

Scope of This Application Guide	1
Table 1: Parameters and Variables Related to Capacitors	
Construction Overview	2
Production Process Overview	3
Device Physics	4
Essential Characteristics and How to Measure Them	5
Capacitance Cs, Resistance Rs, Inductance Ls, Capacitor Impedance Z, DC Leakage Resistance Rl and Leakage Current (DCL), Typical Initial DCL Versus Voltage and Temperature, Zener Diode Dz	
General Limitations, Additional Characteristics and Test Methods	7
Operating Temperature Range; Storage Temperature Range, Short-Term and Long-Term; Shelf Life Test; Re-Ageing, Re-Forming, Reconditioning of High DCL Capacitors; Rated DC Voltage; Rated Surge Voltage; Surge Voltage Test; Reverse Voltage; Transient Overvoltage; Ripple Current Transients and High Inrush Current; Charge-Discharge Duty and High Peak-To-Peak Voltage; Insulation and Grounding, Case and Dummy Pins, Sleeving; Elevation (Altitude) and External Pressure; Mechanical Vibration and Shock; Thermal Cycle, Immersion and Thermal Shock; Polarity – Reverse Voltage; Anti-Series Connection, Non-Polar, AC and Motor-Start Capacitors; Self-Resonant Frequency; Dielectric Absorption (DA)	
Capacitor Bank Configurations	10
General Considerations, Parallel Connection, Bus Structure, Fusing and Soft Start, Series Connection, Voltage Sharing, Balancing Resistors, Parallel/Series Bank, Series/Parallel Bank	
Reliability and Lifetime	12
Reliability Model, The “Bathtub Curve”; Ripple Current, Load Life Tests, Ripple Multipliers; Ripple Multiplier Tables; Operating Lifetime Model; Table of Base Lifetime Lb and Maximum Core Temperature Tm; Lifetime Calculations for Varying Ambient Temperature or Varying Ripple Current; Load Life Test; EIA Ripple Life Test; EIA IS-749; Estimating Lifetime for Capacitors without an Online Calculator	
Cooling and Thermal Resistance	14
Cooling Strategies, Thermal Resistance	
Process Considerations	15
Soldering, Wave and Reflow Soldering Tips, Care After Soldering, Handling Circuit Board Assemblies, Halogenated-Solvent Cleaning, Aqueous Cleaning, Alcohol and Solvent Cleaning to Remove Solder Flux Residue, Cleaning Precautions, Potting and Gluing, Fumigation Warning	
Mounting	20
Mounting Position, Position of the Pressure-Relief Vent, Printed-Circuit Board Precautions Handling Terminals, Screw-Terminal Torque, Screw-Terminal Current Rating, Mounting-Stud Torque	
Safety Considerations	21
Electric Shock Hazard, Pressure-Relief Vent, Contact with Electrolyte, Flammability	
Disposal of Capacitors	21
Quality, Testing and Environmental Certifications	22
Notice and Disclaimer	22

SCOPE OF THIS APPLICATION GUIDE

This guide covers the application of polar, non-solid aluminum electrolytic capacitors, which are those aluminum electrolytic capacitors featuring a wet, aqueous electrolyte with separator membranes such as cellulosic papers between two aluminum foils. Other types of aluminum electrolytic capacitors not covered include the obsolete wet types without separator membranes, “hybrid” aluminum electrolytic capacitors containing both polymer and liquid electrolyte components and solid-polymer electrolytic capacitors. This application guide focuses on the application of polar, non-solid aluminum electrolytic

capacitors used in ripple-filtering applications such as used as input and output capacitors in linear and switch-mode power supplies and inverters. This guide does not cover in detail, application of non-polar aluminum electrolytic capacitors such as AC motor-start capacitors. Photoflash, strobe, pulse discharge and charge-discharge specialty capacitors are not covered. In the case where there is a disagreement between statements made in this application guide and the individual technical datasheet for a capacitor series or an individual capacitor, the latter should be used as the authority. For technical questions on topics not covered in this application guide, please contact us.

Parameters and Variables

Parameter	Unit	Symbol	Formula(s)	Approximately
Capacitance	farads [F]	Cs		
Series resistance	ohms [Ω]	Rs		
Series inductance	henries [H]	Ls		
Time	seconds [s]	t		
Time-dependent voltage	volts [V]	v(t)	$\int i[t]dt/Cs$	
Time-dependent current	amps [A]	i(t)	$Cs \times dv/dt$	
Frequency	hertz [Hz]	f		
Self-resonant frequency	hertz [Hz]	f_{RES}	$\frac{1}{2 \pi \sqrt{Ls Cs}}$	
Capacitive reactance at frequency f	ohms [Ω]	Xc	$-1/(2 \pi f Cs)$	
Inductive reactance at frequency f	ohms [Ω]	X _L	$2 \pi f Ls$	
Reactance at frequency f	ohms [Ω]	X	$Xc + X_L$	
Impedance magnitude at frequency f	ohms [Ω]	Z	$\sqrt{Rs^2 + X^2}$	
Impedance phase angle at frequency f	radians [rad]	θ	$\tan^{-1}(X/Rs), \delta - \pi/2$	
Impedance loss angle at frequency f	radians [rad]	δ	$\tan^{-1}(Rs/ X), \frac{\pi}{2} - \theta $	
Dissipation factor at frequency f	unitless	D	$Rs/ X , \tan(\delta)$	$2 \pi f Cs Rs$
RMS voltage at frequency f	volts [V _{rms}]	V	$I \times Z $	$I / (2 \pi f Cs)$
RMS current at frequency f	amps [A _{rms}]	I	$V / Z $	$2 \pi f Cs V$
Power dissipation at frequency f	watts [W]	P	$V \times I \times D, I^2 Rs$	$2 \pi f Cs D V^2$
Applied DC voltage	volts [VDC]	V _A		
Stored energy	joules [J]	E	$\frac{1}{2} Cs V_A^2$	
Stored charge	coulombs [C]	Q	$Cs V_A$	

Table 1: Parameters and variables related to capacitors

CONSTRUCTION OVERVIEW

An aluminum electrolytic capacitor consists of a wound capacitor element, impregnated with liquid electrolyte, connected to terminals and sealed in a can. See Figures 1 and 2. Voltage ratings are classified as < 100 VDC for low voltage, 101-250 for mid-voltage and 251-700 for high voltage. Typical case volumes range from a few cubic centimeters in radial and axial leaded configurations to over one liter in the largest screw-terminal sizes. Between these extremes there are many snapmount and screw-terminal sizes ranging from about 10 to 1,000 cc's. Typical capacitance ranges are 10 μ F to 3 farads in the low-voltage range, 5 μ F to 0.2 farads in the mid-voltage range, and 2 to 40,000 μ F in the high-voltage range.

All Cornell Dubilier capacitors use compression-fit construction so there is no thermoplastic potting compound to interfere with safety vent operation. Thermal Pak™ and Rilled are Cornell Dubilier's exceptional constructions for 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 in weight. Rilled construction offers superior shock and vibration withstanding, typically withstanding more than 15 g acceleration forces.

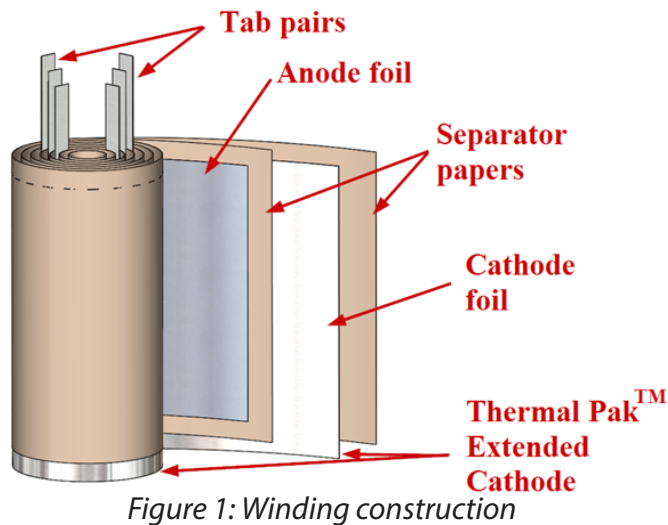


Figure 1: Winding construction

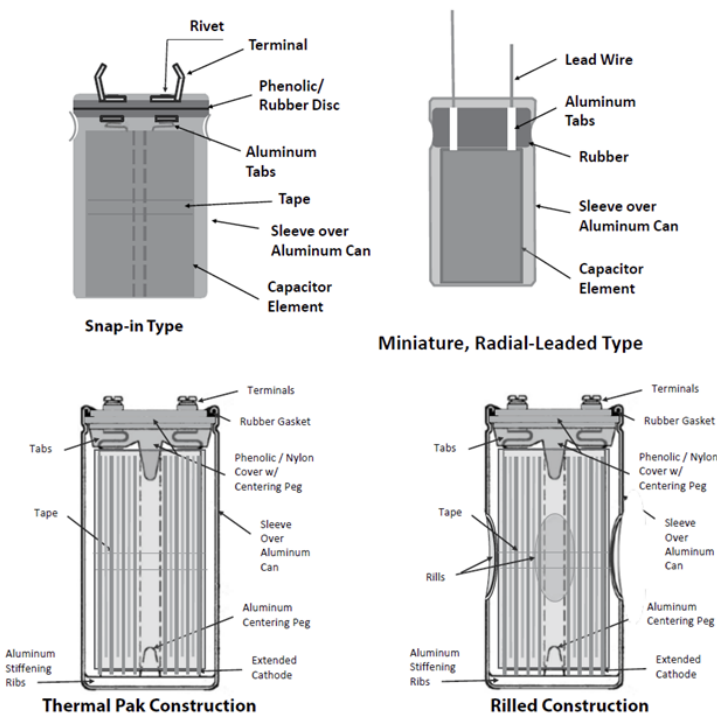


Figure 2: Capacitor construction variations

PRODUCTION PROCESS OVERVIEW

Figure 3 shows the production processes. The anode aluminum foil is etched to increase the surface area, and is later anodized during the Forming process, which grows a thin aluminum oxide insulating coating to a thickness that provides an electrical insulation up to a potential known as the formation voltage, which is always substantially higher than the capacitor’s rated DC voltage. As the formation process progresses, the thickening dielectric coating reduces the microscopic surface area of the etched foil because the etch tunnels become partially occluded by the oxide. So, for a given etched foil as the formation voltage is increased, the capacitance per macroscopic area drops dramatically because the area contacting the electrolyte is decreasing while the thickness of the dielectric is increasing. Increasing the formation voltage— and thus the dielectric thickness— by 10% would typically result in a capacitance decrease of 13%, resulting in a charge storage decrease of 5% and an energy storage increase of 5% at the higher formation voltage.

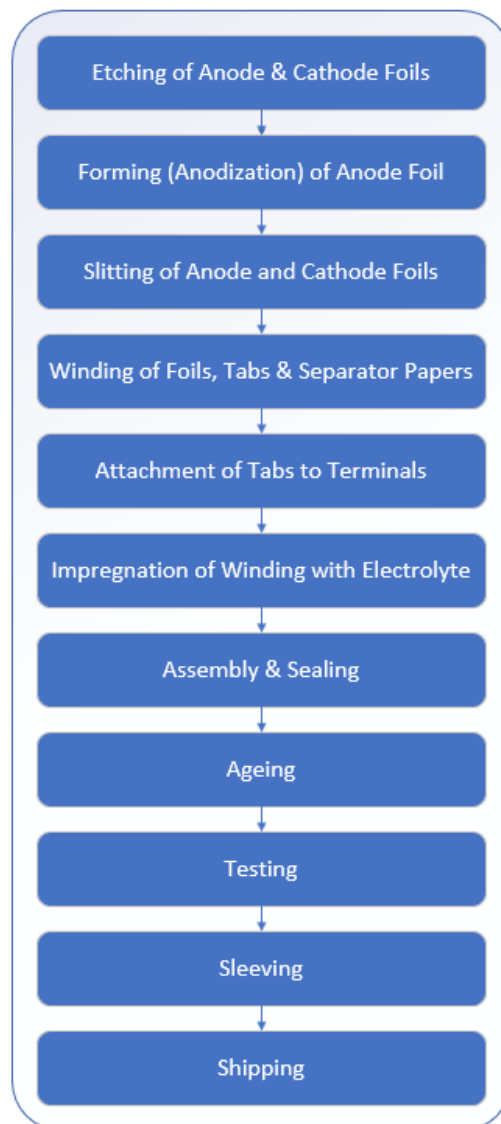


Figure 3: Capacitor manufacturing process

The anode foil etch pattern is optimized for high capacitance or low ESR over a range of formation voltages by choice of foil thickness, alloy, grain structure (cubicity), and etching and forming geometries governed by electrolyte compositions and electrical waveforms. Thus low-voltage anodes have denser tunnel patterns compatible with thin oxide and high-voltage anodes have coarser tunnel patterns compatible with thick oxide.

The cathode foil is etched in a different manner than the anode foil, and may be stabilized or passivated but does not usually go through a Forming process.

The anode and cathode foil rolls typically weigh about 100 kg (220 pounds) and are nearly 0.5 meters (20 inches) wide during the foil processing, and are cut into narrower rolls during the Slitting process.

During the Winding process, the anode foil, cathode foil and multiple separator papers are wound together. One or more pairs of aluminum ribbons known as tabs are attached to the foils prior to or during Winding. During the Impregnation pro-

cess, the liquid electrolyte saturates the winding. The top with terminals may be attached to the tabs of the winding before or after impregnation. In an axial-leaded capacitor, the can is attached to the negative tab(s).

During the Sealing process, the capacitor element is sealed into an outer package, usually made of aluminum, but sometimes stainless steel or other material. To control pressure build-up, the seal is not usually hermetic but rather 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. Unless specially constructed, too tight a seal may cause excessive pressure build up; while too loose a seal shortens the lifetime by permitting dry-out, which is evaporative loss of electrolyte. After the capacitor is sealed, it is usually washed to remove electrolyte residue from the outside of the package.

During the Ageing process, 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 may be used depending upon performance goals. This process re-forms the edges and any damaged spots on the anode foil such as where the tabs were attached. And bare areas or damaged dielectric is repaired with fresh aluminum oxide dielectric. Proper ageing reduces the instance of early application failures (infant mortals). Low initial DC leakage current is a sign of effective ageing. After ageing, the capacitor is tested, sleeved and labeled, packed and finally shipped.

DEVICE PHYSICS

A capacitor is physically created when two conductors are separated by an insulator known as a dielectric. While it may at first appear that an electrolytic capacitor is two conductive aluminum foils separated by an insulating fluid, this is not the situation because the electrolyte is ionically conductive, and is not an insulating fluid. The actual dielectric is the very thin aluminum oxide (anodic alumina) on the highly etched 3D surface of the anode foil. The etch pattern typically comprises billions of microscopic tunnels— $10^7/\text{cm}^2$ is typical for a high-voltage anode— to increase the surface area in contact with the electrolyte. This microscopic to macroscopic areal enhancement factor is often on the order of 50-100 for low-voltage foil and around 20 for high-voltage foil. See Figure 4. The cathode is also chemically or electrochemically roughened, but usually little or no aluminum oxide is grown. The thickness of the anode dielectric coating is proportional to the voltage applied to the foil while in the Formation bath, about 1.0-1.4 nm per volt.

In an operating aluminum electrolytic capacitor, the alumina has a dry positively charged side integral with the anode aluminum foil and a wet negatively charged side contacted by the electrolyte, which conducts ionically through the wet separator papers and finally to the cathode foil surface. The electrolyte can be thought of as a "liquid cathode." The separators (usually cellulosic paper) serve as a wick during impregnation as well as a long-term reservoir for the electrolyte. Additionally the separators prevent physical, electronic contact between the anode and cathode surfaces, which would result in a short-circuit. The

anode foils are usually 80-130 μm thick, the cathode foils 15-50 μm thick and the two paper pads 25-90 μm on each side of the anode.

The wound element comprises an aluminum, high purity anode foil, separator membranes (usually paper) saturated with electrolyte and an aluminum cathode foil, usually of lower purity than the anode foil. The foils have aluminum ribbons called tabs welded to them so that terminals can later be attached.

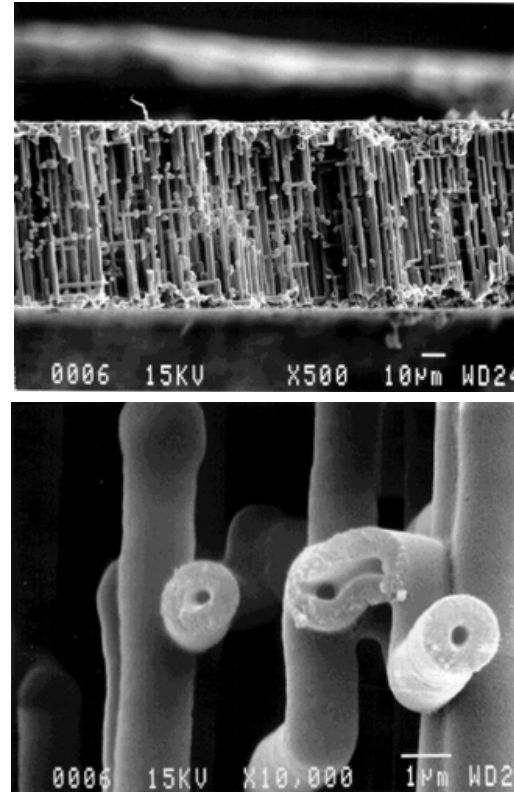


Figure 4: SEM photo of anode foil dielectric structure, after the aluminum which normally fully surrounds the tubes has been dissolved away for clarity. The top photo is an edge view of a 100 μm thick foil from a 400 VDC rated aluminum electrolytic capacitor. The hollow alumina dielectric tubes are seen to be bundled closely together, with some of the tubes having right-angle bend "elbows." The bottom photo of the same foil, at 20 times higher magnification, shows a couple of the tube openings as well as a tube that was broken during handling, revealing its hollow cross-section at an elbow. In a finished capacitor, all of the alumina tubes are filled with electrolyte.

The resulting construction is polar in nature, especially due to the high mobility of protons and hydronium ions readily available in the aqueous electrolyte. The electrolyte is deficient in free electrons, and its main charge carriers are protic hydronium ions H_3O^+ and negative hydroxyl ions OH^- . When the capacitor is forward-biased, the dielectric is dense enough to provide an effective barrier to the flow of hydroxyl ions that are being attracted from the electrolyte to the underlying aluminum of the anode foil. However, if continuous or repetitive reverse voltage exceeding about 0.5 to 1.5 volts such as reverse DC voltage or even the negative half cycle of an AC voltage waveform is applied to a polar electrolytic capacitor, protons— which are, after all, much smaller than hydroxyl ions— will not be effectively blocked, and they will readily flow (conduct) through the dielec-

tric to the negatively biased anode foil. This will cause the water and possibly other ions in the electrolyte to dissociate, attempting to grow aluminum oxide onto the surface of the cathode foil and to liberate hydrogen at the anode foil. Therefore, application of reverse or AC voltage will rapidly cause heating, hydrogen gassing, pressure build-up, loss of capacitance and increase in ESR in a polar electrolytic capacitor.

The capacitor element is vacuum-impregnated with electrolyte to saturate the paper separators and penetrate the etch tunnels so that the ionically conducting, liquid electrolyte is in contact with the cathode foil surface as well as the anode foil's tortuous dielectric surface. The other side of the oxide dielectric is in physical, electronic contact to the metal of the anode foil, and thus the dielectric has positive and negative contacts, forming a capacitor.

The electrolyte is a complex blend of ingredients with different formulations according to the rated voltage and operating temperature range. The principal ingredients are a solvent plus various conductive salts – a solute – to provide ionic conduction. Common solvents are ethylene glycol (EG) and gamma-butyrolactone (GBL). Common solutes are boric acid, weak organic acids and pH-neutralizing additives such as ammonium salts. Other additives increase stability and longevity by providing corrosion resistance and reducing hydrogen gassing over the lifetime of the capacitor.

Water in the electrolyte plays a big role. It increases conductivity, thereby reducing the capacitor's electrical 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 hydrolytically. 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 liberated at the cathode can be tied up chemically or allowed to form gas and escape through provisions in the packaging.

Whenever a polar liquid such as an aqueous electrolyte is in physical contact with a solid conductor— even without an applied voltage— molecular rotations occur in the electrolyte ions near the interface, forming a region of separated, opposite charges. This charge-storage mechanism is called an electric double-layer capacitance, and occurs to a strong degree at the electrolyte-cathode surface and to a lesser degree at the electrolyte-anode surface. This makes the cathode a capacitor in series with the anode. Thus in effect an electrolytic capacitor has several capacitances in series, and these vary in different ways with frequency, temperature and voltage.

The expression below gives the capacitance of a prismatic dielectric plate of relative dielectric constant k , surface area A and thickness d . The dielectric of an aluminum electrolytic capacitor is not actually a flat surface, but this simple expression illustrates the principles at work.

$$C_s = k \epsilon_0 A / d \quad (1)$$

k is a fairly high relative dielectric constant of about 8-10. The constant ϵ_0 is the permittivity of free space, which is 8.854 pF/m. The large effective dielectric area A results from the high degree of etching. A very small value of d is achieved by the high continuous operating electric field (typically 50% to 80% of the aforementioned oxide-growth field of 700-1000 V/ μm). Together these properties result in a very high capacitance C_s , enabling a high specific energy and large charge storage device.

ESSENTIAL CHARACTERISTICS AND HOW TO MEASURE THEM

The equivalent circuit below models an aluminum electrolytic capacitor's normal operation as well as overvoltage and reverse-voltage behavior.

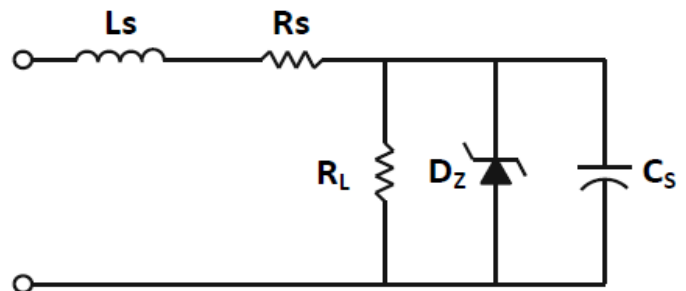
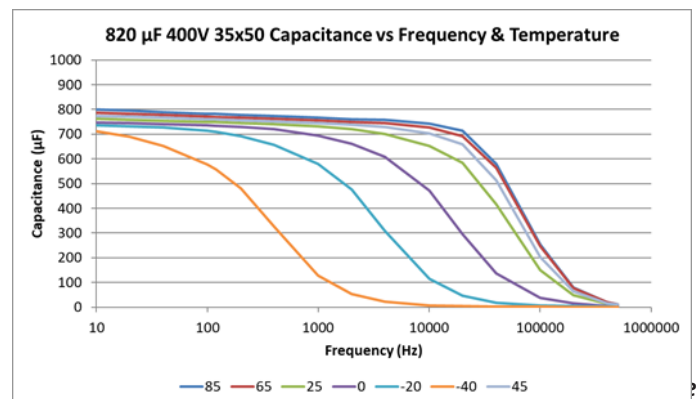


Figure 5: Equivalent circuit model

Capacitance C_s

Capacitance C_s is the equivalent AC series capacitance as measured on a capacitance bridge or LCR meter set to "series circuit" measurement mode with no more than 1-volt rms sinusoidal amplitude and without DC bias. The rated capacitance is generally specified near room temperature, 120 Hz sinusoidal waveform, with 25 °C 120 Hz or 20 °C 100 Hz being the two most common specifications. At low frequency, C_s increases slightly with increasing temperature. Above a certain temperature-dependent frequency, the capacitance drops rapidly with increasing frequency. This behavior is most dramatic at very cold temperatures and is related to the distributed RC nature of the electrolyte-filled etch tunnels, and also to the viscosity of the electrolyte, which directly affects its ionic conductivity. See Figure 6 for a typical plot of C_s versus frequency and temperature.



Resistance R_s

Resistance R_s is the equivalent AC series resistance as measured on a capacitance bridge or LCR meter in the same manner as

the capacitance C_s discussed above. R_s usually decreases with increasing temperature, as it is usually dominated by the variation in electrolyte viscosity. However, R_s has other components (metallic and dielectric) which have a positive temperature coefficient that may dominate in certain capacitors in certain regions of the frequency-temperature space. In all cases the ESR decreases monotonically with increasing frequency until the onset of skin effect of the metallic components, typically at 100 kHz or greater. Figure 7 shows typical behavior of R_s versus frequency and temperature.

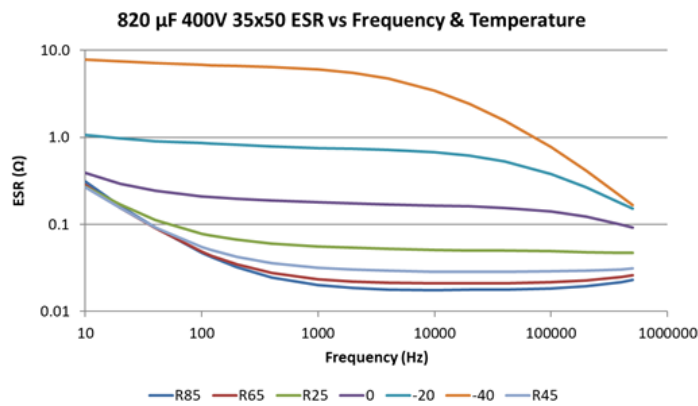


Figure 7: Typical R_s variation with frequency and temperature

Inductance L_s

Inductance L_s is the equivalent series inductance— also known as ESL— which is relatively independent of frequency and temperature. Typical values range from 10 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 and terminal-tab loop area. The inductance of the winding itself is usually very low, often less than 2 nH. At high frequency, the presence of this series inductance causes variations in the measurement of C_s on a bridge or LCR meter.

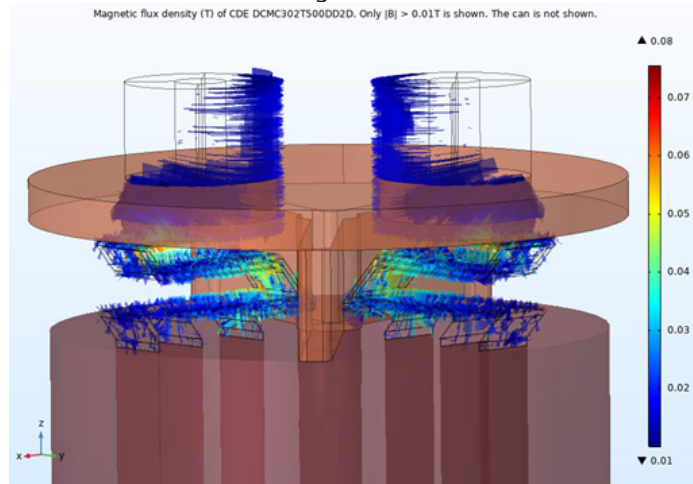


Figure 8: Typical magnetic flux lines in screw-terminal capacitor with ripple current (the can is not shown). Nearly all of the inductance arises from the circuit loop of the terminals and tabs.

C_s , R_s and L_s together with their variations with frequency and temperature impart a device input impedance magnitude seen in Figure 9. At low frequency the capacitive reactance dominates, and at very high frequency the inductive reactance

dominates. In between, the reactances fully or partially offset each other, and R_s constitutes the main component of the impedance. At the self-resonant frequency (SRF) the impedance magnitude and ESR curves touch, as seen in the figure.

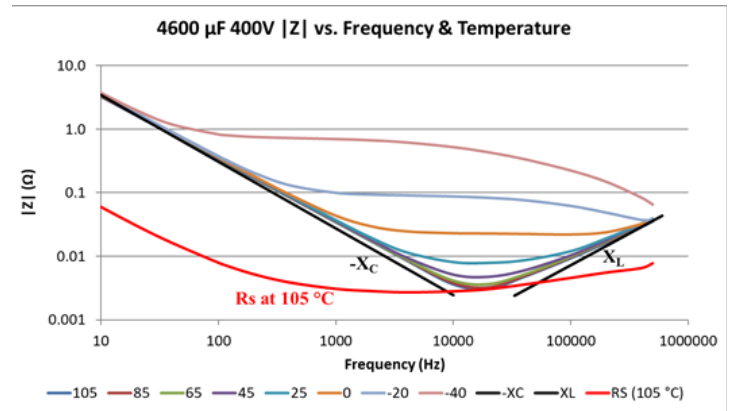


Figure 9: Typical impedance magnitude showing R_s , X_c and X_l components

Capacitor Impedance Z

For detailed information on the device physics impacting the capacitor impedance, and how the impedance varies with temperature, frequency and construction, please refer to our technical paper on impedance models at <http://www.cde.com/resources/technical-papers/impedance.pdf> and also to our online electrical modeler at <http://www.cde.com/spice/ImpedanceAppletIntro.html> which displays charts of C_s , R_s and impedance versus frequency and temperature, and will even generate equivalent circuit models.

DC Leakage Resistance R_L and Leakage Current (DCL)

DC Leakage Resistance R_L is the equivalent parallel resistance and accounts for DC leakage current (DCL) in the capacitor. R_L decreases (so leakage current increases) with increasing capacitor size and with the applied temperature and voltage. However, once a steady-state voltage and temperature are reached, the leakage current decreases over long periods of time. Leakage current is a function of the historical application of voltage, and a capacitor that has been recently charged will generally exhibit lower leakage current when charged again, than a similar capacitor that hasn't been charged in many weeks or months. Note that the product of R_L and C_s suggests a self-discharge time constant. This time constant is typically on the order of 100 to 1000 seconds, implying that for a 1000 μF capacitor a typical R_L value would be 100 k Ω to 1 M Ω . After many hours of steady-state voltage, at moderate core temperature and derated DC voltage, this time constant may increase from minutes to hours.

DCL is measured at 25 $^{\circ}\text{C}$ with the rated voltage applied through a protective resistance of the lesser of 1 k Ω or $10[\Omega \times F]/C_s$ 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. The room-temperature, 5-minute value of R_L may be calculated as the applied voltage divided by the measured leakage current. DC leakage current generally decreases over time, but increases with increasing core temperature and with

the applied DC voltage. Figure 10 shows a typical initial leakage current on a screw-terminal capacitor versus core temperature and applied DC voltage.

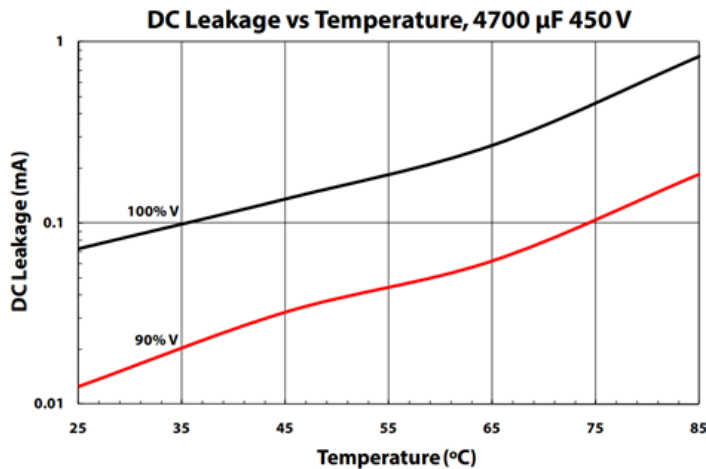


Figure 10: Typical initial DCL versus voltage and temperature

Zener Diode Dz

Zener diode Dz models overvoltage and reverse voltage behavior. Application of overvoltage above the capacitor's surge voltage rating causes a very high leakage current, especially when the capacitor is warm or hot, similar to the 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. It is not advisable to attempt to measure the onset of Zener mode or reverse conduction mode, as such tests are generally considered to be destructive.

GENERAL LIMITATIONS, ADDITIONAL CHARACTERISTICS AND TEST METHODS

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 of the anode foil 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, directly related to the viscosity. The higher cold resistivity often increases the capacitor's ESR at the lowest rated temperature by a factor of 10 to 100 of the room-temperature ESR. Colder temperatures also reduce the capacitance and change the frequency response characteristics of the capacitance, ESR and impedance.

Storage Temperature Range, Short-term and Long-term

The short-term storage temperature range to which the part can be subjected for short periods of time— such as several days— without applied DC voltage, while retaining conformance to specified electrical limits after stabilization at room temperature is generally taken to be -55 °C to the upper category tempera-

ture. The storage atmosphere should be free of halogen gases like chlorine and fluorine that can penetrate the polymeric seals and lead to internal corrosion. Note that subsequent to storage below the minimum operating temperature, the electrolyte may need extra time to recover, to overcome the heat of fusion if it has changed phase from liquid to solid.

Storage without DC bias causes deterioration of the capacitor, especially at high storage temperature. The deterioration manifests itself as a reluctance to charge the first time that DC bias is applied after storage. During the first charge after a prolonged storage period— or after a shorter period at elevated temperature— the leakage current is higher than for a recently charged capacitor. Unless otherwise specified on the product datasheet, the long-term storage temperature range is from 5 °C to 40 °C at up to 75% relative humidity (non-condensing), for a period of up to 5 years without the need to "re-form" (re-age) the capacitor. Hotter storage temperatures tend to degrade the capacitor's initial charge efficiency in a manner that follows the "doubles every 10 °C rule."

Shelf Life Test

Shelf life is a measure of how the capacitors will withstand storage for long times especially at high temperature, with no applied DC voltage. The rated temperature and duration are generally specified in the datasheet for each of our capacitor series. To verify our shelf life ratings, 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 DCL limits. Unless otherwise specified the capacitance, DCL and ESR will meet initial requirements.

Re-ageing, Re-forming, Reconditioning of High DCL Capacitors

If you have a large group of capacitors which need to be re-formed (re-aged), you may contact us, as we may be able to apply a factory re-age procedure at elevated temperature that will more fully rejuvenate the capacitors, for a nominal processing fee. This is generally done on a best-effort basis, without providing warranty on the capacitors. Otherwise, a simple, room temperature re-age and screening procedure is outlined below.

Recondition high DCL units by setting a DC power supply to the rated DC voltage V_R and applying to each capacitor through separate series resistances of value $R = 1 \text{ k}\Omega \pm 10\%$ for 2-4 hours at room temperature. The minimum power rating of the resistor needs to be equal to $2 \times (V_R + 6[V])^2 / R$, or if this is not feasible, the current from the power supply may need to be limited to prevent resistor damage from a delinquent capacitor. Verify that the leakage current of each capacitor— which is equal to the DC voltage across its $1 \text{ k}\Omega$ series resistor divided by $1 \text{ k}\Omega$ — is within its specified limit. Capacitors which do not meet their leakage current limit at this stage should be discarded.

Discharge the remaining capacitors for one hour through their series resistors. This can be done by turning off the power supply and shorting its output for one hour. Next set the power supply to a higher voltage, equal to the rated voltage V_R plus an additional DC voltage calculated as the rated leakage current limit I_{LMAX}

multiplied by 1 k Ω . Apply this voltage to the capacitors, again through their separate series resistances, for a time equal to 5 minutes plus $5 \times C_s \times R$, e.g. for a 22,000 μF capacitor this would be 5 minutes plus 110 seconds. Verify that at the end of this time, the leakage current of each capacitor— which is equal to the DC voltage across its 1 k Ω series resistor divided by 1 k Ω — is within its specified limit. Capacitors which do not meet their leakage current limit at this stage should be discarded.

Rated DC Voltage

The rated DC voltage is the nominal voltage marked on the capacitor, and it is the maximum peak voltage including ripple voltage that may be applied continuously between the terminals, over the rated temperature range.

Rated Surge Voltage

Rated surge voltage is the maximum DC overvoltage to which the capacitor may be subjected at 25 $^{\circ}\text{C}$ for short periods not exceeding approximately 30 s at infrequent intervals of not less than 5 minutes, no more than 1,000 times during the capacitor lifetime.

Surge Voltage Test

Subject the capacitors to their rated surge voltage at normal room temperature and through a 1000 $\Omega \pm 10\%$ resistor (except for capacitances of 2500 μF and up, use a lower value resistor calculated as $2.5[\Omega \times \text{F}] / C_s \pm 10\%$ where C_s is the capacitance). Cycle the voltage $\frac{1}{2}$ minute on followed by $4\frac{1}{2}$ minutes off during which each capacitor is discharged through the charging resistor or equal resistor. Repeat the cycles for 120 h (1,440 total cycles). Post-test requirements are for C_s , R_s , D and DCL to meet initial requirements and for there to be no evidence of mechanical damage or electrolyte leakage. Electrolyte residue around the top or terminals with no droplets or visible flow is permitted. This is considered a destructive test.

Transient Overvoltage

Aluminum electrolytic capacitors can generally withstand rapid charging along with occasional overvoltage transient spikes of limited energy. If transients above the capacitor's rated DC voltage are anticipated in the application, please contact us to discuss the best capacitor for the application.

Ripple Current Transients and High Inrush Current

Electrolytic capacitors are able to survive some transient current abuse, typically more than their metallized film counterparts. As a rule of thumb, for brief ripple current excursions such as several seconds of 2 to 4 times the rated load ripple current, the thermal mass of the capacitor winding will absorb a lot of the extra energy dissipation of such an event. We would encourage you to contact us with your ripple transient requirements. For an example calculation with relevant transient thermal parameters, refer to pages 6-7 of our technical paper at <http://www.cde.com/resources/technical-papers/Predicting-Operating-Temperature-and-Expected-Lifetime.pdf>

For very high inrush or sub-millisecond transient currents such as 10,000 amps peak, please contact us. Although electrolytic capacitors do not suffer from the intrinsically low dv/dt limits of metallized film capacitors, their tabs or terminal connections

may need to be fortified to prevent overheating or even I^2t fusing. See for example, our analysis of a ringing 16 kA pulse on pages 3-5 of our technical paper at <http://www.cde.com/resources/technical-papers/TransientModelingOfLargeScrew-TerminalAluminumElectrolyticCapacitors.pdf>

We would encourage you to contact us when you expect current transients involving over 1,000 amps peak.

Charge-Discharge Duty and High Peak-to-Peak Voltage

Frequent charge and discharge of aluminum electrolytic capacitors— whether rapid or slow— 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, such as our photoflash and strobe capacitors, Type PF, 7P and ST, or contact us for a special design for your requirements.

High continuous ripple voltage can eventually have the same effect as charge-discharge duty, only to a lesser degree. High core temperature accelerates the degradation. As a general rule, if the peak-to-peak capacitor voltage divided by the capacitor's rated voltage V_R exceeds the greater of 10% or

$$0.01352 \times (V_R / 1[\text{V}])^{1/2} \quad (2)$$

on a continuous or frequent basis, then please contact us to review the capacitor design for best performance with your voltage waveform. This is a ratio of 10% up to 55 VDC rating, 14% at 100 VDC, 21% at 250 VDC and 29% at 450 VDC ratings.

Insulation and Grounding, Case and Dummy Pins, Sleeving

In aluminum electrolytic capacitors, the metal cases connect ionically and possibly electronically to the negative terminals by contact with electrolyte. In order to avoid galvanic issues, if objects contacting the cases are to be at a potential other than the negative terminal's potential, use capacitors with insulating sleeves. The key concept is that current flow should be prevented through the can to either terminal. In general the can should be allowed to float, electrically. The same rule applies for any non-electrified dummy pins; it is best not to ground them but rather to let them float.

The plastic insulation can withstand 3000 VDC or 2500 VAC RMS at room temperature, 50 or 60 Hz for 1 minute applied between the case and a $\frac{1}{4}$ inch (6 mm) wide metal foil placed around the sleeve without breakdown or punch-through of the insulation. For testing the stud-mount insulation, apply the voltage between the mounting plate and the case, and mount the capacitor with an approved plastic nut and appropriate clearance hole. For high dielectric withstanding voltage, we offer double-sleeved insulation systems. Contact us for details. Insulation resistance is no less than 100 M Ω after 2 minutes electrification with 100 VDC applied between the foil and the capacitor case.

The standard PVC sleeves that we supply are primarily for labeling purposes. Although they will initially pass the aforementioned breakdown tests, they do degrade (oxidize) over time,

especially above 65 °C. These sleeves are not suitable for long-term, high-voltage insulation at high temperature, especially in critical applications, and we recommend that you provide an additional level of more-durable insulation if permanent insulation at high voltage is required.

Elevation (Altitude) and External Pressure

Unless otherwise specified on our product datasheets, our aluminum electrolytic capacitors can operate to 80,000 feet and pressures as low as 3 kPa. However, above 10,000 feet (3 km, 70 kPa) altitude the ripple current ratings need to be reviewed due to the lowering of the convection coefficient caused by the lower air density and mass flow rate. Above 60,000 feet (17 km, 8 kPa) the creepage and clearance distances for capacitors with DC voltage above 200 VDC should be reviewed for impact by Paschen's Law. For assistance with these potential issues at high altitude, please contact us.

Our electrolytic capacitors can withstand brief or continuous exposure to 1.5 atmospheres absolute pressure (150 kPa or 22 psia). The issue with higher pressure than this is the tendency to drive airborne contaminants or fumes through the capacitor seals and into the capacitor. For assistance with applications that require higher external pressure, please contact us.

Mechanical Vibration and Shock

Most of our aluminum electrolytic capacitors can withstand test conditions imparting peak vibration accelerations of 10 g's. More specific limits are shown in the specifications for each capacitor series. Frequencies are usually in the range of 10 to 2,000 Hertz. We offer some series that are specially constructed to withstand testing up to 80 g's. We can meet many of the standard swept-sine or random vibration profiles of MIL-STD-202. Contact us if you have a particular vibration test profile our capacitor needs to meet. Continuous vibration exposure in the field needs to be well below the peak test levels.

Mechanical shock testing involves a gravimetric drop test with an acceleration waveform such as sawtooth or half-sine, which imparts an acceleration pulse with a shape, width and peak value. The acceleration profile is controlled by the pad or target which the capacitor strikes at the bottom of the drop zone. We can meet many of the standard drop test requirements of MIL-STD-202. Contact us to discuss your particular shock requirements.

Thermal Cycle, Immersion and Thermal Shock

Most of our aluminum electrolytic capacitors can withstand test conditions involving application of several thermal shocks from room temperature to the upper and lower category temperatures in a rapid manner. These are generally tested per the methods specified in MIL-STD-202G, such as Method 107G. If you have thermal shock, thermal cycle or immersion requirements, please contact our Engineering department so that we can discuss your needs and our capabilities.

Polarity – Reverse Voltage

Check the polarity of each capacitor during and after assembly. Polarity is marked on the capacitor. While the capacitors may withstand continuous application of 1.5 V reverse volt-

age, exceeding that can damage the capacitor by overheating, overpressure, and dielectric breakdown. This can result in open-circuit or short-circuit failures and rupture of the capacitor's pressure-relief vent. Non-polar and semi-polar devices are available that can withstand continuous or frequent reverse voltage application. Please contact us for such capacitors if your application requires such capability.

Anti-series Connection, Non-polar, AC and Motor-start Capacitors

If two, same-value, aluminum electrolytic capacitors are connected in anti-series configuration with the positive terminals or, more usually, the negative terminals connected together, the resulting single capacitor is a non-polar capacitor with half the capacitance. When voltage is applied to this anti-series combination, the correct-polarity capacitor gets nearly the full voltage.

CDE also offers non-polar capacitors in a single can, using two anode foils and no cathode foil. Most motor-start capacitors are also constructed this way. These are available for momentary-duty AC applications like motor starting and voltage-reversing applications, but the high dissipation factor of aluminum electrolytic capacitors— often exceeding 2% – causes excess heating and short life in most continuous AC applications. The reverse voltage capability is not constrained to be the same as the forward voltage, as we can also create special designs that have, for example +400 VDC and -25 VDC capability. This is done by using two anode foils with different formation voltages.

If your application requires AC voltage or reverse voltage capability, please contact CDE, as we can often create special designs to handle such requirements, or we can recommend an alternative technology such as metallized film.

Self-Resonant Frequency (f_{RES} or SRF)

The self-resonant frequency is the frequency whose formula is shown in Table 1 near the beginning of this document. At this frequency the capacitive reactance equals the additive inverse of the inductive reactance, thereby causing the remaining impedance to be purely resistive and thus equal to the ESR at that frequency. At frequencies greater than the SRF, the device is inductive. In aluminum electrolytic capacitors the self-resonant frequency typically occurs at less than 100 kHz. It occurs at a frequency higher than expected based on 120 Hz capacitance because the capacitance C_s decreases with increasing frequency. f_{RES} can decrease with increasing temperature because C_s typically increases with increasing temperature.

Dielectric Absorption (DA)

Dielectric absorption may be observed as a voltage rebound on a recently charged capacitor after the terminals have been shorted for a brief period followed by removal of the short circuit. This effect is more pronounced after DC voltage has been applied for an extended period of time, especially at elevated temperature. Due to the relatively high value of DA, electrolytic capacitors may have issues in timing circuits, voltage-controlled oscillators (VCO's), analog memory, analog integrators, A/D converters (ADC's), etc.

For aluminum electrolytic capacitors, dielectric absorption will allow up to 10% recovery of a previously applied voltage. Thus with high-voltage aluminum electrolytic capacitors rebound voltages of 40 to 50 V are possible. While such voltages are not usually a shock hazard, they can certainly cause sparking and even arc damage during installation. CDE fully discharges its capacitors prior to shipment, and uses special packaging to prevent voltage rebound during shipment and during storage in the original packaging. If the capacitors are removed from their original packaging many hours before assembly, the customer should provide additional means of assuring the capacitors are discharged again just prior to assembly.

There are many test methods for measuring dielectric absorption, and they do not all give the same result, due to variations in the charge vs discharge times. One such test method is JIS-C-5012, in which a DC voltage is applied for 60 ± 1 minutes, followed by rapidly discharging and holding the terminals in a short-circuit condition for 10 ± 1 seconds, followed by open circuit. Monitor the voltage that subsequently builds at the terminals in a manner that doesn't tend to load the capacitor down, such as with an electrometer, vacuum tube voltmeter or other monitoring method with high input impedance. The capacitor terminal voltage will build over several minutes, either reaching a peak value or approaching an asymptotic value, depending upon the relative leakage current and other factors. That peak or asymptotic voltage divided by the original charge voltage will give a unitless ratio that is equal to the measured DA, which can be expressed as a fraction or as a percentage.

CAPACITOR BANK CONFIGURATIONS

General Considerations

Capacitor bus structures should be designed to interconnect the capacitors in a reliable and consistent manner. For screw terminal capacitors, make provisions to provide clearance around the vent plug areas, such as through-holes above each vent plug. Provisions such as $\frac{1}{4}$ " (6 mm) diameter through-holes allows the vent plug to swell without being obstructed; in the case of a vent rupture, it gives the electrolyte steam a clear channel. A clearance hole above each vent plug can also provide windows that allow for inspection to determine if the vent plug is visibly swelling, indicating abnormal pressure build-up or end of life-time. An array of such windows can be useful just after bank assembly, prior to first charge-up, to assure that all capacitors have been installed with the correct polarity.

Capacitor bus structures should connect to the capacitor terminals in a manner that does not cause a large local heat rise at the capacitor terminals, as it is much better to be drawing heat out of the capacitor than adding to the capacitor's heat load. This means using the appropriate bus conductor sizing and proper terminal torque. At the same time, the bus plates need to avoid being so heavy that mechanical stress is put on the capacitor terminal surfaces, such as forcing coplanarity of the capacitor terminal surfaces rather than conforming to them.

In the case where more than ten capacitors (large screw-terminal or smaller snap-in) are connected in parallel on a bus, it is advisable to discuss the application with us, as sometimes slight

tweaking in the capacitor design will give higher reliability at little or no additional cost.

When laying out a grid of capacitors, consider the effects of thermal resistance as well as high frequency impedance. A 3×4 physical grid will have two capacitors in the center surrounded by other capacitors. The center capacitors will tend to run much hotter if the ripple current is significant, unless special cooling techniques are implemented. These thermal effects are demonstrated in Figure 11 below. Thus, thermally on an $n \times m$ grid, it is best if n or m is no greater than 2. On the other hand, a long and narrow capacitor bank bus structure can present a tougher challenge to achieve equal sharing of high-frequency ripple current.

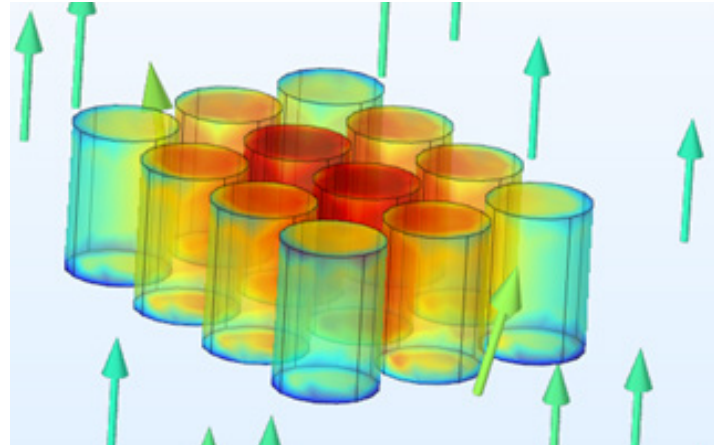


Figure 11: Mutual heating among capacitors: Centermost capacitors run much hotter

PARALLEL CONNECTION

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. For minimum series inductance use 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. At low frequency the variations in capacitance among the capacitors will dominate the variations in ripple current distribution, while at high frequency the ripple current shifts to divide according to the bus admittance and reciprocal-ESR value. The latter tends to vary significantly with core temperature. At high frequency, the ESL of the capacitor also needs to be considered, and the path impedance from the bus feed port(s) to each capacitor should be nearly equal to assure equal current sharing.

Fusing and Soft Start

Fusing capacitors is usually not done in high-power capacitor banks because the fuses add too much resistance and inductance. However, it is worthwhile to contemplate any scheme or feature that can be added to a bus structure to limit the collateral damage of the rare situation of a short-circuited capacitor. Although aluminum electrolytic capacitors do not have the dv/dt limits of their metallized-film counterparts, their slight risk of

failure during start-up after a long period of unenergized storage is reduced if a slow-start circuit is implemented.

SERIES CONNECTION

Capacitors may be connected in series for increased voltage withstanding.

Voltage Sharing

During charging the voltage on each capacitor connected in series is proportional to the inverse of the actual capacitance, but upon reaching the applied voltage, the steady-state DC voltage that each capacitor approaches no longer depends upon its capacitance at all, instead shifting to follow the inverse of the capacitor's leakage current.

In a series-connected string of capacitors there is only one leakage current, and the capacitors with a propensity for higher leakage current will thereby get less voltage. Since leakage current increases with the applied voltage, less voltage results in higher leakage resistance R_L , and voltage mismatches are somewhat mitigated by this mechanism. Over time the leakage current of each capacitor and thus of series connection generally diminishes. But the capacitor voltage division is dependent on the ratios of the various leakage current vs voltage profiles— not to the average magnitude— and these ratios may actually increase even as their magnitudes decrease, resulting in the capacitors becoming less and less well self-balanced. It is possible that a capacitor may even drift to a voltage above its rated voltage, which may cause the electrolyte to spark and lead to a short-circuit of a capacitor.

Since the voltage distribution of series-connected electrolytic capacitors cannot be depended upon to be uniform, we recommend that the voltage ratings be derated and that a balancing scheme be implemented, such as balancing resistors. Assist voltage sharing stability by using capacitors from the same manufacturing lot and mounting them to operate at the same core temperature. This practice typically reduces the spread in the capacitance, ESR, and leakage current profile.

Balancing Resistors

The leakage current of CDE aluminum electrolytic capacitors at rated temperature can be estimated as $I_L = 1.5[\text{mHz}] \times C_s \times V_A$ where V_A is the applied DC voltage, at or below its rated DC voltage. The maximum difference in leakage currents among n capacitors in series, each of capacitance C_s , at rated temperature can be estimated using the same formula by substituting $V_A = V_b/n$ where V_b is the total bus voltage. Using this estimate enables the selection of a value of balancing resistance to be connected in parallel with each capacitor as follows:

$$R \leq \frac{670[\Omega \cdot F] \times (n \cdot V_M - V_b)}{(n-1) C_s V_M} \quad (3)$$

where V_M is the maximum voltage you'll permit on any capacitor. The above typically establishes equalization response time constants of about $n/(n-1)$ minutes after the bus voltage is applied.

Be sure the resistors are rated for power of at least $2V_M^2/R$, and lay them out in a manner that doesn't heat the capacitors. The resistors should be purchased as or matched within $\pm 1\%$ tolerance.

PARALLEL / SERIES BANK

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

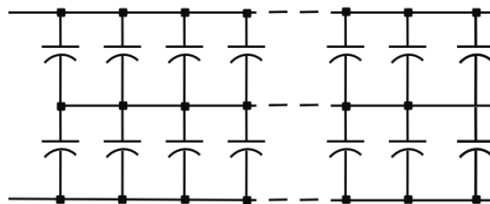


Figure 12: Parallel-series array with common center connection

Advantages: Statistically as the number of capacitors in parallel m increases the capacitance at the top tends to equal the capacitance at the bottom. This improves voltage balance during transients. For the same reason 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 n balancing resistors need be considered. To calculate the R value, use the same equation but increase the value of C_s to be between $\sqrt{m} \times C_s$ (aggressive, assuming RSS statistical distribution of leakage currents) to $m \times C_s$ (conservative, assuming no statistical benefit of parallel connection on leakage current).

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

SERIES / PARALLEL BANK

Capacitors connected as shown below with multiple series combinations in parallel have these considerations.

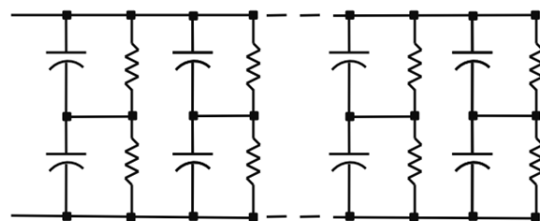


Figure 13: Series - parallel array, no common center connection

Advantages: If one capacitor fails short then the capacitors in series with it also fail, but other capacitors in the bank are unaffected. The independent, series pairs may permit fusing.

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

RELIABILITY AND LIFETIME

Reliability Model

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. The chance of a capacitor failing before the onset of wearout is not zero. This chance per unit time is the failure rate, λ , which is initially high, but is greatly reduced during the ageing and screening processes we perform on each capacitor before shipment. This is the infant mortality rate seen as the left side of the “bathtub curve” shown in Figure 14. During the useful lifetime of the capacitor, the failure rate is low and fairly constant, which establishes the value for λ . Our online lifetime calculators available at <http://www.cde.com/technical-support/life-temperature-calculators> report our estimated value of λ for many of our more popular capacitor series. The equation used to calculate λ is discussed below.

We have a model for the rate of random failures in terms of the number of capacitors in the capacitor bank and the ratings of the capacitors versus how hot they are being run and what percentage of their rated DC voltage is being applied. The details of this model are given in our technical paper on electrolytic capacitor reliability at <http://www.cde.com/resources/technical-papers/reliability.pdf>

The model for the base failure rate (bottom of the bathtub curve) from the above resource is summarized below:

$$\lambda = 0.0004 \times N \times (V_A/1[V]) \times (V_A/V_R)^2 \times (C_s/1[F])^{1/2} \times 2^{(T_c-T_m)/10[^\circ C]} / L_b \quad (4)$$

The above expression has units of inverse-time, i.e. fractional failures per unit time. From this you can readily express as ppm/kh (“FIT” rate) or % per year, etc. In the equation, N is the number of capacitors in the array, V_A is the applied DC voltage, V_R is the rated DC voltage, C_s is the capacitance of each capacitor, T_c is the core temperature, T_m is the maximum rated core temperature and L_b is the base lifetime. T_m and L_b are tabulated for each capacitor type in Table 2.

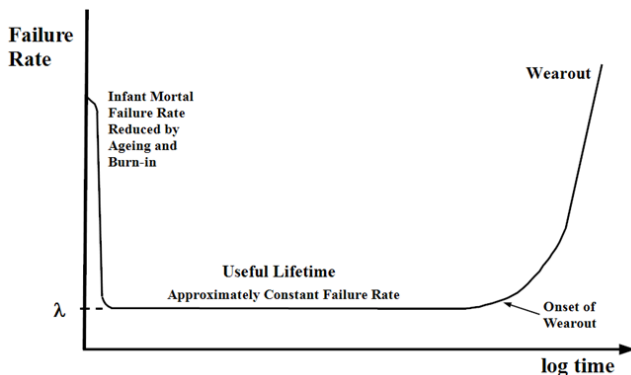


Figure 14: The “Bathtub Curve”

Ripple Current, Load Life Tests, Ripple Multipliers

Ripple current is the AC current flowing through the capacitor. It’s called ripple current because the associated AC voltage rides on the capacitor’s DC bias voltage as a ripple rides on the surface of water. The ripple current heats the capacitor, and the maxi-

imum permitted ripple current is set by how much heat rise can be permitted while still meeting the capacitor’s load life specification. Too much temperature rise will cause the capacitor to exceed its maximum permitted core temperature and fail; even operation close to the maximum permitted core temperature dramatically shortens expected life.

The Load Life Test is a life test at elevated temperature with DC voltage as well as ripple current applied. The load life specifications for aluminum electrolytic capacitors operating near their maximum permitted core temperature are typically 1000 to 20,000 hours. That’s a duration of six weeks to 2.28 years, insufficient for most applications. Nearly all applications have derated conditions of temperature, voltage and ripple current versus the load life test conditions.

Ripple current ratings usually assume that the capacitor is convection-cooled and that the entire can is in contact with air. A total heat transfer coefficient of roughly 10 [W/m²K] predicts the temperature rise from ambient air to the case, and the core temperature is assumed to be the same as the case temperature. The dissipated power is the ripple current squared times the ESR. The heat rise is the dissipated power multiplied by the thermal resistance. Even though the capacitor case is not an isothermal surface, often the thermal resistance is separated into two components, core-to-case and case-to-air. The former is dominated by conduction and the latter by radiation and convection. There is a common misconception that heat transfer from radiation is negligible around room temperature, as compared to convection. In reality, when there is no forced convection— only natural convection— the radiative heat transfer component can be of the same magnitude as that of convection. For a discussion of the details of thermal modeling of aluminum electrolytic capacitors, see our two technical papers on this subject at <http://www.cde.com/resources/technical-papers/thermalmodel.pdf> and <http://www.cde.com/resources/technical-papers/Predicting-Operating-Temperature-and-Expected-Lifetime.pdf>

For DC Link and other filter capacitor applications, usually there is more than one frequency present in the ripple current spectrum. The ESR varies nonlinearly with both frequency and temperature, and the 120 Hz room temperature ESR limit is usually not helpful in estimating the core temperature. Therefore we recommend that you use our online tools to estimate the ESR’s, thermal resistances, core temperatures and lifetimes. You will find these tools at <http://www.cde.com/technical-support/life-temperature-calculators> The “double applets” are best for desktop computer screen and facilitate what-if analysis by transferring information back and forth between two instances of the modeler.

Our online calculators allow up to two ripple frequencies to be inputted. Note that when two frequencies are entered, the total ripple current is the RSS (root sum square) of the two frequencies, not the algebraic sum. When you have many ripple harmonics present, the best way to model as two frequencies is to partition the components and assign to a low-frequency and a high-frequency. Because the ESR decreases monotonically with increasing frequency, any error with this spectral allocation will be conservative (slightly overestimating core temperature

heat rise and underestimating the expected lifetime) if you lump the low-frequency components to the lowest frequency in that low-frequency range, and all of the high-frequency components to the lowest frequency in that high-frequency range. You may perform a sensitivity analysis by noting the effect of increasing the two frequencies.

For qualification of our capacitors, we can provide capacitors with thermocouples embedded in the core so that you may take measurements and compare to the estimates from our online modelers. Our online modelers allow you to refine the modeled ESR's, and you may thereby tweak these values or the applied ripple currents to agree with the heat rises measured in the thermocoupled capacitors, in order to provide more accurate heat-rise inputs to the lifetime modeler.

Avoid using total effective ripple multipliers (i.e. including both frequency and ambient temperature multipliers) greater than about 2 for ripple current ratings at and below 85 °C ambient, and about 3 for ripple current ratings at and above 105 °C ambient, since high ripple current can cause shorter operating lifetime than expected due to ESR increase during the capacitor lifetime, which accelerates wearout.

Ripple Multiplier Tables

In the datasheets for our various product series, we usually publish ripple multiplier tables for frequencies other than 120 Hz and for ambient temperatures other than the rated life test temperature. As these tables typically cover a range of different capacitors, they should be used as a rough guide as to the equivalent ripple current to cause the lifetime to be about the same as the rated load life test lifetime. For example, if the load life test rating is 5,000 hours at 85 °C with 15 amps of 120 Hz ripple current and your application is at 45 °C ambient with a frequency of 20 kHz, and our ripple multiplier tables indicate a ripple multiplier of 2.0 for an ambient temperature of 45 °C and a ripple multiplier of 1.2 for 20 kHz, then the overall effective ripple multiplier is the product of these two multipliers, which is $2.0 \times 1.2 = 2.4$. However, it is important to not “try to have your cake and eat it, too” by taking license to actually apply $2.4 \times 15 = 36$ amps of ripple current in your application, because the expected lifetime would only be the rated load life test duration of 5,000 hours. Most applications target 100+ kh lifetime and would need to limit the ripple current to no more than the load life ripple rating even at the lower application temperature. For further information on how ripple current multipliers work, see our IEEE paper, available at <http://www.cde.com/resources/technical-papers/multipliers.pdf>

Operating Lifetime Model

Onset of wear-out is determined mainly by the capacitor's 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. Our online lifetime calculators available at <http://www.cde.com/technical-support/life-temperature-calculators> report our best estimates of the useful lifetime for many of our more popular capacitor series. The expected operating lifetime is approximately

$$Lop = Mv \times Lb \times 2^{((Tm - Tc)/10[^\circ C])} \quad (5)$$

The above equation is the simple, classic “doubles every 10 °C” rule used for many decades, and Mv is a DC voltage derating multiplier equal to

$$Mv = 4.3 - 3.3 V_A / V_R \quad (6)$$

Thus for example when the DC voltage is derated by 10%, this multiplier is equal to $Mv = 1.33$. As in the failure rate equation discussed in the previous section, V_A is the applied DC voltage, V_R is the rated DC voltage, Tc is the core temperature, Tm is the maximum rated core temperature and Lb is the base lifetime. Tm and Lb are tabulated for each capacitor type in Table 2.

Type	Lb (h)	Tm
<i>Screw-Terminal Styles</i>		
DCMC	5000	95
500C	7500	98
520C	12000	103
550C	15000	108
101C	8000	108
<i>Flatpack Styles</i>		
MLSG	5000	125
MLSH	5000	125
THA	3000	85
THAS	3000	105
<i>Snapmount Styles</i>		
380LQ	4000	95
SLPX	4500	95
380LX	5000	95
381LQ	4000	110
SLP	4500	110
381LX	5000	110
LMB	6000	110
381LR	7000	110
LMX	12000	110
<i>Plug-In Styles</i>		
4CMC	5000	95
400C	7500	98
420C	12000	103
450C	15000	108
401C	8000	108
<i>Radial Leaded Styles</i>		
300/301	6000	108
325	3000	128
330	12000	108

Table 2: Parameters base lifetime Lb and maximum core temperature Tm used in calculations of typical expected failure rate and lifetime.

When the ripple current is small and the core temperature is only a few degrees or less above the ambient temperature, the initial

value of T_c may be used in the lifetime equation, with the tacit assumption that T_c is constant during the capacitor's useful lifetime. In actuality R_s increases during the capacitor's lifetime—generally assumed to double from the initial value by the end of the useful lifetime—and the heat rise would rise in proportion to the increasing value of R_s . To account for the increase in core temperature T_c we recommend that for an initial core rise ΔT_o above ambient, when the lifetime equation is used, instead of the usual initial core temperature value of $T_c = T_A + \Delta T_o$ that the following value for T_c be used

$$T_c = T_A + 1.5 \times \Delta T_o \quad (7)$$

Cornell Dubilier was the first in the industry to develop and use the lifetime estimate refinement of equation (7), implemented in our online calculators since the mid-1990's. Effectively, the ambient temperature is penalized as halving the lifetime every 10 °C while the ripple current heat rise is penalized as halving the lifetime every 10 °C ÷ 1.5 = 6.67 °C.

Though the equations for lifetime are simple, it can be a challenge to estimate the initial heat rise ΔT_o because to do so one needs to know both the R_s value at the core temperature and frequency (which is actually often multiple frequencies) as well as the total thermal resistance θ_T from the core to the ambient.

$$\Delta T_o = P \theta_T = I^2 R_s \theta_T \quad (8)$$

We recommend that you use our online thermal/lifetime calculators to estimate the dissipated power, core temperature and lifetime. If possible, cross-check those temperature rise estimates using sample capacitors with embedded thermocouples. It may be feasible to measure the dissipated power using a wide-band power meter, but you need to account for the resistance of the leads. Then you can use the appropriate Thermal Resistance Chart in this application guide along with equation (8) to estimate temperature rise.

Lifetime calculations for varying ambient temperature or varying ripple current

When the applications stressors such as applied DC voltage, ambient temperature or ripple current vary over time, the lifetime equations we have presented can still be used, but they need to be averaged nonlinearly. This is discussed on pages 15-18 of our presentation at

<http://www.cde.com/resources/technical-papers/TransientModelingOfLargeScrew-TerminalAluminumElectrolyticCapacitors.pdf>

Load Life Test

Place the capacitors in a circulating air oven set to the upper temperature limit ± 2 °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-749

Conduct the wear-out lifetime test per EIA Interim Standard 749. 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% of initial limit or
- DCL > initial value or
- there is evidence of mechanical damage or leakage of electrolyte.

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

Estimating Lifetime for Capacitors without an Online Calculator

We offer online calculators for many of our capacitor series such as our screw-terminal, snapmount and flatpack capacitors. For our capacitor series without a calculator, you will find on its datasheet a "load life rating" with an ambient test temperature and duration at the rated ripple current, which is tabulated for each capacitor within that series. To estimate the minimum lifetime, you may select a capacitor whose tabulated ripple current is at least equal to your application's ripple current, and apply the "doubles every 10 °C" rule between the load life test ambient temperature and your application's ambient temperature. If your DC voltage is derated, then you may multiply the lifetime by the voltage multiplier M_v given in equation (6). This will be an estimate of the minimum expected lifetime. Typical lifetime will be greater, up to twice this estimate.

COOLING AND THERMAL RESISTANCE

Cooling Strategies

Because of their ThermalPak™ construction, Cornell Dubilier screw-terminal capacitor windings conduct heat from the core of the winding to the can bottom much more effectively than to the sides of the can. You can take advantage of this heat path by mounting the capacitors directly to a metal chassis. In many case sizes this can double the permitted ripple current for the same temperature rise.

Mounting can be done by using capacitors with mounting studs and screwing the capacitors directly to the plate or it can be achieved by pressing the capacitors against a plate using the interconnecting bus structure. Cornell Dubilier offers sil-pad inserts at the bottom of the capacitors for this application. The sil-pads 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 pulled tightly into place. Calculators are available on the Cornell Dubilier website which permits you to explore cooling options and directly see the effect on operating life.

Thermal Resistance

In large-can capacitors there can be significant temperature rise from the case to the core, the hottest spot at the center of the capacitor. For Cornell Dubilier Thermal Pak screw-terminal capacitors use the thermal resistance data tables in this application guide to determine temperature rise from power dissipated. As an illustration, consider 20 amps of ripple current at 120 Hz in a 3 x 5 5/8 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^2R s, $20^2 \times 0.01$ or 4 W. For the DF case code the table shows that the thermal resistance from core to bottom of the can is about 0.41 °C/W. That varies a little depending on how the capacitor is cooled, but 0.41 °C/W predicts a temperature rise of 1.6 °C between the core and the can for 4 watts of power dissipation. 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. The 3.07°C/W predicts a temperature rise of 12.3 °C, and 1.02 °C/W predicts 4.1 °C.

PROCESS CONSIDERATIONS

SOLDERING

Wave and reflow soldering tips

Don't exceed the maximum storage temperature while preheating the capacitors. If this cannot be avoided, contact the supplier first. Strictly adhere to soldering conditions for temperature, duration and minimum distance of solder from body. Don't contact 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 Circuit Board Assemblies

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 end-seals 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 and solvent cleaning to remove solder flux residue

Avoid the use of halogenated cleaning solutions for cleaning aluminum electrolytic capacitors. Our standard sleeve material is PVC. Most cleaning solvents may cause slow hydrolytic degradation of the alternative, higher-temperature polyester (PET) sleeves, so check carefully before cleaning capacitors with PET sleeving. For standard aluminum electrolytic capacitors with PVC sleeves, there are halogen-free solvents available such as ethanol, propanol, isopropanol, isobutanol, propyleneglycol ether, diethyleneglycol ether but these might not be as effective in removing flux residue as the newer, fatty alcohol, alkaline saponification or surfactant cleaning solvents. Certain of the latter have been reported to be sufficiently low in halide content, such as:

Pine Alpha ST-100S
Techno Care FRW 14 through 17
Sanelek B-12
Clean-Through 750H, 750L, 710M
Aqua Cleaner 210SEP

Cleaning Precautions

Clean at no higher than 60 °C for no longer than 10 minutes. The capacitor's insulating sleeve may re-shrink or crack if rapidly heated to above 100 °C just after cleaning, so dry after cleaning at no higher than 85 °C. 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 force or temperatures.

Potting and Gluing

Be certain that varnishing, coating, lacquering, embedding and 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 capacitors' pressure-relief vent with potting or glue.

Fumigation Warning

International shipments of electronic equipment are often in wooden crates, and these crates may be fumigated with methyl bromide gas during shipment to control insect infestation. Also, some factories such as flourmills are routinely fumigated with this gas. Methyl bromide can penetrate cardboard boxes, vinyl bags and other packaging materials used to protect the shipment. Methyl bromide can also penetrate the seals of aluminum electrolytic capacitors; cause corrosion and cause open-circuit

Thermal Resistance °C/W Thermal Pak Screw Terminal Aluminum Electrolytic Capacitors

Case Code	Case Size D x L (in)	Free Convection						200 LFM Airflow (1.0 m/s)					
		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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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

Thermal Resistance °C/W Thermal Pak Screw Terminal Aluminum Electrolytic Capacitors

Case Code	Case Size D x L (in)	500 LFM Airflow (2.5 m/s)						1000 LFM Airflow (5.0 m/s)					
		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
AK	1 3/8 X 1 5/8	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	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	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	1.71	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	1.05	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	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	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	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	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	0.32	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	0.32	0.91	1.22	0.39	0.31	0.70	0.32	0.72	1.04	0.38	0.28	0.66

Thermal Resistance Chart °C/W Snap-in Aluminum Electrolytic Capacitors (page 1)

Case Code	D×L(mm)	Free Convection			200 LFM (1.0 m/s)			500 LFM (2.5 m/s)			1000 LFM (5.0 m/s)		
		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
H01	22×25	8.61	21.72	30.33	8.61	12.32	20.93	8.61	7.59	16.20	8.61	5.07	13.68
H02	22×30	8.62	19.07	27.69	8.62	10.82	19.44	8.62	6.66	15.28	8.62	4.45	13.07
H03	22×35	8.62	17.00	25.62	8.62	9.64	18.26	8.62	5.94	14.56	8.62	3.97	12.59
H04	22×40	8.62	15.33	23.95	8.62	8.70	17.32	8.62	5.36	13.98	8.62	3.58	12.20
H05	22×50	8.62	12.82	21.44	8.62	7.27	15.89	8.62	4.48	13.10	8.62	2.99	11.61
J01	25×25	6.48	18.35	24.83	6.48	10.41	16.89	6.48	6.41	12.89	6.48	4.28	10.76
J02	25×30	6.51	16.19	22.70	6.51	9.18	15.69	6.51	5.66	12.17	6.51	3.78	10.29
J03	25×35	6.53	14.49	21.02	6.53	8.22	14.75	6.53	5.06	11.59	6.53	3.38	9.91
J04	25×40	6.55	13.11	19.66	6.55	7.43	13.98	6.55	4.58	11.13	6.55	3.06	9.61
J45	25×45	6.56	11.97	18.53	6.56	6.79	13.35	6.56	4.18	10.74	6.56	2.79	9.35
J05	25×50	6.58	11.01	17.59	6.58	6.24	12.82	6.58	3.85	10.43	6.58	2.57	9.15
J55	25×55	6.59	10.19	16.78	6.59	5.78	12.37	6.59	3.56	10.15	6.59	2.38	8.97
J06	25×63	6.61	9.11	15.72	6.61	5.17	11.78	6.61	3.18	9.79	6.61	2.13	8.74
J07	25×70	6.63	8.34	14.97	6.63	4.73	11.36	6.63	2.91	9.54	6.63	1.95	8.58
J75	25×75	6.64	7.86	14.50	6.64	4.46	11.10	6.64	2.75	9.39	6.64	1.84	8.48
J08	25×80	6.65	7.44	14.09	6.65	4.22	10.87	6.65	2.60	9.25	6.65	1.74	8.39
J09	25×92	6.66	6.58	13.24	6.66	3.73	10.39	6.66	2.30	8.96	6.66	1.54	8.20
J10	25×105	6.67	5.86	12.53	6.67	3.32	9.99	6.67	2.05	8.72	6.67	1.37	8.04
K01	30×25	4.35	14.34	18.69	4.35	8.13	12.48	4.35	5.01	9.36	4.35	3.35	7.70
K02	30×30	4.38	12.74	17.12	4.38	7.23	11.61	4.38	4.45	8.83	4.38	2.97	7.35
K03	30×35	4.40	11.47	15.87	4.40	6.50	10.90	4.40	4.01	8.41	4.40	2.68	7.08
K04	30×40	4.43	10.43	14.86	4.43	5.91	10.34	4.43	3.64	8.07	4.43	2.43	6.86
K45	30×45	4.45	9.56	14.01	4.45	5.42	9.87	4.45	3.34	7.79	4.45	2.23	6.68
K05	30×50	4.48	8.82	13.30	4.48	5.00	9.48	4.48	3.08	7.56	4.48	2.06	6.54
K55	30×55	4.50	8.19	12.69	4.50	4.65	9.15	4.50	2.86	7.36	4.50	1.91	6.41
K06	30×63	4.53	7.35	11.88	4.53	4.17	8.70	4.53	2.57	7.10	4.53	1.72	6.25
K07	30×70	4.56	6.75	11.31	4.56	3.83	8.39	4.56	2.36	6.92	4.56	1.57	6.13
K75	30×75	4.58	6.37	10.95	4.58	3.61	8.19	4.58	2.23	6.81	4.58	1.49	6.07
K08	30×80	4.60	6.04	10.64	4.60	3.42	8.02	4.60	2.11	6.71	4.60	1.41	6.01
K09	30×92	4.64	5.36	10.00	4.64	3.04	7.68	4.64	1.87	6.51	4.64	1.25	5.89
K10	30×105	4.69	4.78	9.47	4.69	2.71	7.40	4.69	1.67	6.36	4.69	1.12	5.81
A01	35×25	3.12	11.56	14.68	3.12	6.56	9.68	3.12	4.04	7.16	3.12	2.70	5.82
A02	35×30	3.14	10.35	13.49	3.14	5.87	9.01	3.14	3.61	6.75	3.14	2.42	5.56
A03	35×35	3.17	9.36	12.53	3.17	5.31	8.48	3.17	3.27	6.44	3.17	2.19	5.36
A04	35×40	3.19	8.55	11.74	3.19	4.85	8.04	3.19	2.99	6.18	3.19	2.00	5.19
A45	35×45	3.21	7.86	11.07	3.21	4.46	7.67	3.21	2.75	5.96	3.21	1.84	5.05
A05	35×50	3.23	7.28	10.51	3.23	4.13	7.36	3.23	2.54	5.77	3.23	1.70	4.93
A55	35×55	3.26	6.78	10.04	3.26	3.85	7.11	3.26	2.37	5.63	3.26	1.58	4.84
A06	35×63	3.29	6.11	9.40	3.29	3.46	6.75	3.29	2.13	5.42	3.29	1.43	4.72
A07	35×70	3.32	5.62	8.94	3.32	3.19	6.51	3.32	1.96	5.28	3.32	1.31	4.63
A75	35×75	3.34	5.31	8.65	3.34	3.01	6.35	3.34	1.86	5.20	3.34	1.24	4.58
A08	35×80	3.36	5.04	8.40	3.36	2.86	6.22	3.36	1.76	5.12	3.36	1.18	4.54
A09	35×92	3.41	4.49	7.90	3.41	2.55	5.96	3.41	1.57	4.98	3.41	1.05	4.46
A10	35×105	3.45	4.01	7.46	3.45	2.28	5.73	3.45	1.40	4.85	3.45	0.94	4.39
N01	40×25	2.34	9.56	11.90	2.34	5.42	7.76	2.34	3.34	5.68	2.34	2.23	4.57
N02	40×30	2.36	8.60	10.96	2.36	4.88	7.24	2.36	3.00	5.36	2.36	2.01	4.37

Thermal Resistance Chart °C/W Snap-in Aluminum Electrolytic Capacitors (page 2)

Case Code	D×L(mm)	Free Convection			200 LFM (1.0 m/s)			500 LFM (2.5 m/s)			1000 LFM (5.0 m/s)		
		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
N03	40 × 35	2.38	7.82	10.20	2.38	4.44	6.82	2.38	2.73	5.11	2.38	1.83	4.21
N04	40 × 40	2.40	7.17	9.57	2.40	4.07	6.47	2.40	2.50	4.90	2.40	1.67	4.07
N45	40 × 45	2.42	6.62	9.04	2.42	3.75	6.17	2.42	2.31	4.73	2.42	1.54	3.96
N05	40 × 50	2.44	6.14	8.58	2.44	3.48	5.92	2.44	2.15	4.59	2.44	1.43	3.87
N55	40 × 55	2.46	5.73	8.19	2.46	3.25	5.71	2.46	2.00	4.46	2.46	1.34	3.80
N06	40 × 63	2.49	5.18	7.67	2.49	2.94	5.43	2.49	1.81	4.30	2.49	1.21	3.70
N07	40 × 70	2.52	4.78	7.30	2.52	2.71	5.23	2.52	1.67	4.19	2.52	1.12	3.64
N75	40 × 75	2.54	4.53	7.07	2.54	2.57	5.11	2.54	1.58	4.12	2.54	1.06	3.60
N08	40 × 80	2.56	4.30	6.86	2.56	2.44	5.00	2.56	1.50	4.06	2.56	1.00	3.56
N09	40 × 92	2.60	3.84	6.44	2.60	2.18	4.78	2.60	1.34	3.94	2.60	0.90	3.50
N10	40 × 105	2.64	3.44	6.08	2.64	1.95	4.59	2.64	1.20	3.84	2.64	0.80	3.44
E01	45 × 25	1.83	8.05	9.88	1.83	4.56	6.39	1.83	2.81	4.64	1.83	1.88	3.71
E02	45 × 30	1.84	7.28	9.12	1.84	4.13	5.97	1.84	2.54	4.38	1.84	1.70	3.54
E03	45 × 35	1.86	6.65	8.51	1.86	3.77	5.63	1.86	2.32	4.18	1.86	1.55	3.41
E04	45 × 40	1.88	6.12	8.00	1.88	3.47	5.35	1.88	2.14	4.02	1.88	1.43	3.31
E45	45 × 45	1.89	5.66	7.55	1.89	3.21	5.10	1.89	1.98	3.87	1.89	1.32	3.21
E05	45 × 50	1.91	5.27	7.18	1.91	2.99	4.90	1.91	1.84	3.75	1.91	1.23	3.14
E55	45 × 55	1.93	4.93	6.86	1.93	2.80	4.73	1.93	1.72	3.65	1.93	1.15	3.08
E06	45 × 63	1.95	4.47	6.42	1.95	2.54	4.49	1.95	1.56	3.51	1.95	1.04	2.99
E07	45 × 70	1.97	4.13	6.10	1.97	2.34	4.31	1.97	1.44	3.41	1.97	0.96	2.93
E75	45 × 75	1.99	3.92	5.91	1.99	2.22	4.21	1.99	1.37	3.36	1.99	0.92	2.91
E08	45 × 80	2.01	3.73	5.74	2.01	2.12	4.13	2.01	1.30	3.31	2.01	0.87	2.88
E09	45 × 92	2.04	3.34	5.38	2.04	1.89	3.93	2.04	1.17	3.21	2.04	0.78	2.82
E10	45 × 105	2.08	3.00	5.08	2.08	1.70	3.78	2.08	1.05	3.13	2.08	0.70	2.78
B01	50 × 25	1.46	6.88	8.34	1.46	3.90	5.36	1.46	2.40	3.86	1.46	1.61	3.07
B02	50 × 30	1.48	6.26	7.74	1.48	3.55	5.03	1.48	2.19	3.67	1.48	1.46	2.94
B03	50 × 35	1.49	5.73	7.22	1.49	3.25	4.74	1.49	2.00	3.49	1.49	1.34	2.83
B04	50 × 40	1.51	5.29	6.80	1.51	3.00	4.51	1.51	1.85	3.36	1.51	1.24	2.75
B45	50 × 45	1.52	4.92	6.44	1.52	2.79	4.31	1.52	1.72	3.24	1.52	1.15	2.67
B05	50 × 50	1.53	4.59	6.12	1.53	2.60	4.13	1.53	1.60	3.13	1.53	1.07	2.60
B55	50 × 55	1.55	4.30	5.85	1.55	2.44	3.99	1.55	1.50	3.05	1.55	1.00	2.55
B06	50 × 63	1.57	3.91	5.48	1.57	2.22	3.79	1.57	1.37	2.94	1.57	0.91	2.48
B07	50 × 70	1.59	3.62	5.21	1.59	2.05	3.64	1.59	1.27	2.86	1.59	0.85	2.44
B75	50 × 75	1.60	3.44	5.04	1.60	1.95	3.55	1.60	1.20	2.80	1.60	0.80	2.40
B08	50 × 80	1.62	3.28	4.90	1.62	1.86	3.48	1.62	1.14	2.76	1.62	0.76	2.38
B09	50 × 92	1.65	2.94	4.59	1.65	1.67	3.32	1.65	1.03	2.68	1.65	0.69	2.34
B10	50 × 105	1.68	2.65	4.33	1.68	1.50	3.18	1.68	0.92	2.60	1.68	0.62	2.30

capacitor failure after the equipment is put into service. To protect aluminum electrolytic capacitors against such failures, use capacitors proven to be able to withstand fumigation or individually sealed to prevent penetration of the methyl bromide gas. Screw terminal capacitors with rubber vent plugs are the most susceptible type.

MOUNTING

Mounting Position

Aluminum electrolytic capacitors have longer operating lives at lower ambient temperatures; 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.

For two-leaded radials and snapmount capacitors mounted directly to the circuit board, consider vibration requirements. A lone, unsupported two-leaded capacitor may tend to rock and break at the leads more than its counterparts with 3 or more leads. Banks of two-terminal, radial-leaded capacitors in close proximity may benefit from adhesive applied to them, creating a more rigid structure that is more resistant to vibration and mechanical shock. However, the ripple current capability of such a bundle will be less than the sum of the individual ripple currents of individual units because the effective surface area is reduced.

Some customers have reported issues when using conformal coating on radial-leaded capacitors that have been mounted tightly against the board. This may tend to trap flux residue or, if washed but not thoroughly dried, water vapor. Also, if such capacitors are run with high core temperature, the small amount of gas that escapes around the seal of the capacitor during its operation may tend to be trapped in the cavity. If this is an issue in your application, we do offer snap-in and other style capacitors with three or more leads with built-in standoffs that prevent such gas entrapment. Another alternative might be to design a ventilation through-hole in the circuit board beneath the capacitor.

For most capacitor styles the orientation is not important. However, for screw terminal capacitors the best orientation is upright with terminals up. If screw terminal capacitors are mounted horizontally, orient the pressure-relief vent plug at the 12-o'clock position so that least amount of electrolyte will be expelled if the vent operates. Do not mount upside down with terminals down as this may reduce the operating life and could impair the operation of the pressure-relief vent. Place the capacitors so that a person working on the equipment would be protected from the hot vapor in the event that a vent was to operate.

Position of the Pressure-Relief Vent

Aluminum electrolytic capacitors with liquid electrolyte have pressure-relief vents. The vents are scored lines or patterns on the end or side of the cans or rubber plugs in the molded tops. Vents are designed to rupture, release gas and electrolyte vapor, and prevent possible explosion from pressure build up during capacitor abuse, e.g. overvoltage, reverse voltage or application of AC voltage.

Provide adequate clearance for proper operation of the pressure-relief vent. 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
Rubber vent plug	≥ 6 mm

Mount the capacitors with the vents up to reduce the amount of electrolyte expelled if a vent operates.

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 voltage 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 Torque

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

Terminal	Recommended Torque
10-32, Low Post	25 in-lb, 2.8 N-m
10-32, High Post	25 in-lb, 2.8 N-m
¼-28, Low Post	50 in-lb, 5.6 N-m
¼-28, High Post	60 in-lb, 6.8 N-m
Small M5 Post	25 in-lb, 2.8 N-m
M5 Post	30 in-lb, 3.4 N-m
M6 Low Post	50 in-lb, 5.6 N-m
M6 High Post	60 in-lb, 6.8 N-m

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 Aac
10-32, High Post	30 Aac
¼-28, Low Post	50 Aac
¼-28, High Post	50 Aac
Small M5 Post	30 Aac
M5 Post	35 Aac
M6 Low Post	50 Aac
M6 High Post	50 Aac

The ripple current ratings may exceed the currents listed here. Terminals can withstand continuous currents of up to double the maximum currents listed if you assure gas-tight connections to avoid formation of aluminum oxide. Use Belleville washers and a commercial electrical joint compound, e.g. Penetrox A, and tighten the terminals to the recommended torque for the washers. We recommend that the terminal steady-state temperature not exceed the maximum can temperature by more than 20 °C.

Mounting-Stud Torque

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

Plastic Nut Thread	Recommended Torque
M8	25 in-lb, 2.8 N-m
M12	75 in-lb, 8.5 N-m

SAFETY CONSIDERATIONS

Electric Shock Hazard

Aluminum electrolytic capacitors rated above 35 VDC may contain lethal energy at lethal voltage, and should be handled as such, ensuring that the capacitors are discharged before handling. Be aware that the metal case will usually be approximately at the same potential as the negative terminal, so an electric shock can occur even when only one terminal is touched, if the case is also contacted. Capacitors can build voltage if they are not kept discharged. See the subject of Dielectric Absorption (DA) in a previous section of this document.

Pressure-Relief Vent

During operation of an aluminum electrolytic capacitor with non-solid electrolyte, its internal pressure normally increases as some gas is generated during operation. This gas is mostly hydrogen, and excessive pressure is avoided by permeation of the gas through the capacitor's seal. Our anti-gassing technology has progressed to the point where our capacitors are better sealed, and in fact we have multiple patents on glass-to-metal hermetically sealed aluminum electrolytic capacitors that meet helium leak rate tests for hermeticity.

But in cases like application of overvoltage, reverse voltage, AC voltage or capacitor failure, internal gas pressure can be generated at a rate that the seals cannot pass and that the package cannot mechanically contain. To reduce the risk of violent rupturing of the case itself, aluminum electrolytic capacitors are usually equipped with pressure-relief vent structures that limit the maximum internal pressure. These safety vents are intended to rupture and release the gas pressure. After rupture the capacitor has limited life because its electrolyte evaporates.

Be careful not to interfere with the operation of the vent, for instance by obstructing the vent area by using mounting measures such as clamps, glue or potting compounds.

In rare cases for capacitors mounted alone and more often for capacitors in multiple-unit parallel capacitor banks a fully func-

tioning pressure relief device may not react quickly enough to avoid rupture of the package. 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 sturdy cabinet doors as well as blast diversion tactics. Be sure that cabinets containing electrolytic capacitors are ventilated to exhaust any hydrogen gas and electrolyte vapor that evolves during use. In normal application, these amounts are normally very small, but avoid tightly sealed enclosures that may allow such gasses to accumulate. During fault conditions such as vent rupture, the amount of gas evolved is much greater, comprising mostly water and electrolyte solvent steam, but also potentially other organic gases as well as more hydrogen than usual.

If you wish to test the operation of the safety vent, contact us for the procedure as it is rather involved. Obviously the test is a destructive one.

Contact with Electrolyte

The electrolyte in non-solid electrolytic capacitors is a biodegradable liquid based on a stable solvent with a high boiling point as the main ingredient. The most common solvent is ethylene glycol (EG). Gammabutyrolactone (GBL) or other solvents may also be used. The electrolyte solutes include an acid-base system of weaker boric and organic materials, and other additives for enhanced performance and stability. The electrolyte pH is nearly neutral and contains no PCBs or halogenated compounds. Avoid ingestion, contact with the skin or eyes, and avoid prolonged inhalation.

In the case of electrolyte contact to skin, immediately rinse the exposed area with soap and water. If electrolyte contacts eyes, flush for 10 minutes with running water and seek medical attention. If vapors are present, ventilate the room. Smoke from burning electrolyte is irritating but does not contain dioxins or similar toxic substances. Seek medical attention if any symptoms persist. An SDS (Safety Data Sheet) is available for the electrolyte solvent base material.

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 in some cases the electrolyte. Most intact capacitors will pass the needle-flame test requirements of UL 94V-0 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 gas generated in the capacitor during normal and especially abnormal operation can ignite if sparking occurs during capacitor failure.

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.

QUALITY, TESTING AND ENVIRONMENTAL CERTIFICATIONS

All of Cornell Dubilier's manufacturing facilities have been ISO-9001 certified since 1996. Our Liberty, SC manufacturing facility is also registered to AS-9100 and MIL-STD-790. For further information on these and other certifications as well as for the latest updates on the status of environmental compliance issues including REACH, conflict materials, RoHS, Prop 65, rare-earth metals, ozone-depleting chemicals and other issues, please visit the Technical Support area of our website <http://www.cde.com>

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