This Application Guide

This guide is a full handbook on aluminum electrolytic capacitors, of course with emphasis on Cornell Dubilier's types. It covers construction in depth and discloses the latest information on performance and application for the major aluminum electrolytic types made worldwide. We encourage you to tell us what more you'd like to know, so we can improve this guide.

Aluminum Electrolytic Capacitor Overview

Except for a few surface-mount technology (SMT) aluminum electrolytic capacitor types with solid electrolyte systems an aluminum electrolytic capacitor consists of a wound capacitor element, impregnated with liquid electrolyte, connected to terminals and sealed in a can. The element is comprised of an anode foil, paper separators saturated with electrolyte and a cathode foil. The foils are high-purity aluminum and are etched with billions of microscopic tunnels to increase the surface area in contact with the electrolyte.

While it may appear that the capacitance is between the two foils, actually the capacitance is between the anode foil and the electrolyte. The positive plate is the anode foil; the dielectric is the insulating aluminum oxide on the anode foil; the true negative plate is the conductive, liquid electrolyte, and the cathode foil merely connects to the electrolyte.

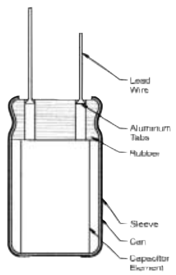
This construction delivers colossal capacitance because etching the foils can increase surface area more than 100 times and the aluminum-oxide dielectric is less than a micrometer thick. Thus the resulting capacitor has very large plate area and the plates are awfully close together.

These capacitors routinely offer capacitance values from 0.1 µF to 3 F and voltage ratings from 5 V to 500 V. They are polar devices, having distinct positive and negative terminals, and are offered in an enormous variety of styles which include molded and can-style SMT devices, axial- and radial-leaded can styles, snap-in terminals styles and large-can, screw-terminal styles. Representative capacitance-voltage combinations include

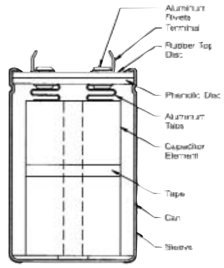
> 330 µF at 100 V and 6800 µF at 10 V for SMT devices,
>
> 100 µF at 450 V, 6,800 µF at 50 V and 10,000 µF at 10 V for miniature-can styles,
>
> 1200 µF at 450 V and 39,000 µF at 50 V for snap-in can styles and
>
> 9000 µF at 450 V and 390,000 µF at 50 V for large-can, screw-terminal styles.

If two, same-value, aluminum electrolytic capacitors are connected in series, back-to-back with the positive terminals or the negative terminals connected, the resulting single capacitor is a non-polar capacitor with half the capacitance. The two capacitors rectify the applied voltage and act as if they had been bypassed by diodes. When voltage is applied, the correct-polarity capacitor gets the full voltage. In non-polar aluminum electrolytic capacitors and motor-start aluminum electrolytic capacitors a second anode foil substitutes for the cathode foil to achieve a non-polar capacitor in a single case.

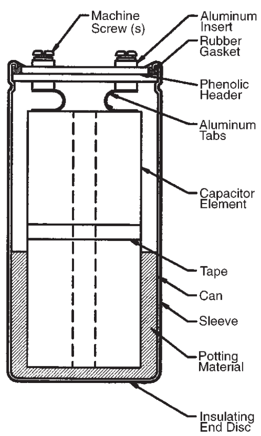
Capacitor Construction



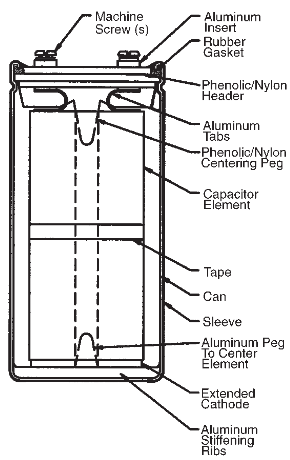
Miniature,
Radial-Leaded Type



Snap-in Type



Conventional Construction



Cornell Dubilier Thermal Pak

Large-Can, Screw-Terminal Type

These figures show typical constructions of the non-surface-mount aluminum electrolytic capacitors. All Cornell Dubilier capacitors use compression-fit construction so there is no thermoplastic potting compound to interfere with safety-vent operation. Thermal Pak™ is Cornell Dubilier's unique construction for computergrade, screw terminal capacitors. Compared to conventional, potted construction, Thermal Pak operates cooler, provides longer life, withstands higher shock and vibration, delivers more reliable safety vent operation and is lighter weight.

Etching

The anode and cathode foils are made of high purity, thin aluminum foil, 0.02 to 0.1 mm thick. To increase the plate area and the capacitance, the surface area in contact with the electrolyte is increased by etching the foils to dissolve aluminum and create a dense network of billions of microscopic tunnels penetrating through the foil.

Etching involves pulling the aluminum foil on rollers through a chloride solution while applying an AC, DC or AC-and-DC voltage between the etch solution and the aluminum foil. Surface area can increase as much as 100 times for foil in low-voltage capacitors and 20 to 25 times for high-voltage capacitors.

Forming

The anode foil carries the capacitor's dielectric. The dielectric is a thin layer of aluminum oxide, Al_2O_3, that is chemically grown on the anode foil during a process called "formation." Formation is accomplished by pulling the anode foil on rollers through an electrolyte bath and continuously applying a DC voltage between the bath and the foil. The voltage is 135% to 200% of the final capacitor's rated voltage. The thickness of the aluminum oxide is about 1.4 to 1.5 nm for each volt of the formation voltage, e.g., the anode foil in a 450 V capacitor may get a formation voltage in excess of 600 V and have an oxide thickness of about 900 nm. That's less than a hundredth the thickness of a human hair.

Formation reduces the effective foil surface area because the microscopic tunnels are partially occluded by the oxide. The tunnel etch pattern is adjusted by choice of foil and etching process so that low-voltage anodes have dense tunnel patterns compatible with thin oxide and high-voltage anodes have coarse tunnel patterns compatible with thick oxide. The cathode foil is not formed and it retains its high surface area and dense etch pattern.

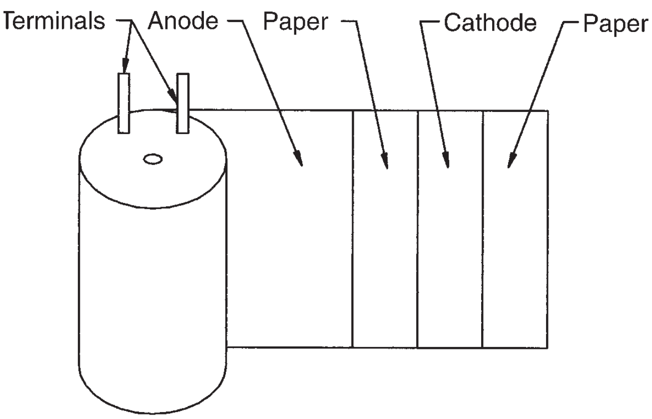
Slitting

Foil is etched and formed in jumbo rolls of 40 to 50 cm wide and then slit into various widths according to the lengths of the final capacitors.

Winding

The capacitor element is wound on a winding machine with spindles for one-to-four separator papers, the anode foil, another set of one-to-four separator papers and the cathode foil. These are wound into a cylinder and wrapped with a strip of pressure-sensitive tape to prevent unwinding. The separators prevent the foils from touching and shorting, and the separators later hold the reservoir of electrolyte.

Before or during winding aluminum tabs are attached to the foils for later connection to the capacitor terminals. The best method is by cold-welding of the tabs to the foils with tab locations microprocessor controlled during winding so that the capacitor element's inductance can be less than 2 nH. The older method of attachment is by staking, a process of punching the tab through the foil and folding down the punched metal. Cold welding reduces short-circuit failures and performs better in high-ripple current and discharge applications in which the individual stakes may fail from high current like buttons popping off one at a time from a fat-man's vest.



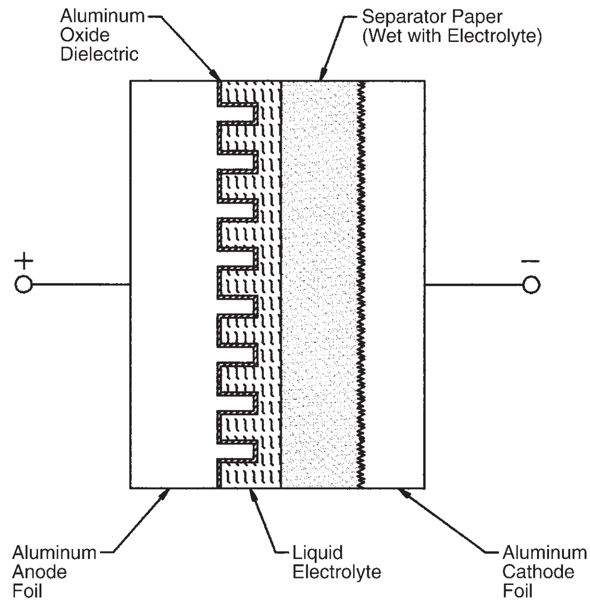
Wound Capacitor Elements

Connecting Terminals

In SMT capacitors and miniature capacitors with rubber-bungs, extensions of the tabs are the capacitor terminals. But in large-can capacitors like snap-ins and screw-terminal styles, the tabs are riveted or welded on the underside of the capacitor tops to terminal inserts. Welding produces the lowest contact resistance and highest current handling. Both resistive welding and ultrasonic welding are used. The up to 12 tab pairs that may be used in large screw-terminal capacitors often require more mechanical support during assembly so the tabs in such capacitors may be both riveted to post extensions on the terminals and then welded. In an axial-leaded capacitor the cathode tab is welded to the can before sealing.

Impregnation

The capacitor element is impregnated with electrolyte to saturate the paper separators and penetrate the etch tunnels. The method of impregnation may involve immersion of the elements and application of vacuum-pressure cycles with or without heat or, in the case of small units, just simple absorption. The electrolyte is a complex blend of ingredients with different formulations according to voltage and operating temperature range. The principal ingredients are a solvent and a conductive salt – a solute – to produce electrical conduction. Common solvents are ethylene glycol (EG), dimethylformamide (DMF) and gammabutyrolactone (GBL). Common solutes are ammonium borate and other ammonium salts. EG is typically used for capacitors rated –20 °C or –40 °C. DMF and GBL are often used for capacitors rated –55 °C.



Capacitor-Element Materials

Water in the electrolyte plays a big role. It increases conductivity thereby reducing the capacitor's resistance, but it reduces the boiling point so it interferes with high temperature performance, and it reduces shelf life. A few percent of water is necessary because the electrolyte maintains the integrity of the aluminum oxide dielectric. When leakage current flows, water is broken into hydrogen and oxygen by hydrolysis, and the oxygen is bonded to the anode foil to heal leakage sites by growing more oxide. The hydrogen escapes by passing through the capacitor's rubber seal.

Sealing

The capacitor element is sealed into a can. While most cans are aluminum, phenolic cans are often used for motor-start capacitors. In order to release the hydrogen the seal is not hermetic and it is usually a pressure closure made by rolling the can edge into a rubber gasket, a rubber end-plug or into rubber laminated to a phenolic board. In small capacitors molded phenolic resin or polyphenylene sulfide may replace the rubber. Too tight a seal causes pressure build up, and too loose a seal shortens the life by permitting drying out, loss of electrolyte.

Aging

Here the capacitor assembly comes full circle. The last manufacturing step is "aging" during which a DC voltage greater than the rated voltage but less than the formation voltage is applied to the capacitor. Usually the voltage is applied at the capacitor's rated temperature, but other temperatures and even room temperature may be used. This step reforms the cut edges and any damaged spots on the anode foil and covers any bare aluminum with aluminum oxide dielectric. Aging acts as burn-in and reduces or eliminates early life failures (infant mortals). Low, initial DC leakage current is a sign of effective aging.

Comparison to Other Types of Capacitors

Ceramic Capacitors

Ceramic capacitors have become the preeminent, general-purpose capacitor, especially in SMT chip devices where their low cost makes them especially attractive. With the emergence of thinner-dielectric, multilayer units with rated voltages of less than 10 V capacitance values in the hundreds of microfarads have become available. This intrudes on the traditional, high-capacitance province of aluminum electrolytic capacitors.

Ceramic capacitors are available in three classes according to dielectric constant and temperature performance. Class 1 (NPO, COG) is suitable for low capacitance, tight tolerance applications in the range of 1 pF to a few mF. Class 2 (X7R) has 20 to 70 times as much capacitance per case size, but capacitance typically varies about ± 10% over its –55 to 125 °C temperature range. The maximum change is +15 % to –25%. Class 3 (Z5U) with about 5 times the capacitance of Class 2 has wild swings of capacitance with voltage and temperature. The temperature range is –25 °C to 85 °C, and capacitance varies about +20% –65% over the range. Ceramic chip capacitors are brittle and sensitive to thermal shock, so precautions need to be taken to avoid cracking during mounting, especially for high-capacitance large sizes.

The typical temperature range for aluminum electrolytic capacitors is –40 °C to 85 °C or 105 °C. Capacitance varies about +5% –40% over the range with the capacitance loss all at cold temperatures. Capacitors rated –55 °C generally only have –10 % to –20 % capacitance loss at –40 °C. Cold temperature performance for rated voltages of 300 V and higher is often worse, and temperature performance varies by manufacturer. Thus Class 1 and 2 ceramic capacitors perform better than aluminum electrolytic capacitors at cold temperatures, and Class 3 ceramic capacitors perform worse at all temperatures.

Aluminum electrolytic capacitors readily deliver much more capacitance. Aluminum electrolytic capacitors give more capacitance and energy storage per unit volume than ceramic capacitors for all types except for low-voltage, Class 3 ceramic SMT chip capacitors. While tolerances of ±5% and ±10% are routine for ceramic capacitors, ± 20% and –10% +50% are the norms for aluminum electrolytic. This makes aluminum electrolytics the choice for high-capacitance applications like rectification filters and power hold up where more capacitance is a bonus.

Ceramic capacitors are not polarized and therefore can be used in AC applications. The low DF and high capacitance stability of Class 1 and 2 are especially suited to AC and RF applications. By comparison, aluminum electrolytic capacitors are polarized and cannot withstand voltage reversal in excess of 1.5 V. While non-polar aluminum electrolytics are available for momentary-duty AC applications like motor starting and voltage-reversing applications, the high DF of aluminum electrolytic capacitors – from 2% to 150% – causes excess heating and short life in most AC applications.

Ceramic capacitors are generally no more reliable than aluminum electrolytic capacitors because aluminum electrolytics self heal. Since high-capacitance ceramic capacitors may develop micro-cracks, aluminum electrolytic capacitors are preferred for high capacitance values. However, small sizes of aluminum electrolytic capacitors may have limited life due to dry out, and so consider reliability in your choice for applications operating at high temperatures, over 65 °C.

Film Capacitors

Film capacitors offer tight capacitance tolerances, very low leakage currents and small capacitance change with temperature. They are especially suited to AC applications through their combination of high capacitance and low DF that permits high AC currents. However, they have relatively large sizes and weights.

The popular polymers used for plastic-film dielectric capacitors are polyester and polypropylene. The popular polymer for SMT devices is polyphenylene sulfide (PPS). While film/foil construction is often used for small capacitance values – less than 0.01 µF – and for high-current applications, metallized-film is usually preferred because it gives smaller size, lower cost and is self healing. Film capacitors are general-purpose capacitors for through-hole applications and have special uses for tight-tolerance, AC voltage, high voltage and snubbing.

Polyester film capacitors operate from is –55 °C to 85 °C at rated voltage; +85 °C to 125 °C with linear voltage derating to 50% rated voltage. The typical capacitance change over the entire range is less than –5% +15% with ±1% from 0 °C to 50 °C. Capacitance values are readily available up to 10 µF with special large sections to 100 µF. Generally available voltages are 50 to 1000 Vdc and 35 to 600 Vac. AC current handling is limited by polyester's high-temperature DF of about 1%.

Polypropylene film capacitors operate from –55 °C to 85 °C at rated voltage; 85 °C to 105 °C with linear voltage derating to 50% rated voltage. The typical capacitance change over the entire range is less than +2% –4% with ±1% from –20 °C to 60 °C. Capacitance values are readily available up to 65 µF with special large sections to 1000 µF. Generally available voltages are 100 to 3000 Vdc and 70 to 500 Vac. AC current handling permits use in motor-run and other continuous duty AC applications.

Compared to aluminum electrolytic capacitors, film capacitors take the lead in high voltage, AC voltage and tight tolerance applications. Aluminum electrolytics excel in capacitance and energy storage.

Solid Tantalum Capacitors

Like aluminum electrolytic capacitors solid tantalum capacitors are polar devices (1 V maximum reverse voltage), having distinct positive and negative terminals and are offered in a variety of styles. Case styles include both molded and conformal-coated versions of radial, axial and surface mount configurations. Typical capacitance values are from 0.1 µF to 1000 µF in voltage ratings from 2 V to 50 V. Typical maximum capacitance-voltage combinations are approximately 22 µF at 50 V for leaded styles and 22 µF at 35 V for surface mount. Strengths are temperature stability, volumetric efficiency and compatibility with all automated assembly systems. Weaknesses are the limited voltage and capacitance ranges and a short-circuit failure mode accompanied by catching fire.

The operating temperature range is –55 °C to 85 °C at rated voltage; +85 °C to 125 °C with linear voltage derating to 2/3 rated voltage. The typical capacitance change over the entire range is less than ±5%. Thus aluminum electrolytic capacitors have a much broader voltage and capacitance ranges than solid tantalum capacitors but perform worse at cold temperature.

Solid tantalum capacitors are generally considered more reliable than aluminum electrolytic capacitors because solid tantalum capacitors do not wear out. Their failure rate decreases with time, while aluminum electrolytic capacitors wear out by drying out. As a practical matter, dry-out only affects the smallest capacitors operating in high-temperature environments.

Larger aluminum electrolytics do not dry out in the 10 to 20 years expected of most applications, and the open-circuit, dry-out failure is benign compared to solid-tantalum's short circuit failure mode.

Characterization

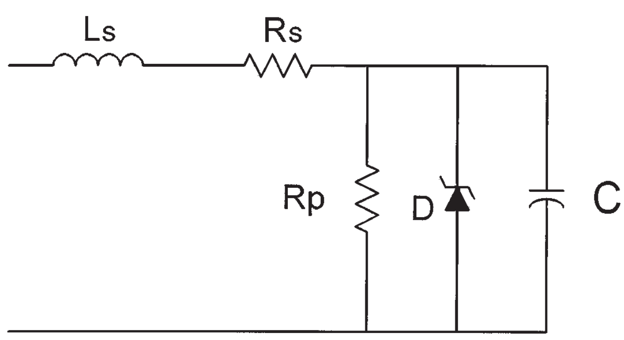
CIRCUIT MODEL

Capacitance occurs when two electrical conductors are separated by an insulator. A capacitor is an electronic component optimized to deliver capacitance. The capacitance in µF is

$$C = 8.855(n-1)\varepsilon A/d$$

Where n is the number of plates or electrodes, ε is the dielectric constant, A is the plate surface area in cm^2 and d is the thickness of the dielectric between the plates in cm. Dielectric constant is the multiplier increase in capacitance that the dielectric delivers compared to a vacuum. The dielectric constant for aluminum oxide is about 8.

The circuit at the right models the aluminum electrolytic capacitor's normal operation as well as overvoltage and reverse-voltage behavior.



Equivalent Circuit

Capacitance C is the equivalent capacitance and it decreases with increasing frequency. Common values range from 1 µF to 1 F, a six-decade range.

Resistance Rs is the equivalent series resistance, and it decreases with increasing frequency and temperature. It increases with rated voltage. Typical values range from 10 mΩ to 1 Ω, and Rs is inversely proportional to capacitance for a given rated voltage.

Inductance Ls is the equivalent series inductance, and it is relatively independent of both frequency and temperature. Typical values range from 10 nH to 30 nH for radial-leaded types, 20 to 50 nH for screw-terminal types, and up to 200 nH for axial-leaded types. It increases with terminal spacing.

Resistance Rp is the equivalent parallel resistance and accounts for leakage current in the capacitor. It decreases with increasing capacitance, temperature and voltage, and it increases with time. Typical values are on the order of 100/C MΩ with C in µF.

Zener diode D models overvoltage and reverse voltage behavior. Application of overvoltage on the order of 50 V beyond the capacitor's surge voltage rating causes high leakage current and a constant-voltage operating mode quite like the reverse conduction of a zener diode.

Application of reverse voltage much beyond 1.5 V causes high leakage current quite like the forward conduction of a diode. Neither of these operating modes can be maintained for long because hydrogen gas is produced by the capacitor, and the pressure build up will cause failure.

In terms of parameters in the next section, Rated Capacitance is C, Dissipation Factor is 2πfCRs, Equivalent Series Resistance is Rs, Impedance is

$$[(Rs)^2 + (1/(2\pi fC) - 2\pi fLs)^2]^{1/2}$$

and Inductance is Ls. The table below expresses these and other parameters in terms of the equivalent-circuit model.

Parameter	Unit	Symbol	Formula	Approximately
Capacitance	farads (F)	C		
Capacitive Reactance	ohms (Ω)	Xc	1/(2πfC)	Z
Current	amperes (A)	I	C(dV/dt), Vz/Z	
Dissipation Factor	none	DF	Rs/Xc, 2πfCRs, tan(δ), cot (θ)	PF
Energy	Joules (J)	E	$\frac{1}{2}CV^2$	
Equivalent Series Resistance	ohms (Ω)	Rs	DF/(2πfC)	
Frequency	hertz (Hz)	f		
Impedance	ohms (Ω)	Z	$[Rs^2+(Xc^2-X_L^2)]^{1/2}$	Xc
Inductance	henries (H)	Ls		
Inductive Reactance	ohms (Ω)	X_L	2πfL	
Loss Angle	degrees (°)	δ	$\tan^{-1}(DF)$	
Phase Angle	degrees (°)	θ	$\cot^{-1}(DF)$	
Power	watts (W)	P	I^2Rs	
Power Factor	none	PF	Rs/Z, sin(δ), cos(θ)	DF
Quality Factor	none	Q	Xc/Rs, 1/DF, cot(δ), tan(θ)	1/PF
Self-Resonant Frequency	hertz (Hz)	ω_0	$1/[2\pi(LC)^{1/2}]$	
Voltage	volts (V)	V	Vc=IXc, Vz=IZ	
Volt-Amperes	V-A	VA	IVz, I^2Z	

Parameters

Temperature Range

Operating Temperature Range

The Operating Temperature Range is the temperature range over which the part will function, when electrified, within the limits given in the specification. It is the range of ambient temperatures for which the capacitor has been designed to operate continuously. Largely the formation voltage sets the high-temperature limit. Higher formation voltages permit higher operating temperatures but reduce the capacitance. The low-temperature limit is set largely by the cold resistivity of the electrolyte. The higher cold resistivity increases the capacitor's ESR 10 to 100 fold and reduces the available capacitance.

Typical temperature ranges are –20 °C to 55 °C, –25 °C to 85 °C, –40 °C to 85 °C, –55 °C to 85 °C, –40 °C to 105 °C, –55 °C to 105 °C and –55 °C to 125 °C.

Storage Temperature Range

The Storage Temperature Range is the temperature range to which the part can be subjected unbiased, and retain conformance to specified electrical limits. It is the range of ambient temperatures over which the capacitor may be stored without damage for short periods. For long periods of storage keep capacitors at cool room temperatures and in an atmosphere free of halogen gases like chlorine and fluorine that can corrode aluminum.

Storage temperature ranges are from –55 °C to the upper limit of the operating-temperature ranges.

Rated Capacitance

The rated capacitance is the nominal capacitance and it is specified at 120 Hz and a temperature of 25 °C. The rated capacitance is also the capacitance marked on the unit.

Capacitance Tolerances

Capacitance tolerance is the permitted minimum and maximum capacitance values expressed as the percentage decrease and increase from the rated capacitance, ΔC/C. Typical capacitance tolerances are ±20%, –10% +50%, and –10% +75%.

Tighter tolerances are more readily available in high voltage capacitors, e.g., above 150 V, but tolerances tighter than ±10% are generally not available. Note that tighter tolerance parts may meet other tolerance requirements and are readily substitutable.

The capacitance varies with temperature and frequency. This variation itself is also dependent on the rated voltage and capacitor size.

Capacitance measurement

For aluminum electrolytic capacitors, capacitance is measured as the capacitance of the equivalent series circuit at 25 °C in a measuring bridge supplied by a 120 Hz source free of harmonics with maximum AC signal voltage of 1 V rms and no forward-bias voltage.

Capacitance Temperature characteristics

The capacitance varies with temperature. This variation itself is dependent to a small extent on the rated voltage and capacitor size. Capacitance increases less than 5% from 25 °C to the high-temperature limit. For devices rated –40 °C capacitance typically declines 20% at –40 °C for low-voltage units and up to 40% for high-voltage units. Most of the decline is between –20 °C and –40 °C. For devices rated –55 °C capacitance typically declines less than 10% at –40 °C and less than 20% at –55 °C.

Capacitance Frequency characteristics

The effective capacitance decreases as frequency increases. Self-resonance is typically below 100 kHz depending on capacitance. At self-resonance the device is resistive and beyond it is inductive. The termination style (i.e., axial, radial, screw-terminal) will influence the inductive characteristics. Small radial-leaded capacitors have inductance of less than 20 nH. Larger capacitors have more inductance according to terminal spacing.

Dissipation Factor (DF)

Dissipation factor is the measurement of the tangent of the loss angle (tan δ) expressed as a percentage. It is also the ratio of the ESR to the capacitive reactance and is thus related to ESR by this equation:

$$DF = 2\pi fC(ESR)/10{,}000$$

Where DF is a unit-less number express in percent, test frequency f is in Hz, capacitance C is in µF and ESR is in Ω.

DF measurement

The measurement of DF is carried out at +25 °C, 120 Hz, and no voltage bias, with a maximum 1 Vac rms signal voltage free of harmonics. The value of DF is temperature and frequency dependent.

DF Temperature characteristics

The dissipation factor decreases with increasing temperature. DF declines about 50% from 25 °C to the high-temperature limit, but increases more than 10 fold at the low-temperature limit. The DF of the better devices rated –55 °C increase less than 5 times at –40 °C.

DF_{lf}, defined in the next paragraph, varies little with temperature and ESR_{hf}, also in the next paragraph, increases 10 to 100 times from 25 °C to the low-temperature limit. The increase in DF at cold temperatures is set by the ESR_{hf}.

DF Frequency characteristics

The dissipation factor varies with frequency at high frequencies. DF can be modeled as below:

$$DF = DF_{lf} + 2\pi fC(ESR_{hf})/10{,}000$$

Where DF is the total dissipation factor in percent, DF_{lf} is the low-frequency dissipation factor in percent, ESR_{hf} is the high-frequency ESR in Ω, f is the test frequency in Hz and C is the capacitance in µF at the test frequency. DF_{lf} results from the power lost by the applied electric field in orienting the molecules of the aluminum oxide dielectric. ESR_{hf} results from the resistive losses in the foils, connections and the electrolyte/separator pad. The electrolyte/ separator pad resistance usually dominates and its resistance varies little with frequency. DF_{lf} ranges from about 1.5% to 3%. ESR_{hf} ranges from 0.002 to 10 Ω and decreases with temperature.

The DF equation above shows that DF is constant for low frequencies and crosses over to declining-DF, constant-ESR, at a crossover frequency inversely proportional to capacitance. Since high-capacitance capacitors have low crossover frequencies, DF decreases more with increasing frequency than for lower-capacitance capacitors.

Equivalent Series Resistance (ESR)

The equivalent series resistance (ESR) is a single resistance representing all of the ohmic losses of the capacitor and connected in series with the capacitance.

ESR measurement

For aluminum electrolytic capacitors, ESR is measured as the resistance of the equivalent series circuit at 25 °C in a measuring bridge supplied by a 120 Hz source free of harmonics with maximum AC signal voltage of 1 V rms and no forward-bias voltage.

ESR Temperature characteristics

The ESR declines with increasing temperature. ESR declines about 35% to 50% from 25 °C to the high-temperature limit, but increases more than 10 fold at the low-temperature limit. The ESR of devices rated –20 °C or –40 °C can increase more than 100 times at –40 °C.

DF_{lf} varies little with temperature and ESR_{hf} increases 10 to 100 times from 25 °C to the low-temperature limit. The increase in ESR at cold temperatures is set by the ESR_{hf}.

ESR Frequency characteristics

Like DF, the ESR varies with frequency. Rewriting the DF equation above, ESR can be modeled as below:

$$ESR = 10{,}000(DF_{lf})/(2\pi fC) + ESR_{hf}$$

Expressing the ideas in ESR terms, at low frequencies the ESR declines steadily with increasing frequency and crosses over to constant ESR at a frequency inversely proportional to capacitance. This crossover is typically below 10 kHz. The ESR of high-capacitance capacitors changes little with increasing frequency because high-capacitance causes them to have low crossover frequencies. The ESR_{hf} ranges from 0.002 Ω for large, screw-terminal capacitors to 10 Ω for miniature devices.

Impedance (Z)

For aluminum electrolytic capacitors impedance is actually impedance magnitude. It is the ratio of voltage to current at a given frequency and is related to the capacitor's capacitance, ESR and series inductance as follows:

$$Z = [(ESR)^2 + (1/(2\pi fC) - 2\pi fL)^2]^{1/2}$$

Where Z is impedance in Ω, ESR is equivalent series resistance in Ω, f is frequency in Hz, C is capacitance in F and L is equivalent series inductance in H.

Z measurement

For aluminum electrolytic capacitors, Z is measured as the impedance magnitude of the equivalent series circuit at 25 °C in a measuring bridge supplied by a variable frequency source capable of delivering an AC signal voltage of 1 V rms free of harmonics from 10 Hz to 100 kHz. Impedance measurements are mostly for typical performance curves and for low-temperature limit measurements.

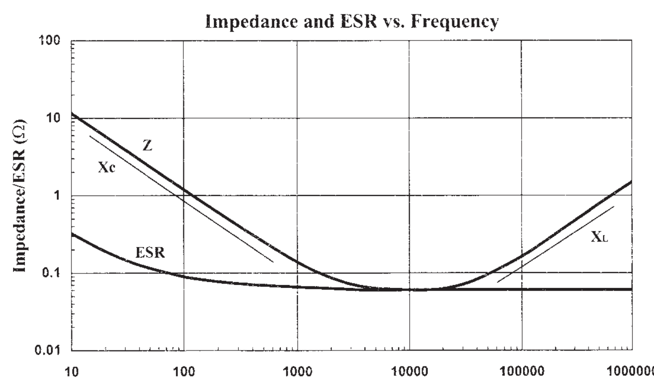
For low-temperature impedance measurement, place the capacitors in a chamber set to the low-temperature limit ±2 °C. Measure impedance at 120 ±5 Hz using any suitable method providing an accuracy of ±2½%. After temperature stabilization, make the measurements quickly using as small as practical an AC measuring voltage in order that it will not cause heating of the capacitors. Assure that the capacitors have reached thermal stability by demonstrating that two successive measurements taken at 15 minute intervals show no change.

Z Temperature characteristics

Impedance typically decreases less than 5% from 25 °C to the high-temperature limit but increases up to 10 times to the low-temperature limit.

Z Frequency characteristics

The frequency characteristics of impedance are dictated by the contributions from capacitive reactance (1/(2πfC)), inductive reactance (2πfL) and from resistive losses in the electrolyte. A typical impedance-versus-frequency curve is shown below. The low point is at the self-resonant frequency, and the impedance is equal to the ESR at that frequency.



Impedance versus Frequency

DC Leakage Current (DCL)

DC Leakage Current is the DC current flowing through the capacitor with the rated voltage applied. The value of leakage current depends on the voltage applied, the charging period and capacitor temperature.

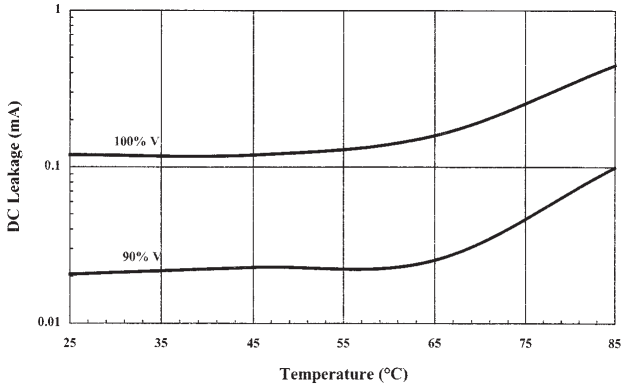
DCL Method of measurement

Measure leakage current at 25 °C with the rated voltage applied through a protective resistance of 1000 Ω in series with the capacitor in the measuring circuit. Five minutes after the application of voltage, the leakage current is not to exceed the maximum value indicated in the specification.

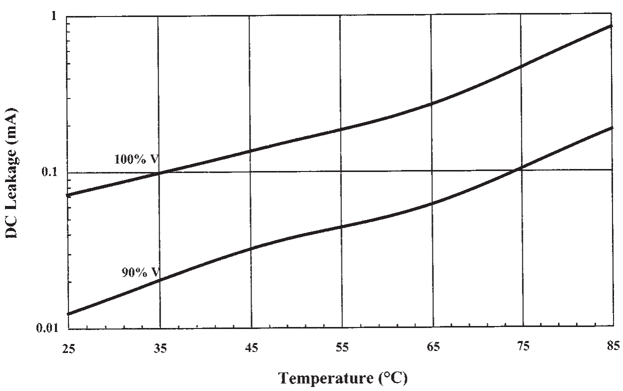
DCL Temperature characteristics

Typical characteristic curves are shown below:

DC Leakage versus Temperature, 8600 µF 100 V



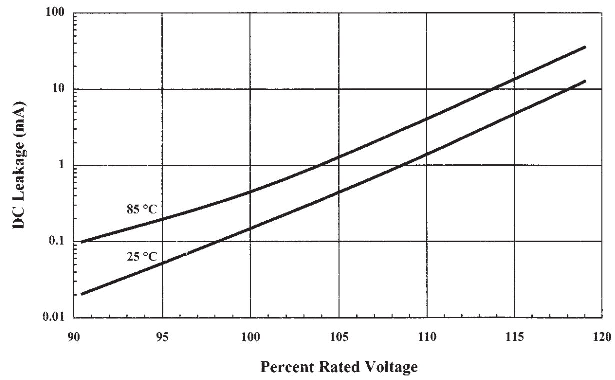
DC Leakage versus Temperature, 4700 µF 450 V



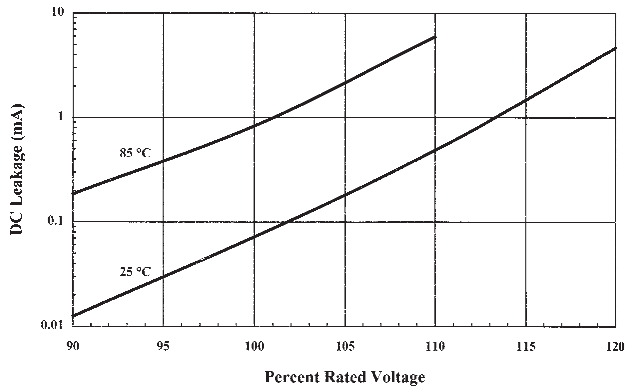
DCL Voltage characteristics

The leakage current value drops rapidly as the applied voltage decreases below the capacitor's rated voltage. The effect of voltage derating on the leakage current is shown below.

DC Leakage versus Voltage, 8600 µF 100 V



DC Leakage versus Voltage, 4700 µF 450 V



Voltage

Rated DC voltage

Rated DC voltage is the voltage marked on the capacitor, and it is the maximum peak voltage including ripple voltage that may be applied continuously between the terminals and over the rated temperature range. Higher rated voltage capacitors may be substituted for lower rated voltage capacitors as long as case size, DF, and ESR ratings are also compatible.

Rated surge voltage

Rated surge voltage is the maximum DC overvoltage to which the capacitor may be subjected at 25 °C for short periods not exceeding approximately 30 s at infrequent intervals of not less than 5 min.

Surge voltage measurement

Subject the capacitors to their rated surge voltage at normal room temperature and through a 1000 Ω ±10% resistor (except for capacitances of 2500 µF and up, use a 2,500,000/C Ω ±10% resistor where C is the capacitance in µF). Cycle the voltage ½ minute on followed by 4½ minutes off during which each capacitor is discharged through the charging resistor or equal resistor. Repeat the cycles for 120 h. Post test requirements are for DCL, ESR and DF to meet initial requirements and for there to be no evidence of mechanical damage or electrolyte leakage. Electrolyte residue with no droplets or visible flow is permitted.

Reverse voltage

Aluminum electrolytic capacitors are polarized and must be connected in the correct polarity. They can withstand reverse voltages up to 1.5 V. Higher reverse voltage can cause failure by pressure build up and rupture of the capacitor's safety vent structure. Non-polar and semi-polar devices are available that can withstand reverse voltage.

Transient overvoltage

Aluminum electrolytic capacitors can generally withstand extreme overvoltage transients of limited energy. Application of overvoltage more than about 50 V beyond the capacitor's surge voltage rating causes high leakage current and a constant-voltage operating mode quite like the reverse conduction of a zener diode. The capacitor may fail short if the electrolyte cannot take the voltage stress, but even if it can, this operating mode cannot be maintained for long because hydrogen gas is produced by the capacitor, and the pressure build up will cause failure. However, special designs are available that use the overvoltage, zener-clamping affect to successfully protect equipment from overvoltage transients such as lightning strikes.

Ripple Current

Ripple Current

Ripple current is the AC current flowing in the capacitor. It's called ripple current because the associated AC voltage rides like ripple on water on the capacitor's DC bias voltage. The ripple current heats the capacitor and the maximum permitted ripple current is set by how much can be permitted and still meet the capacitor's load life specification. Too much temperature rise will cause the capacitor to exceed its maximum permitted core temperature and fail quickly, but operation close to the maximum permitted core temperature dramatically shortens expected life. The load life specifications for aluminum electrolytic capacitors operating at maximum permitted core temperature are typically 1000 to 10,000 hours. That's six weeks to a year and a seventh and not long enough for most applications.

Ripple current specification

Ripple current ratings are specified for an expected temperature rise at rated temperature. Commonly capacitor types rated 85 °C permit a temperature rise of 10 °C and have a maximum permitted core temperature of 95 °C. Often types rated 105 °C permit a temperature rise of 5 °C and have a maximum core temperature of 110 °C. Actual maximum permitted core temperatures vary by type and manufacturer.

Ripple current ratings usually assume that the capacitor is convection cooled and that the entire can is in contact with air. A convection coefficient of 0.006 W/°C/in^2 predicts the temperature rise from air to the case, and the core temperature is assumed to be the same as the case temperature. The power dissipated is the ripple current squared times the ESR. Often the 25 °C, 120 Hz maximum ESR is used, but since ESR decreases at elevated temperatures, less than maximum ESR may be used to calculate power dissipated.

Here's an example. Suppose you wanted the ripple-current rating for a 4700 µF, 450 V capacitor in a 3 inch (76 mm) diameter and 5⅝ inches (143 mm) long can and the maximum ESR at 25 °C and 120 Hz is 30 mΩ. The can area – not including the terminal end – is 60.1 in^2 (388 cm^2). The thermal conductance is (0.006)(60.1) = 0.36 W/°C. For a 10 °C temperature rise the case may dissipate 3.6 W. So the permitted ripple current with an ESR of 30 mΩ is 11 A. If you assume that the ESR would decrease 35% by 85 °C, then the maximum ripple current can be 13.6 A.

With large-can capacitors like the one in this example neglecting the temperature rise from the case to the core can seriously overstate the ripple current capability. With some constructions the core is 3 to 5 °C per watt of ripple power hotter than the case. So the total temperature rise would be more than double the intended 10 °C with rated ripple current and maximum ESR. It is generally safe to assume that the core temperature is the same as the case temperature for capacitors smaller than 25 mm diameter. For larger cases with high ripple current, verify the temperature rise by requesting samples with thermocouples imbedded in the cores.

Cornell Dubilier Thermal Pak, computergrade capacitors have controlled, low thermal resistance from core to case. You can predict temperature rise using the thermal resistance table later in this section or by using the thermal-resistance/expected-life model available on the Web site, http://www.cornell-dubilier.com

Ripple current temperature characteristics

Rated ripple current can be increased for operating temperatures less than rated temperature. Multipliers are shown in the specifications. Generally the multipliers are derived based on maximum core temperature (T_c), rated temperature (T_r) and ambient temperature (T_a) as

$$\text{Ripple Temperature Multiplier} = [(T_c - T_a)/(T_c - T_r)]^{1/2}$$

Counting on multipliers for temperatures below 60 °C and for more than $1^1/_2$ times rated ripple current is risky. High ripple currents can cause shorter operating lives than expected because as the capacitor ages its ESR increases and causes more heating for the same ripple current. This accelerates wearout.

Ripple current frequency characteristics

Rated ripple current can be adjusted for operation at frequencies other than 120 Hz. Multipliers are shown in the specifications. Generally the multipliers are derived based on expected ESR change with frequency; however, as discussed above, ESR is a complex function of temperature, capacitance and rated voltage as well as frequency. So it is difficult to create ripple-frequency multiplier tables that accurately model the frequency dependence. For high-ripple current applications verify ESR at frequencies of interest and calculate total power dissipated.

Inductance

Inductance is the equivalent series inductance, and it is relatively independent of both frequency and temperature. Typical values range from 2 to 8 nH for SMT types, 10 nH to 30 nH for radial-leaded types, 20 to 50 nH for screw-terminal types, and up to 200 nH for axial-leaded types. These low values are achieved by tab location and intrinsic, low inductance of the dielectric contact geometry. The capacitor element has typical inductance of less than 2 nH.

Low-Temperature Impedance

Low-temperature impedance is the capacitor's 120 Hz impedance measured at the low-temperature limit. It is usually expressed as a multiple of the device's 25 °C impedance.

For low-temperature impedance measurement, place the capacitors in a chamber set to the low-temperature limit ±2 °C. Measure impedance at 120 ±5 Hz using any suitable method providing an accuracy of $\pm 2^1/_2$%. After temperature stabilization, make the measurements quickly using as small as practical an AC measuring voltage in order that it will not cause heating of the capacitors. Assure that the capacitors have reached thermal stability by demonstrating that two successive measurements taken at 15 minute intervals show no change.

Self-resonant Frequency

The self-resonant frequency is the frequency at which the capacitive reactance ($1/(2\pi fC)$) equals the inductive reactance ($2\pi fL$). Because the capacitive reactance is 180 degrees out of phase with the inductive reactance, the two reactances subtract out, and the remaining impedance is purely resistive and is equal to the ESR at that frequency. Above self resonance the device is inductive. In aluminum electrolytic capacitors the self-resonant frequency typically occurs at less than 100 kHz. The self-resonant frequency is equal to $1/[2\pi(LC)^{1/2}]$. It occurs at a frequency higher than expected based on 120 Hz capacitance because capacitance decreases with increasing frequency, and it can decrease with increasing temperature from capacitance increase.

Dielectric Absorption

Dielectric absorption may be observed as the reappearance of a voltage across a capacitor after the terminals have been shorted for a brief period and the short removed. This characteristic is important in RC timing circuits, triggering systems and phase shift networks. For aluminum electrolytic capacitors dielectric absorption will allow up to 10% recovery of the charging voltage between 100 s and 1000 s at 25 °C, and is more pronounced at higher temperatures. Maximum dielectric absorption can be obtained by charging capacitors for 1 hour at rated voltage and discharging through a dead short for 1 minute. Subsequent measurements over time can be made with a high impedance micrometer.

With high-voltage aluminum electrolytic capacitors rebound voltages of 40 to 50 V are possible. While such voltages are not a safety hazard, they can certainly create a frightening distraction if the terminals are shorted by a tool during installation. Conductive tape and wire shorting straps can be supplied for the faint of heart. The tradeoff is extra cost and the labor to remove them.

Insulation and Grounding

With non-solid electrolyte aluminum electrolytic capacitors the aluminum cases connect to the negative terminals by contact with electrolyte. The resulting isolation resistance may vary from a few ohms to a few thousand ohms. For axial-leaded capacitors and flatpacks the case is connected to the negative lead. If objects contacting the cases are to be at a potential other than the negative terminals, use capacitors with insulating sleeves.

The plastic insulation can withstand 3000 Vdc or 2500 Vac, 60 Hz for 1 minute applied between the case and a ¼ inch wide metal foil placed around the sleeve. For stud-mounting, apply the voltage between the chassis and the case, and mount the capacitor with an approved nylon nut and clearance hole.

Insulation resistance is no less than 100 MΩ after 2 minutes electrification with 100 volts applied between the foil and the capacitor case.

External Pressure

Not relevant for capacitors with solid electrolyte. Aluminum electrolytic capacitors can operate to 80,000 feet and pressures as low as 3 kPa. Maximum air pressure depends on the size and style of the capacitor. Exceeding the maximum value can damage the capacitor by crushing the case, opening the pressure-relief vent or causing a short circuit.

Vibration

Aluminum electrolytic capacitors can generally withstand 10 g vibration forces. Limits are shown in the specifications. Adjust the procedure below as required by the individual type specifications.

To test vibration resistance, clamp the capacitors to a vibrating platform and subject them to a simple harmonic motion having a maximum peak-to-peak amplitude of 0.06 inches and a maximum acceleration of 10 g or 15 g as specified. Vary the frequency of vibration linearly between 10 and 55 Hz. Traverse the entire frequency range in 1 minute. Unless specified otherwise, vibrate the capacitors for 1½ hours with the direction of motion being parallel to the axis of the capacitor, then place the capacitors so that the direction of motion is perpendicular to the axis and continue vibration for 1½ hours. During the last ½ hour of test connect the capacitor to a bridge and observe for a 3-minute period.

There will be no evidence of loosening of the capacitor element within the container when shaken by hand following the test. Also there will be no indication of intermittent contact, open or shorting during the 3-minute observation period.

Pressure-Relief Vent

During operation of an aluminum electrolytic capacitor with non-solid electrolyte, gas pressure normally increases. This gas is mostly hydrogen and excess pressure is avoided by permeation of the gas through the capacitor's seal. But in cases like application of overvoltage, reverse voltage, AC voltage or capacitor failure, excess pressure can cause the capacitor to explode. To avoid the risk of explosion aluminum electrolytic capacitors are usually equipped with pressure-relief vent structures. These safety vents are intended to rupture and release the gas pressure. After rupture the capacitor has limited life because it loses electrolyte and dries out.

Be careful not to interfere with the operation of the vent, for instance by mounting measures such as clamps, glue or potting compounds. In the case of large capacitors with the capacitor elements secured by thermoplastic potting, don't mount them with the safety vents down as the potting may flow when the capacitors overheat and block the vents.

In rare cases for capacitors mounted alone and more often for capacitors in multiple-unit parallel capacitor banks a fully functioning pressure relief device may not react in time. This could be from extreme overload or ignition of gas inside the capacitor through sparking caused by breakdown. Protect personnel from possible rupture of high-energy capacitors with shielding, and be sure to use substantial shielding when testing the pressure-relief vent. Examples of appropriate shielding for testing are ¼-inch thick steel or ½-inch thick polycarbonate enclosures with one end open to redirect the explosion rather than contain it.

Test the capacitor's pressure-relief capability by applying voltage or current using one of the following three methods.

A. Subject the capacitor to AC current according to the rated capacitance as below:

Rated Capacitance µF	Test Current A rms, 60 Hz
up to 3000	1 to 100
3,000 to 20,000	85 to 150
above 20,000	100 to 175

B. For a capacitor rated 150 Vdc and above, apply 110 to 125 Vac, 60 Hz through a 5 Ω ±10% series, current-limiting resistor.

C. Subject the capacitor to reverse polarity, DC voltage sufficient to allow a current from 1 to 10 A to flow.

The excess internal pressure will be relieved without violent expulsion of the capacitor element or cover or ignition of surrounding material. To demonstrate non-ignition, wrap the case loosely with two layers of cheese cloth which must not ignite during test. A short or open circuit is not a failure of the test.

Contact with Electrolyte

The electrolyte in non-solid electrolyte capacitors is a biodegradable liquid based on a stable solvent with a high boiling point as the main ingredient. Common solvents are ethylene glycol (EG), dimethylformamide (DMF) and gammabutyrolactone (GBL). The electrolyte includes an acid base system and other chemicals. The electrolyte is chemically neutral and contains no PCBs or halogenated compounds. It has low toxicity but avoid contact with the skin or eyes and avoid prolonged inhalation. A Material Safety Data Sheet is available upon request.

Immediately treat contact with electrolyte by rinsing exposed area with water. If electrolyte contacts eyes, flush for 10 minutes with running water. Seek medical attention if any symptoms persist. Avoid inhalation of electrolyte vapors or dust particles. If vapors are present, ventilate the room. Smoke from burning electrolyte is irritating but does not contain dioxins or similar toxic substances. If electrolyte gets on clothing, wash it off with water.

Charge-Discharge

Frequent, rapid charge and discharge of aluminum electrolytic capacitors not designed for such service can damage the capacitors by overheating and overpressure or breakdown with consequent failure by open or short circuit. For charge-discharge applications use capacitors designed for that use, and don't exceed the manufacturer's recommended discharge rate.

Polarity – Reverse Voltage

Check the polarity of each capacitor both in circuit design and in mounting. Polarity is marked on the capacitor. While the capacitors can withstand continuous application of 1.5 V reverse voltage, exceeding that can damage the capacitor by overheating, overpressure, and dielectric breakdown. This can result in associated open-circuit or short-circuit failures and rupture of the capacitor's pressure-relief vent.

Flammability

Aluminum electrolytic capacitors contain materials which can catch fire and support combustion when contacted by flames. Flammable parts include plastic parts, insulating sleeves, paper, and the electrolytes. Most capacitors will pass the needle-flame test requirements of UL 94V-O and not support combustion to the requirements of Category B or C.

In rare cases the capacitor may self-ignite from heavy overload or capacitor defect. Hydrogen in the capacitor can ignite if sparking occurs during capacitor failure. In critical applications such as mining applications consider providing fire-resistant shields.

Circuit Configurations

PARALLEL

Capacitors may be connected in parallel for increased capacitance and ripple-current capability.

Bus Structure

When connecting capacitors in parallel, design the connecting bus with these features in mind. Minimum series inductance requires a laminated bus or strip-line structure. For example, have one plane of the circuit board as the plus connection and another plane as the minus connection to all capacitors. Path resistance to each capacitor should be equal to assure equal current sharing. While ripple current divides among the capacitors in proportion to capacitance values for low-frequency ripple, high-frequency ripple current divides in proportion to ESR values and path resistance.

Fusing

In order to fuse the individual capacitors, include a slow-start circuit at equipment turn-on, and fuse each capacitor at twice its expected, maximum ripple current. The slow-start circuit can be a resistor in series with the capacitors that is shorted after initial charging.

SERIES

Capacitors may be connected in series for increased voltage withstanding.

Voltage Sharing

During charging the voltage on each of the capacitors connected in series is proportional to the inverse of the actual capacitance, but upon reaching final voltage, the voltage on each capacitor is proportional to the inverse of the capacitor's leakage current. Of course in a series string all leakage currents are the same, and the capacitors with a propensity for higher leakage current will get less voltage. Since leakage current increases with applied voltage, less voltage results in higher leakage resistance, and the voltages tend to equalize. Tests of high voltage bus capacitors in series pairs connected to supply voltages 10% below two-times the rated voltage showed good voltage sharing over the full temperature range, and no capacitor's voltage was ever higher than its rated voltage.

When only two capacitors are in series, balancing resistors are seldom needed for voltage sharing. Before including them anyway for voltage bleed-down, consider that not using balancing resistors often increases system reliability by reducing the temperature near the capacitors and by eliminating components less reliable than the capacitors they are meant to protect. As an alternative, use capacitors from the same manufacturing lot to assure equal leakage currents or use a higher rated voltage to permit voltage imbalance with different manufacturers. And assure that capacitors in series have the same thermal environment.

Balancing Resistors

The difference in leakage currents for two capacitors in series at rated temperature can be estimated as 0.0015CVb in µA where C is rated capacitance in µF and Vb is the voltage across the two capacitors in Vdc. Using this approximation, select a value of balancing resistance for each capacitor using this formula:

$$R = (2Vr - Vb)/(0.0015CVb)$$

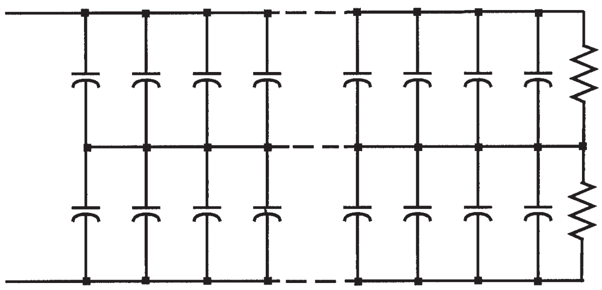
Where R is the balancing resistance in MΩ, Vr is the maximum voltage you want on either capacitor and Vb is the maximum bus voltage across the two capacitors.

For three or more capacitors in series use the following equation where n is the number of capacitors in series:

$$R = (Vr - Vb/n)/(0.00075CVb)$$

PARALLEL/SERIES

Capacitors connected as shown below with a common connection between multiple series combinations have these considerations.



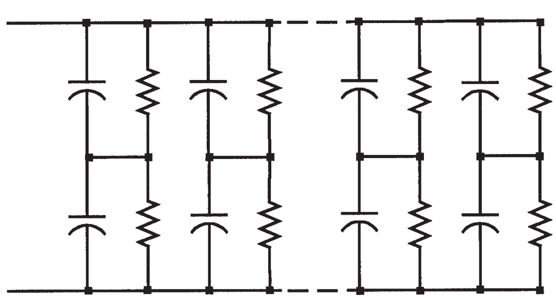
Parallel-series array with common center connection

Advantages: As the number of capacitors in parallel increases the capacitance at the top tends to equal the capacitance at the bottom. This improves voltage balance during transients. Also the leakage current at the top tends to equal the leakage current at the bottom, so voltage balance improves during steady-state conditions. Finally, only two balancing resistors need be considered, and the top and bottom may be so well matched as to eliminate the need for balancing resistors.

Disadvantage: If one capacitor fails short, the other half of the bank gets the entire bus voltage, so other capacitors will fail too. Thus one capacitor failure can cause failure of the entire bank unless the shorted capacitor is blown open.

SERIES/PARALLEL

Capacitors connected as shown below with multiple series combinations in parallel have these considerations. This configuration is the clear choice when balancing resistors are not used.



Series-parallel array, no center connection

Advantages: If one capacitor fails short then the capacitor in series with it also fails, but other capacitors in the bank are unaffected. If balancing resistors are not used, high leakage current of one capacitor affects only a single pair of capacitors. The independent, series pairs permit fusing.

Disadvantages: With balancing resistors the construction is more complex; many resistors need to be fitted, and the additional resistors cost more.

NON-POLAR

If two, same-value, aluminum electrolytic capacitors are connected in series, back-to-back with the positive terminals or the negative terminals connected, the resulting single capacitor is a non-polar capacitor with half the capacitance to either of the original pair. The two capacitors rectify the applied voltage and act as if they had been bypassed by diodes. When voltage is applied, the correct-polarity capacitor gets the full voltage.

In non-polar aluminum electrolytic capacitors and motor-start aluminum electrolytic capacitors a second anode foil substitutes for the cathode foil to achieve a non-polar capacitor in a single case. While non-polar aluminum electrolytics are available for momentary-duty AC applications like motor starting and voltage-reversing applications, the high DF of aluminum electrolytic capacitors – from 2% to 150% – causes excess heating and short life in most AC applications.

MOTOR START

Aluminum electrolytic, motor-start capacitors are non-polar and designed for intermittent operation in starting single-phase induction motors or for other brief AC applications such as motor-run capacitors in electric door openers.

Reliability

Aluminum electrolytic capacitors are quite reliable largely because of their effective, self-healing mechanism. While wearout is the most common failure mode, most such failures are gradual conversions to open circuits as the units become more and more resistive.

FAILURE MODES

Early-Life Failures

Early-life failures, infant mortals, are mostly short-circuit failures from weaknesses in the aluminum oxide dielectric. Incidence can be reduced with extended aging or burn-in.

Wear-Out

Wear-out failures are mostly open-circuit failures from loss of electrolyte or ESR increase from other causes. In the case of large capacitors enduring high levels of ripple current, the increasing ESR can cause overheating and short-circuit failures as wear-out failures.

Operating Life

Onset of wear-out is determined mainly by the capacitor's size and average operating temperature. Operating voltage has some effect. For capacitors operating at moderate temperatures the operating life doubles for each 10 °C that operating temperature is reduced. Operating life can be expressed as

$$Lop = MvLb2^{[(Tm - Ta)/10]}$$

Where

Lop is the expected operating life in h,

Mv is a unitless voltage multiplier for voltage derating,

Lb is the expected operating life in h for full rated voltage and temperature,

Tm is the maximum permitted internal operating temperature in ˚C, and

Ta is the actual capacitor internal operating temperture in °C.

Most manufacturers use this model to predict operating life; however, values for Mv, Lb, and Tm vary both by capacitor type and by manufacturer. For case diameters larger than 25 mm with significant ripple current, take into account the temperature rise of the capacitor element over its case.

Often Mv is neglected, and values for the other variables change by case size. Typical values for Lb are 1000 to 2000 h for miniature types, 2000 to 10,000 h for snap-in types and 2000 to 20,000 h for large-can screw terminal types. Lb can be greater than the rated load life because no ripple is applied and because it's typical life rather than minimum. Often Tm is 95 ˚C when rated temperature is 85 °C and is 108 to 110 ˚C when it's 105 °C.

Mv based on life tests for Cornell Dubilier, capacitor types is

$$Mv = 4.3-3.3Va/Vr$$

where Va is applied voltage and Vr is rated voltage. Types 400C, 401C, 420C, 450C and 4CMC are tightly sealed and behave differently when full rated voltage and temperature are applied. For these types when both Va/Vr > 0.9 and Ta/Tm > 0.9, the voltage multiplier is

$$Mv = 4.3 - 3.3Va/Vr - 1000(Ta/Tm - 0.9)^{1.65}(Va/Vr - 0.9)^{1.65}$$

Values for expected operating life Lb and maximum permitted core temperature Tm are

Type	Lb	Tm
101C	8000 h	108 °C
300/301	6000 h	108 °C
325	3000 h	128 °C
330	12000 h	108 °C
380L/LX	5000 h	95°C
380LQ	4000 h	95 °C
381EL	10000 h	110 °C
381L/LX	5000 h	110 °C
381LQ	4000 h	110 °C
381LR	5000 h	115 °C
400C	7500 h	98 °C
401C	8000 h	108 °C
420C	12000 h	103 °C
450C	15000 h	108 °C
4CMC	5000 h	95 °C
500C	7500 h	98 °C
520C	12000 h	103 °C
550C	15000 h	108 °C
DCMC	5000 h	95 °C
MLP up to 250V	12000 h	88 °C
MLP 300V & up	5000 h	88 °C
MLS	4000 h	125 °C

Determining Operating Life

Determine expected operating life from the capacitor's expected operating temperature and voltage using the operating-life formula.

The operating temperature is the expected average ambient temperature plus temperature rise from ripple current and leakage current. Leakage-current power is small compared to ripple-current power and can be neglected. Measure temperature rise from ripple current using sample capacitors with thermocouples installed at the core hotspot, or calculate temperature rise from dissipated power. If you calculate the power, do so at each significant ripple frequency and add the powers together for total power. Use the **Thermal Resistance Chart** on page 2.178 to determine temperature rise. It's equal to power multiplied by thermal resistance.

Calculating power at a frequency other that 120 Hz requires knowing the ESR at the new frequency. You may infer the ESR value from the ripple current frequency multipliers for each type.

$$ESR_f = ESR_{120}/M_f^2$$

Where ESR_f = ESR at a frequency f, ESR_{120} = ESR at 120 Hz and M_f = Frequency multiplier for frequency f.

Or you may calculate the new ESR using the equation in **ESR Frequency Characteristics**. Using that equation to solve for ESR_{hf} and including 3% for DF_{lf},

$$ESR_f = ESR_{120} – 39800(f – 120)/fC$$

Where ESR is in mΩ, f is in Hz and C is in µF. Although 3% is at the high end for DF_{lf}, it fits with ESR_{120} which is a maximum limit for the ESR at 120 Hz.

Besides knowing ESR at the new frequency you also need to know the ESR at a new temperature, the expected operating temperature. For Cornell Dubilier capacitors with electrolytes rated to –40 ºC this table shows representative ratios of ESR at elevated temperatures to ESR at 25 ºC.

Rated Voltage Vdc	Capacitor Temperature 45 °C	65 °C	85 °C
	Ratio to ESR at 25 °C		
Up to 150	82%	77%	77%
200 to 300	75%	70%	70%
350 to 450	70%	60%	60%
500	61%	49%	45%

Here's an illustration to unify this information. Consider the earlier example, a 4700 µF, 450 V capacitor in a 3 inch (76 mm) diameter and 5⅝ inches (143 mm) long can with a maximum ESR at 25 ˚C and 120 Hz of 30 mΩ. Suppose that the capacitor is used as a bus capacitor in a motor-drive inverter, and the ripple current consists of 11 A at 360 Hz and 6.5 A at 8000 Hz. And the average applied voltage, the bus voltage, is 390 Vdc.

First, calculate the ESRs at the two frequencies. While you would use one or the other of the methods above to calculate ESR, here we'll use both to illustrate. If the capacitor is a Type DCMC, the frequency multiplier from page 5 for 360 Hz is 1.13. Thus the 360 Hz ESR is $30/1.13^2$ or 23.5 mΩ. Or using the **ESR Frequency Characteristics** equation, the 360 Hz ESR is [30–39800(360-120)/360/4700] or 24.4 mΩ. Similarly at 8000 Hz the ESRs calculate to be 19.5 and 21.6 mΩ.

Next calculate the total power. At 360 Hz it's $(11^2)(0.0244)$ or 2.9 W. At 8000 Hz it's $(6.5^2)(0.0216)$ or 0.9 W. That's a total power of 3.8 W.

Then calculate the core hot-spot temperature. From the **Thermal Resistance Chart** the thermal resistance for free convection cooling is 3.07 ˚C/W. So the temperature rise is (3.8)(3.07) or 14 ˚C. If the ambient temperature were 50 ˚C, the core temperature would be 64 ˚C.

Now predict operating life capability using the **Operating Life** equation. The voltage multiplier, Mv is [4.3–3.3(390/450)] or 1.44. Operating life is

$$Lop = (1.44)(5000)2^{[(95 - 64)/10]}$$
$$= 61{,}700 \text{ h}$$

But if the core temperature is 64 ˚C, the ESR would have decreased about 40%. The new total power would be 0.6(3.8) or 2.3 W. The new temperature rise would be (3.07) (2.3) or 7 ˚C, and the core temperature would be 57 ˚C. Recalculating operating life with the lower core temperature gives

$$Lop = (1.44)(5000)2^{[(95 - 59)/10]}$$
$$= 100{,}300 \text{ h}$$

And actual ESRs are typical 70% of limit so you could argue that the total power is 1.6 W. Thus the temperature rise would be 5˚C, the core temperature, 55 ˚C, and the operating life, 115,000 h. However, it is more accurate to use the maximum limit because that takes into account the ESR increase over life.

The above example shows the iterative approach. If a higher core temperature gives the operating life you require, you are done.

If all of the math needed to calculate operating life seems burdensome, take cheer. You can shortcut the calculations and consider more mounting and cooling options by visiting our Web site, http://cornell-dubilier.com. There you will find Java applets that calculate core temperature and expected life for computergrade screw-terminal capacitors, for snap-in capacitors and for plug-in capacitors. Plug-in capacitor types start with the number 4, like Type 4CMC.

Transient over-temperature

As said, life of aluminum electrolytic capacitors generally doubles for each 10 °C that the core temperature is reduced. The core is the hottest spot at about the center of the capacitor. However, as a capacitor heats up toward its maximum permitted core temperature, the rules change. At temperatures above the maximum core temperature and by 125 °C for most types the electrolyte can be driven from capacitor element and the ESR can increase as much as 10 times. By this mechanism transient over-temperature or over-current can permanently increase the ESR and make the capacitor unusable. Be alert to this possibility in high-temperature and high-ripple applications, and pay extra attention to system cooling.

Load Life Test

Place the capacitors in a circulating air oven set to the upper temperature limit, 85 °C, 105°C or 125 °C, ± 3 °C. Apply a DC voltage and an AC ripple voltage. Adjust the AC voltage to cause current equal to the rated ripple current to flow and adjust the DC voltage such that the peak voltage equals the capacitors' rated voltage. Apply the voltage for the rated load-life period –0 +6 h. Upon completion allow the capacitors to stabilize at 25 °C for 24 h or more. The capacitors will meet the specified post-test limits for capacitance, ESR and DCL.

EIA Ripple Life Test, EIA IS-479

Conduct the wear-out lifetime test per EIA Interim Standard 479. The highlights of that test are as follows: Apply ripple current at 120 Hz or adjust to maintain the same power dissipation if performed at another frequency. Set DC bias voltage equal to rated voltage minus peak applied AC voltage. Set ambient temperature to 85 ± 2 °C with airflow less than 0.5 m/s. Periodic test interval ≤ 1000 h. Sample size is 10 or more. Mount capacitors horizontally and spaced 25 mm or more. Choose any temperature ≤85 ˚C for measurements, and make all measurements at that temperature. End of lifetime is ≤ the time when 10% or more of the sample have

capacitance < 80% initial value or
ESR > 200% initial requirement or
DCL > initial value or
evidence mechanical damage or leakage of electrolyte.

10% of sample may fail short or open and not be counted.

Voltage Derating

Voltage derating is expressed as the percentage that the applied voltage is less than rated voltage, e.g., a 450 V capacitor operating at 400 V would have 11% voltage derating.

Aluminum electrolytic capacitors made with formation voltages at least 35% higher than rated voltage and with rated temperatures of 85 °C or higher, don't require much voltage derating. In applications operating at less than 45 °C no derating is needed, and with up to 75 °C, 10% is sufficient. For higher temperatures and with high ripple current, 15% or 20% is appropriate. Since operating life continues to increase for further derating, military and space applications use 50% voltage derating.

Photoflash capacitors may be used at full rated voltage at normal room temperatures because they are designed for such duty. Strobe capacitors benefit from at least 10% voltage derating because their continuous operation makes them run hot.

Cooling

Cooling Strategies

Cornell Dubilier computergrade capacitors conduct heat from the core to the bottom much more effectively than out the sides. You can take advantage of this heat path by mounting the capacitors directly to metal chassis. In many case sizes this can double the permitted ripple current for the same temperature rise.

Mounting can be by using capacitors with mounting studs and screwing the capacitors directly to the plate or it can be by pressing the capacitors against a plate using the interconnecting bus structure. Cornell Dubilier furnishes silpad inserts at the bottom of the capacitors for this application. The silpads create smooth bottoms by eliminating the steps at the sleeve rollovers. The thermal resistance between the can and the underlying plate for capacitors merely sitting on the plate is about 2.5 °C/W. This decreases to less than 1 °C/W if the capacitors are pressed in place.

An Operating Life and Temperature Calculator is available on the Cornell Dubilier Web site which permits you to explore cooling options and directly see the affect on operating life. Go to *http://www.cornell-dubilier.com.*

Thermal Resistance

In large-can capacitors, especially ones with potting, there is significant temperature rise from the case to the core, the hottest spot at the center of the capacitor. For Cornell Dubilier Thermal Pak computergrade capacitors use the following thermal resistance data to determine temperature rise from power dissipated. As an illustration, consider 20 amps of ripple current at 120 Hz in a 3 x 5⅝ case with a maximum ESR of 20 mΩ. The hot, typical ESR would be about half that or 10 mΩ, and the power dissipated would be I^2Rs, 20^2x0.01 or 4 W.

The Free-Convection cooling column shows a total thermal resistance of 3.07 °C/W for air on all sides and 1.02 °C/W for the capacitor pressed against a large metal plate or chassis. With 4 W the 3.07 °C/W predicts a temperature rise of 12.3 °C, and 1.02 °C/W predicts 4.1 °C. The 1.02 °C assumes that there is no temperature rise in the metal plate. So, consider it the best you can do. Increase the Air & Metal Chassis thermal resistance by 0.3 °C/W if you do not use a thermal pad.

Thermal Resistance Chart °C/W Computergrade Capacitors

Case Code	Case Size D x L (in)	Free Convection						200 lfm Airflow						500 lfm Airflow						1000 lfm Airflow					
		Air on Side & End			Air & Metal Chassis			Air on Side & End			Air & Metal Chassis			Air on Side & End			Air & Metal Chassis			Air on Side & End			Air & Metal Chassis		
		Core to bottom	Case to air	Total	Core to bottom	Case to air	Total	Core to bottom	Case to air	Total	Core to bottom	Case to air	Total	Core to bottom	Case to air	Total	Core to bottom	Case to air	Total	Core to bottom	Case to air	Total	Core to bottom	Case to air	Total
AK	1 3/8 X 1 5/8	1.67	17.12	18.78	1.68	3.29	4.97	1.66	12.19	13.86	1.68	3.08	4.76	1.66	7.83	9.49	1.68	2.75	4.43	1.66	5.62	7.29	1.68	2.46	4.14
AA	1 3/8 X 2 1/8	1.70	13.72	15.42	1.74	3.13	4.87	1.70	9.80	11.50	1.74	2.90	4.64	1.70	6.31	8.02	1.73	2.53	4.26	1.70	4.56	6.26	1.73	2.22	3.95
AH	1 3/8 X 2 5/8	1.72	11.49	13.21	1.78	2.99	4.77	1.72	8.23	9.94	1.77	2.73	4.51	1.72	5.33	7.05	1.76	2.35	4.11	1.72	3.87	5.59	1.76	2.04	3.79
AB	1 3/8 X 3 1/8	1.72	9.91	11.63	1.80	2.86	4.66	1.71	7.12	8.83	1.79	2.59	4.38	1.71	4.64	6.35	1.78	2.19	3.97	1.71	3.39	5.11	1.77	1.88	3.65
AJ	1 3/8 X 3 5/8	1.69	8.73	10.43	1.81	2.74	4.55	1.69	6.29	7.99	1.80	2.46	4.25	1.69	4.13	5.82	1.78	2.05	3.83	1.69	3.04	4.73	1.76	1.75	3.52
AC	1 3/8 X 4 1/8	1.66	7.82	9.48	1.81	2.63	4.44	1.66	5.65	7.32	1.79	2.33	4.13	1.66	3.73	5.39	1.77	1.93	3.70	1.66	2.76	4.42	1.75	1.64	3.39
AD	1 3/8 X 4 5/8	1.62	7.09	8.71	1.80	2.52	4.32	1.62	5.14	6.76	1.78	2.22	4.00	1.62	3.41	5.03	1.75	1.82	3.57	1.62	2.54	4.16	1.72	1.54	3.27
AE	1 3/8 X 5 1/8	1.58	6.49	8.07	1.79	2.42	4.21	1.58	4.72	6.30	1.76	2.12	3.88	1.58	3.15	4.73	1.72	1.73	3.45	1.58	2.36	3.93	1.70	1.46	3.15
AF	1 3/8 X 5 5/8	1.53	5.99	7.52	1.77	2.33	4.10	1.53	4.37	5.90	1.74	2.02	3.76	1.53	2.93	4.46	1.69	1.64	3.33	1.53	2.20	3.73	1.66	1.38	3.04
EA	1 3/4 X 2 1/8	1.03	10.40	11.43	1.05	1.90	2.96	1.03	7.43	8.46	1.05	1.79	2.84	1.03	4.79	5.83	1.05	1.61	2.66	1.03	3.46	4.50	1.05	1.45	2.49
EH	1 3/4 X 2 5/8	1.06	8.77	9.83	1.09	1.84	2.93	1.06	6.28	7.34	1.09	1.71	2.80	1.06	4.08	5.14	1.09	1.51	2.60	1.06	2.97	4.03	1.08	1.35	2.43
EB	1 3/4 X 3 1/8	1.08	7.61	8.68	1.13	1.77	2.90	1.08	5.47	6.55	1.12	1.64	2.76	1.08	3.57	4.65	1.12	1.43	2.55	1.08	2.62	3.69	1.11	1.26	2.37
EJ	1 3/4 X 3 5/8	1.08	6.73	7.82	1.15	1.72	2.87	1.08	4.86	5.94	1.15	1.57	2.72	1.08	3.20	4.28	1.14	1.36	2.50	1.08	2.36	3.44	1.13	1.19	2.32
EC	1 3/4 X 4 1/8	1.08	6.06	7.13	1.17	1.66	2.83	1.08	4.39	5.47	1.16	1.51	2.67	1.08	2.91	3.99	1.15	1.29	2.44	1.08	2.16	3.24	1.14	1.13	2.27
ED	1 3/4 X 4 5/8	1.07	5.51	6.58	1.19	1.61	2.79	1.07	4.01	5.08	1.17	1.45	2.62	1.07	2.67	3.74	1.16	1.23	2.39	1.07	2.00	3.07	1.14	1.07	2.21
EE	1 3/4 X 5 1/8	1.05	5.07	6.12	1.19	1.55	2.75	1.05	3.70	4.75	1.18	1.39	2.57	1.05	2.48	3.54	1.16	1.18	2.33	1.05	1.87	2.92	1.14	1.02	2.16
EF	1 3/4 X 5 5/8	1.03	4.69	5.72	1.20	1.50	2.70	1.03	3.43	4.47	1.18	1.34	2.52	1.03	2.32	3.35	1.15	1.13	2.28	1.03	1.76	2.79	1.13	0.97	2.11
BA	2 X 2 1/8	0.78	8.89	9.67	0.80	1.45	2.24	0.78	6.35	7.14	0.80	1.37	2.17	0.78	4.10	4.88	0.79	1.25	2.04	0.78	2.97	3.75	0.79	1.14	1.93
BH	2 X 2 5/8	0.81	7.53	8.34	0.84	1.40	2.24	0.81	5.40	6.21	0.83	1.32	2.15	0.81	3.50	4.32	0.83	1.18	2.01	0.81	2.55	3.36	0.83	1.07	1.89
BB	2 X 3 1/8	0.83	6.55	7.38	0.87	1.36	2.23	0.83	4.71	5.54	0.87	1.27	2.13	0.83	3.08	3.91	0.86	1.13	1.99	0.83	2.26	3.09	0.86	1.01	1.86
BJ	2 X 3 5/8	0.84	5.82	6.66	0.90	1.32	2.22	0.84	4.20	5.04	0.89	1.22	2.11	0.84	2.77	3.61	0.88	1.07	1.96	0.84	2.05	2.89	0.88	0.95	1.83
BC	2 X 4 1/8	0.85	5.24	6.09	0.92	1.28	2.20	0.85	3.80	4.65	0.91	1.18	2.09	0.85	2.52	3.37	0.90	1.03	1.93	0.85	1.88	2.73	0.89	0.91	1.80
BD	2 X 4 5/8	0.84	4.78	5.63	0.93	1.25	2.18	0.84	3.48	4.33	0.93	1.14	2.07	0.84	2.33	3.17	0.91	0.99	1.90	0.84	1.75	2.59	0.90	0.87	1.77
BE	2 X 5 1/8	0.84	4.40	5.24	0.95	1.21	2.16	0.84	3.22	4.06	0.94	1.10	2.04	0.84	2.17	3.01	0.92	0.95	1.87	0.84	1.64	2.48	0.91	0.83	1.74
BF	2 X 5 5/8	0.83	4.09	4.92	0.96	1.18	2.14	0.83	3.00	3.83	0.94	1.06	2.01	0.83	2.03	2.86	0.93	0.91	1.84	0.83	1.55	2.38	0.91	0.80	1.71
CH	2 1/2 X 2 5/8	0.52	5.80	6.32	0.53	0.89	1.42	0.52	4.16	4.68	0.53	0.85	1.38	0.52	2.70	3.22	0.53	0.78	1.31	0.52	1.97	2.49	0.53	0.71	1.24
CB	2 1/2 X 3 1/8	0.54	5.07	5.61	0.56	0.87	1.43	0.54	3.65	4.19	0.56	0.82	1.38	0.54	2.39	2.93	0.55	0.75	1.30	0.54	1.76	2.29	0.55	0.68	1.23
CJ	2 1/2 X 3 5/8	0.55	4.53	5.08	0.58	0.85	1.43	0.55	3.27	3.82	0.58	0.80	1.38	0.55	2.16	2.71	0.58	0.72	1.30	0.55	1.60	2.15	0.57	0.65	1.23
CC	2 1/2 X 4 1/8	0.56	4.10	4.66	0.60	0.83	1.43	0.56	2.98	3.54	0.60	0.78	1.38	0.56	1.98	2.54	0.59	0.70	1.29	0.56	1.48	2.04	0.59	0.63	1.22
CD	2 1/2 X 4 5/8	0.57	3.47	4.04	0.64	0.79	1.43	0.57	2.55	3.11	0.63	0.74	1.37	0.57	1.72	2.29	0.62	0.65	1.27	0.57	1.31	1.88	0.62	0.58	1.20
CD	2 1/2 X 5 1/8	0.57	3.47	4.04	0.64	0.79	1.43	0.57	2.55	3.11	0.63	0.74	1.37	0.57	1.72	2.29	0.62	0.65	1.27	0.57	1.31	1.88	0.62	0.58	1.20
CF	2 1/2 X 5 5/8	0.57	3.23	3.80	0.65	0.78	1.43	0.57	2.38	2.95	0.64	0.72	1.36	0.57	1.62	2.19	0.63	0.63	1.26	0.57	1.24	1.81	0.62	0.56	1.19
DB	3 X 3 1/8	0.37	4.10	4.47	0.39	0.61	0.99	0.37	2.95	3.33	0.39	0.58	0.97	0.37	1.94	2.31	0.39	0.53	0.92	0.37	1.42	1.80	0.38	0.49	0.88
DJ	3 X 3 5/8	0.39	3.67	4.06	0.41	0.59	1.00	0.39	2.66	3.04	0.41	0.56	0.97	0.39	1.76	2.14	0.40	0.52	0.92	0.39	1.30	1.69	0.40	0.47	0.88
DC	3 X 4 1/8	0.40	3.34	3.73	0.43	0.58	1.01	0.40	2.43	2.82	0.42	0.55	0.97	0.40	1.62	2.02	0.42	0.50	0.92	0.40	1.21	1.61	0.42	0.46	0.88
DC	3 X 4 5/8	0.40	3.34	3.73	0.43	0.58	1.01	0.40	2.43	2.82	0.42	0.55	0.97	0.40	1.62	2.02	0.42	0.50	0.92	0.40	1.21	1.61	0.42	0.46	0.88
DE	3 X 5 1/8	0.41	2.85	3.26	0.46	0.56	1.02	0.41	2.09	2.50	0.45	0.53	0.98	0.41	1.42	1.83	0.45	0.47	0.92	0.41	1.08	1.49	0.44	0.43	0.88
DF	3 X 5 5/8	0.41	2.66	3.07	0.47	0.55	1.02	0.41	1.96	2.37	0.46	0.51	0.98	0.41	1.34	1.76	0.46	0.46	0.92	0.41	1.03	1.44	0.45	0.42	0.87
DP	3 X 5 7/8	0.41	2.58	2.99	0.47	0.55	1.02	0.41	1.91	2.32	0.47	0.51	0.98	0.41	1.31	1.72	0.46	0.46	0.92	0.41	1.01	1.42	0.46	0.41	0.87
DG	3 X 8 5/8	0.40	1.95	2.35	0.52	0.49	1.01	0.40	1.47	1.87	0.51	0.45	0.96	0.40	1.05	1.45	0.50	0.39	0.89	0.40	0.83	1.23	0.48	0.36	0.84
FC	3 1/2 X 4 1/8	0.30	2.79	3.09	0.32	0.43	0.75	0.30	2.03	2.33	0.31	0.41	0.72	0.30	1.36	1.65	0.31	0.38	0.69	0.30	1.02	1.31	0.31	0.35	0.66
FD	3 1/2 X 4 5/8	0.30	2.58	2.88	0.33	0.42	0.75	0.30	1.88	2.19	0.33	0.40	0.73	0.30	1.27	1.57	0.32	0.37	0.69	0.30	0.96	1.26	0.32	0.34	0.66
FE	3 1/2 X 5 1/8	0.31	2.40	2.71	0.34	0.42	0.76	0.31	1.76	2.07	0.34	0.39	0.73	0.31	1.20	1.51	0.34	0.36	0.70	0.31	0.91	1.22	0.33	0.33	0.67
FF	3 1/2 X 5 5/8	0.31	2.24	2.56	0.35	0.41	0.76	0.31	1.66	1.97	0.35	0.39	0.74	0.31	1.14	1.45	0.35	0.35	0.70	0.31	0.87	1.19	0.34	0.33	0.67
FP	3 1/2 X 5 7/8	0.31	2.18	2.49	0.36	0.41	0.77	0.32	1.61	1.93	0.36	0.38	0.74	0.32	1.11	1.43	0.35	0.35	0.70	0.32	0.86	1.17	0.35	0.32	0.67
FG	3 1/2 X 8 5/8	0.31	1.67	1.98	0.40	0.37	0.78	0.31	1.26	1.58	0.40	0.34	0.74	0.32	0.91	1.22	0.39	0.31	0.70	0.32	0.72	1.04	0.38	0.28	0.66

Shelf Life

Aluminum electrolytic capacitors stored for more than 5 to 10 years may have increased levels of DC leakage current. Check if DCL meets application requirements before placing in service. Recondition high DCL units by applying rated voltage through 1,000 Ω resistor for 30 minutes.

Shelf life is a measure of how the capacitors will withstand storage for long times especially at high temperature. To test shelf life place the capacitors in an oven set to the shelf-life test temperature –0 +3 °C for the shelf-life test period. Upon completion of the test stabilize the capacitors at 25 °C for 24 h or more. Apply the rated voltage for 30 minutes, then verify the post test limits. Unless otherwise specified the capacitance, DCL and ESR will meet initial requirements.

Process Considerations

Soldering

Preheat

Don't exceed the maximum storage temperature during preheating of the capacitors. If this cannot be avoided, contact the supplier first.

Temperature and Duration

Strictly adhere to soldering conditions for temperature, duration and minimum distance of solder from body. Don't contact the insulating sleeve or other plastic parts with a soldering iron or molten solder. Reflow solder only SMT types, and then only one reflow cycle. Contact the supplier if more than one reflow is necessary.

Care after Soldering

Do not exert any mechanical force like bending, straightening, twisting or tilting of capacitors after soldering into a printed circuit board.

Handling Assembled Devices

During transport and handling of assembled devices do not misuse capacitors as a handle. Ensure that capacitors are protected from physical damage during mounting of printed circuit boards into assemblies or during stacking.

Halogenated-Solvent Cleaning

Halogenated hydrocarbon solvents (CFC) are ozone depleting chemicals harmful to the environment. Such solvents can penetrate the capacitors' seals and cause corrosion and failure when voltage is applied, and so use them to clean aluminum electrolytic capacitors only to the limited conditions given by the component supplier and then only as a last resort. Solvent-proof miniature capacitors and capacitors with epoxy endseals are available for limited use with halogenated solvents.

Aqueous Cleaning

Water with a mild detergent may be used to clean aluminum electrolytic capacitors. However, immediately dry the capacitors in hot air at about 85 °C for 5 or more minutes but not hotter than the capacitors' maximum storage temperature. Water can become trapped beneath the sleeve which may not be dispelled by evaporation at room temperature. Water can be trapped under the sleeve and cause hydration and discoloration of the aluminum cases, although this does not affect capacitor operation.

Alcohol Cleaning

Alcohol solvents like isopropanol, methanol, ethanol and propanol have no harmful affects on aluminum electrolytic capacitors. While they are fine for cleaning, they are not very effective in removal of commercial soldering fluxes.

Cleaning Precautions

The capacitor's insulating sleeve may re-shrink or crack if rapidly heated to above 100 °C just after cleaning. If the solder flux contains chlorine as many active flux types do, frequently regenerate or replace the cleaning solvent to avoid damaging the capacitors. Cleaning solvents may swell the insulating sleeves and affect the legibility of marking if applied too long or with too high mechanical forces or temperatures.

Potting and gluing

Be certain that varnishing, coating, lacquering, embedding or gluing near the capacitors' seals are halogen free. And be sure all constituent parts including base material, thinners, binders, reacting agents, propellants and additives are halogen free. If the printed circuit board has been cleaned with halogenated solvent, be sure it's fully dry before installation of capacitors. When gluing, don't apply glue to the full capacitor circumference, and don't cover the capacitor's pressure-relief vent with potting or glue.

Mounting

Mounting position

At lower ambient temperatures aluminum electrolytic capacitors have longer operating lives; so, put the capacitors at the coolest place on the board. Ensure that aluminum electrolytic capacitors are away from hot components like power resistors, power transistors or diodes and transformers. Adequately space components apart for cooling air to circulate. This is especially important when high ripple current or charge/discharge loads are applied.

Polarity indication

Aluminum electrolytic capacitors are normally polarized and require correct-polarity installation in the circuitry. To ensure correct mounting and identification of the polarity, put a clear + and/or – on the board layout marking. If the circuit voltage can reverse polarity or is unknown, consider using non-polar capacitors. Disadvantages are that non-polar capacitors are larger and more expensive.

Position of the pressure-relief device

Provide adequate clearance for proper operation of the pressure-relief devise. The following distances are a guide.

Nominal Case Diameter	Space around pressure relief device
≤ 16 mm	> 2 mm
> 16 mm to < 40 mm	> 3 mm
≥ 40 mm	> 5 mm

Mount the capacitors with the vent uppermost or in the upper part of the capacitor. This assures that the least amount of electrolyte will be expelled if the vent operates. Mount capacitors that include thermal-plastic potting such that the potting cannot block the vent should the potting melt during capacitor failure. No Cornell Dubilier aluminum electrolytic capacitors contain potting.

Printed-circuit board precautions

Avoid positioning holes in places where parts of a capacitor could be on the other side and be touched by molten solder. Because the can and sometimes extra terminals of an aluminum electrolytic capacitor have resistive connections to the negative terminal through the electrolyte,

- don't locate tracks or lands under upright capacitors,
- don't permit metal capacitor parts other than active terminals to contact conductive tracks or other components, and
- leave dummy pins potential free.

Handling terminals

Before handling a capacitor be sure it is sufficiently discharged. To avoid damaging the capacitor, don't bend rigid terminals, and be sure to clamp the terminals during cutting or bending to avoid excess stress on terminations, welds and capacitor seals.

Don't use extra force to insert capacitors. If they cannot be inserted easily, correct the problem. Discard capacitors showing signs of mechanical damage.

Screw-terminal mounting torque

Excess torque during tightening screw terminals may affect the performance of the capacitor or damage the terminal. The following torque settings are recommended. Be certain that at least six threads are engaged.

Terminal	Recommended Torque
10–32, Low Post	25 in-lb
10–32, High Post	25 in-lb
¼–28, Low Post	50 in-lb
¼–28, High Post	60 in-lb
M5 Post	30 in-lb

Screw-terminal current rating

For normal operation the maximum recommended continuous AC currents for screw terminals are as tabulated below.

Terminal	Maximum Current
10–32, Low Post	30 A rms
10–32, High Post	30 A rms
¼–28, Low Post	50 A rms
¼–28, High Post	50 A rms
M5 Post	35 A rms

The ripple current ratings may exceed the currents listed here. Terminals can withstand these higher continuous currents if you assure gas-tight connections to avoid formation of aluminum oxide. Use Belleville washers and a commercial electrical joint compound, and tighten the terminals to their recommended torque.

Mounting-stud mounting torque

Computergrade, screw-terminal capacitors are available with threaded mounting studs on the can bottoms, and nylon nuts are available for insulated mounting. The following torque settings are recommended.

Nylon Nut Thread	Recommended Torque
M8	25 in-lb
M12	75 in-lb

Disposal of Capacitors

Aluminum electrolytic capacitors with non-solid electrolyte principally include high-purity aluminum foils, capacitor paper, electrolyte, aluminum case, cover and sealing parts (phenolic, thermoplastic, rubber and phenolic board), insulating sleeve (polypropylene, polyester or polyvinylchloride) and, perhaps, safety-vent plugs made of synthetic rubber. If incinerated, be certain that the temperature is more than 1200 °C. Disposal is permitted in appropriate landfills. For more details contact the manufacturer.