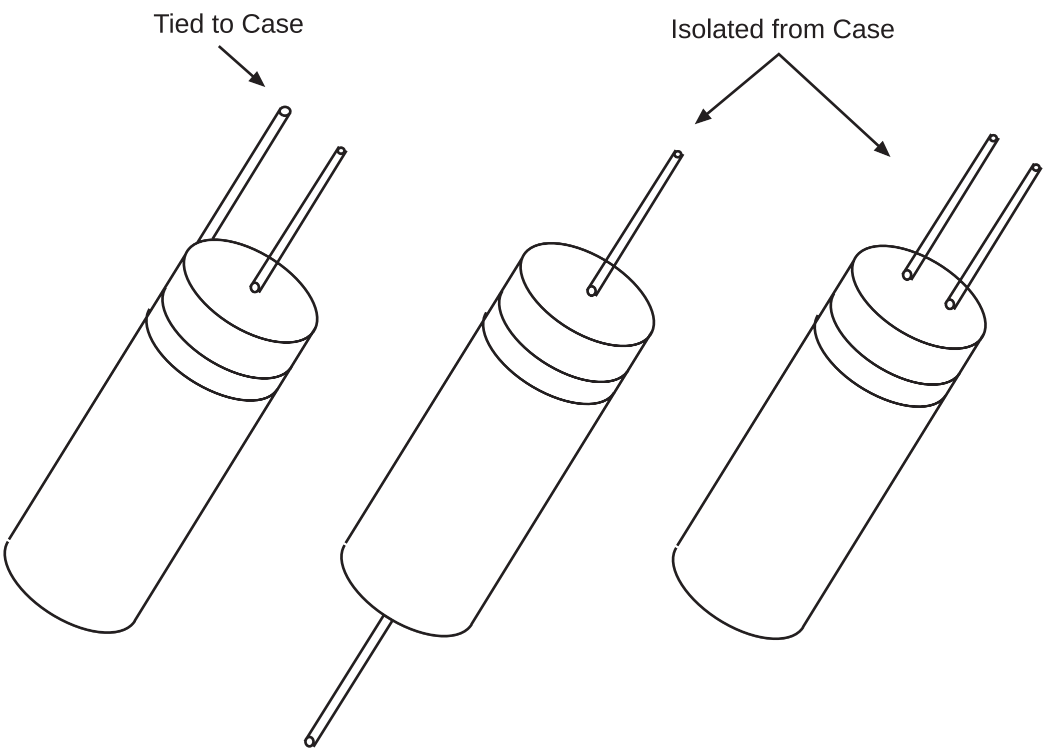


Figure F-10
Non-Polarized Electrolytic Capacitor Can Leads

Ceramic Capacitors

Ceramic capacitors are the most versatile of all capacitors (see Figure F-11). Many variations of capacity can be created by altering the ceramic material. Ceramic capacitors change value with a change in temperature, applied voltage, and frequency of the signal that is applied to them.

Circuit designers utilize these characteristics to take advantage of other circuit variables. A ceramic capacitor marked GMV means that the value marked on the capacitor is the guaranteed minimum value of capacitance at room temperature (see Figure F-12). The actual value of the capacitor can be much higher. This type of capacitor is used in bypass applications where the actual value of capacitance is not critical.

Ceramic capacitors have been the most popular capacitors in electronics because of the versatility of the different temperature coefficients and the cost. When replacing a ceramic disc capacitor, be sure to replace the defective capacitor with one having the same temperature characteristics and voltage rating.

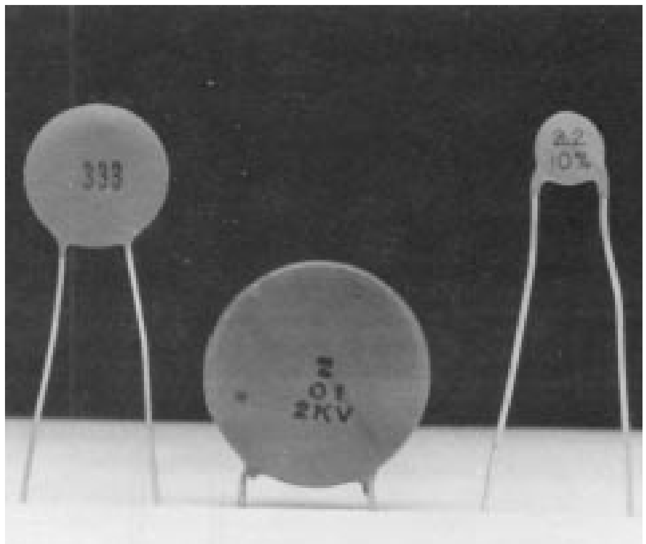
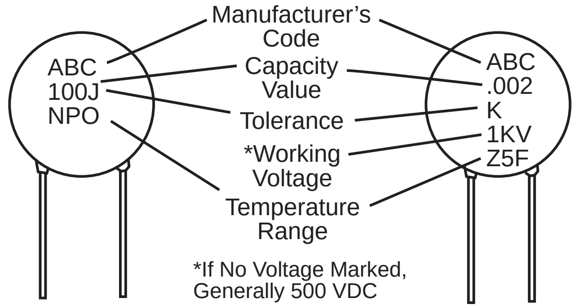


Figure F-11
Ceramic Capacitors

All Other Capacitors

The final capacitor type is the “all other capacitor” category (see Figures F-13 and F-14.). As the name implies, capacitors that fall under this category do not have the same electrical or physical characteristics to fit any of the other capacitor types. Capacitors included in this grouping are films, micas, air dielectrics, and paper types. Film-type capacitors include Mylar, polyester, polycarbonate, polystyrene, and polypropylene.

Ceramic Disc Capacitors



Typical Ceramic Disc Capacitor Markings

Z 5 F 1 0 0 J

Low Temp.	Letter Symbol	High Temp.	Numerical Symbol	Max. Capac. Change Over Temp. Range	Letter Symbol
+ 10˚C	Z	+ 45˚C	2	±1.0%	A
- 30˚C	Y	+ 65˚C	4	±1.5%	B
- 55˚C	X	+ 85˚C	5	±1.1%	C
		+105˚C	6	±3.3%	D
		+125˚C	7	±4.7%	E
				±7.5%	F
				±10.0%	P
				±15.0%	R
				±22.0%	S
				+22%–33%	T
				+22%–56%	U
				+22%–62%	V

Temperature Range Identification of Ceramic Disc Capacitors

1st and 2nd Fig. of Capacitance	Multiplier	Numerical Symbol	Tolerance on Capacitance	Letter Symbol
	1	0		
	10	1		
	100	2	±5%	J
	1,000	3	±10%	K
	10,000	4	±20%	M
	100,000	5	+100%, 0%	P
		–	+80%, 20%	Z
		–		
	.01	8		
	.1	9		

Capacity Value and Tolerance of Ceramic Disc Capacitors

Figure F-12
Markings on Ceramic Capacitors

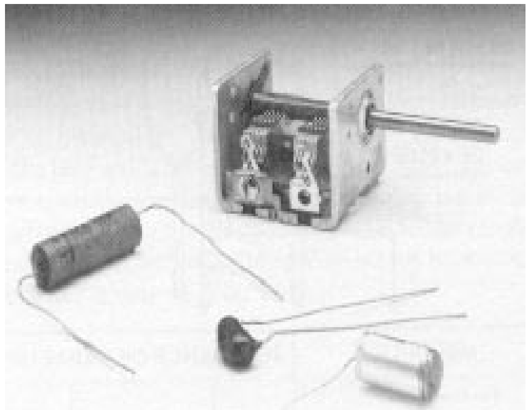
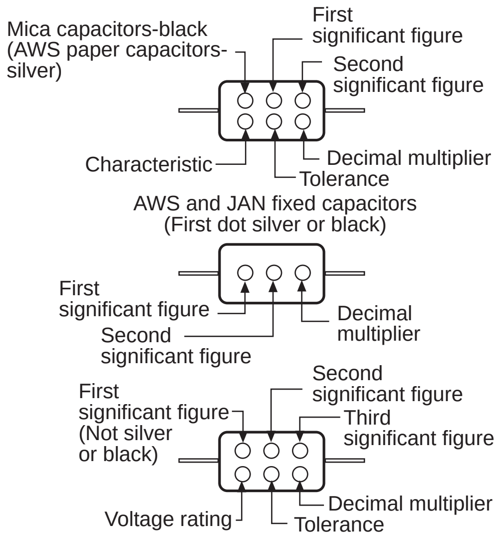


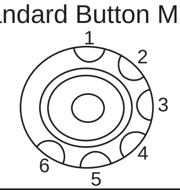
Figure F-13
Other Types of Capacitors [A.5.13]

Postage Stamp Mica Capacitors



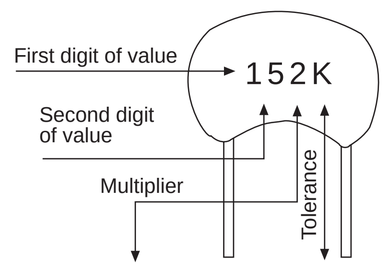
Color	Significant Figure	Multiplier	Tolerance (%)	Voltage Rating
Black Brown	0 1	1 10	– 1	– 100
Red Orange	2 3	100 1,000	2 3	200 300
Yellow Green	4 5	10,000 100,000	4 5	400 500
Blue Violet	6 7	1,000,000 10,000,000	6 7	600 700
Gray White	8 9	100,000,000 1,000,000,000	8 9	800 900
Gold Silver	– –	0.1 0.01	5 10	1000 2000
No color	–	–	20	500

Standard Button Mica



1st DOT	2nd & 3rd DOT		4th DOT	5th DOT		6th DOT
Identifier	Capacitance in pF		Multiplier	Capacitance Tolerance		Temp. Characteristic
–	Color	1st & 2nd Sig. Fig		Percent	Letter Symbol	
Black	Black Brown	0 1	1 10	± 20% ± 1%	F F	
Note: Identifier is omitted if capacitance must be specified to three significant figures	Red Orange	2 3	100 1,000	± 7% or ± 1 pF ± 3%	G or B H	
	Yellow Green	4 5				+100
	Blue Violet	6 7				± 20 PPM/°C above 50 pF
	Gray White Gold	8 9	0.1	± 5%	J	± 100 PPM/°C below 50 pF
	Silver			± 10%	K	

Film Type Capacitors



Multiplier		Tolerance of Capacitor		
For the Number	Multiplier	Letter	10 pF or Less	Over 14 pF
0 1	1 10	B C	±0.1pF ±.25pF	
2 3	100 1,000	D F	±0.5pF ±1.0pF	± 1%
4 5	10,000 100,000	G H	±2.0pF	± 2% ± 3%
8	0.01	J K		± 5% ±10%
9	0.1	M		±20%

Examples:
152K = 15 x 100 = 1500 µF or .0015 µF, ±10%
759J = 75 x 0.1 = 7.5 pF, ± 5%

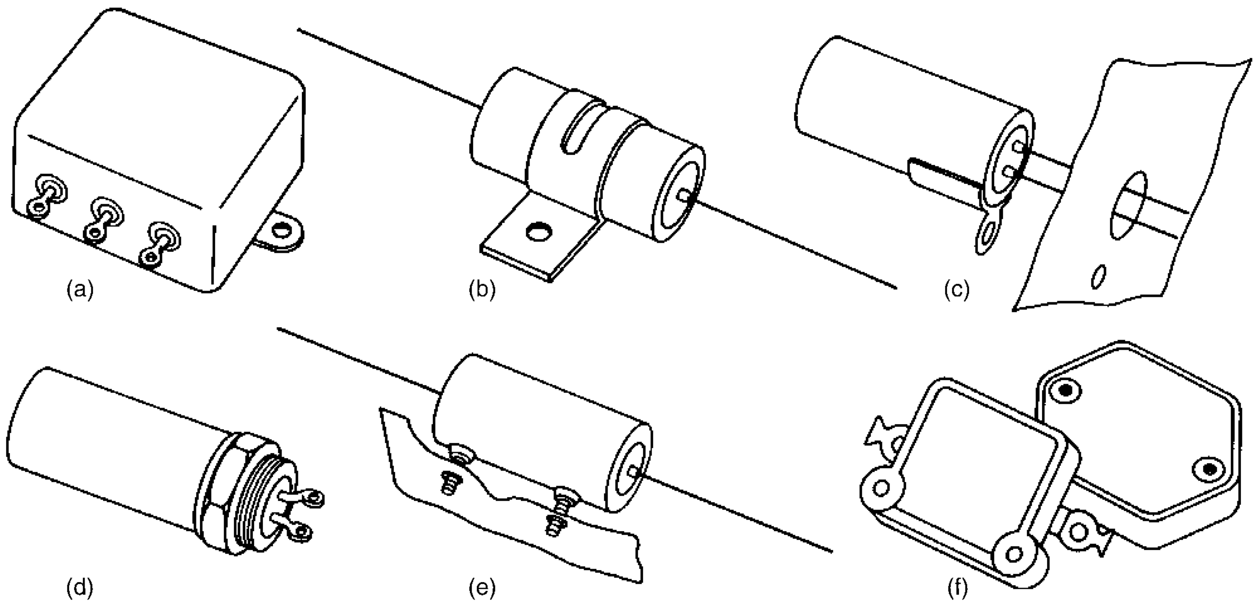
Note: The letter “R” may be used at times to signify a decimal point: as in: 2R2 = 2.2 (pF or µF).

Figure F-14
Charts to Identify Markings on Various Types of Capacitors [A.5.13]

Capacitor Mounting

Along with the identification of capacitor types, there are mounting considerations that must be taken into account when a replacement capacitor is considered. The mounting hardware can be an integral part of the capacitor, a separate mounting, or a combination of the two.

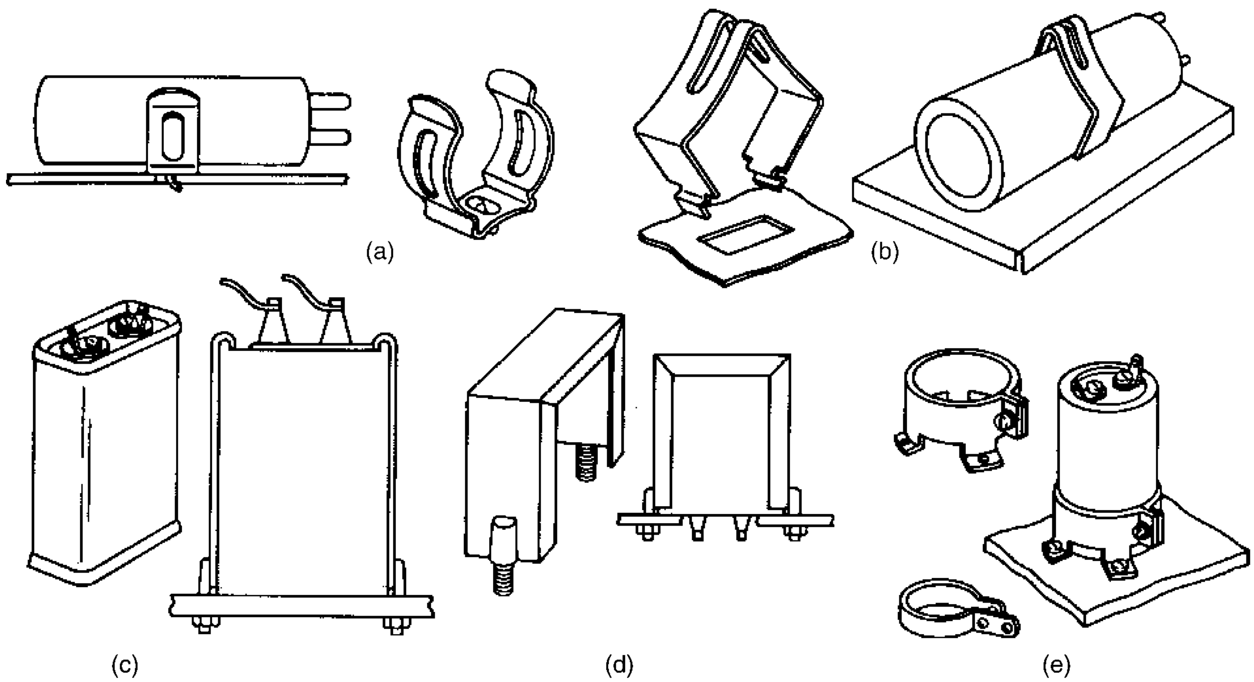
The integral mounting involves having a portion of a capacitor case or some attachment to a case that allows for direct installation of the capacitor. The mounting hardware can be part of the actual capacitor exterior body. Several examples of integral mounting arrangements are shown in Figure F-15.



Capacitors with integral mounting. (a) Ear tabs, (b) C-clamp, (c) angle bracket, (d) Threaded housing, (e) Threaded studs, and (f) Special provisions.

Figure F-15
Capacitors with Integral Mounting

Separate mounting fixtures for capacitors make use of special attachments that are configured to hold the capacitor and facilitate secure attachment within a cabinet or other enclosure. The mounting hardware should be chosen and selected to allow for easy installation and removal of a capacitor. Several examples of separate mounting arrangements are shown in Figure F-16.



Capacitors with separate mounting. (a) Spring-steel clip, (b) Snapover clip, (c) Hook strap, (d) Inverted U strap, (e) Strap and ring.

Figure F-16
Capacitor with Separate Mounting