1. General Description of Aluminum Electrolytic Capacitors

1-1 Principles of Aluminum Electrolytic Capacitors

An aluminum electrolytic capacitor consists of cathode aluminum foil, capacitor paper (separator), electrolyte, and an aluminum oxide film, which acts as the dielectric, formed on the anode foil surface.

A very thin oxide film formed by electrolytic oxidation (formation) offers superior dielectric constant and has rectifying properties. When in contact with an electrolyte, the oxide film possesses an excellent forward direction insulation property. Together with an increased effective surface area attained by etching the foil, a high capacitance small sized capacitor is available.

As previously mentioned, an aluminum electrolytic capacitor is constructed by using two strips of aluminum foil (anode and cathode) with paper interleaved. This foil and paper are then wound into an element and impregnated with electrolyte. The construction of an aluminum electrolytic capacitor is illustrated in Fig.1-1.

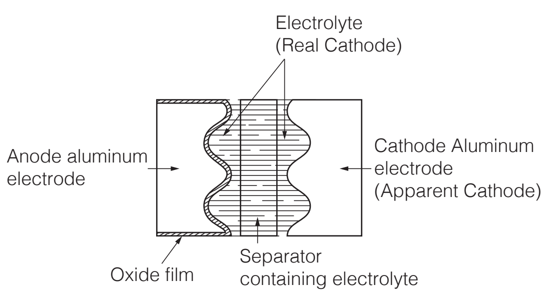


Fig. 1 - 1

Since the oxide film has rectifying properties, the capacitor is polarized. If both the anode and cathode foils have an oxide film, the capacitors would be bipolar (non-polar) type capacitor.

These technical notes refer to "non-solid" aluminum electrolytic construction in which the separator is impregnated with liquid electrolyte. There is another type of aluminum electrolytic capacitor that uses solid electrolyte.

1-2 Capacitance of Aluminum Electrolytic Capacitors

The capacitance of an aluminum electrolytic capacitor may be calculated from the following formula.

$$C = 8.854 \times 10^{-12} \frac{\varepsilon S}{d} \text{ (F)} \cdots\cdots\cdots (1 - 1)$$

ε : Dielectric constant of dielectric
S : Surface area (m^2) of dielectric
D : Thickness (m) of dielectric

To attain higher capacitance "C", the dielectric constant "ε" and the surface area "S" must increase while the thickness "d" must decrease. Table 1-1 shows the dielectric constants and minimum thickness of dielectrics used in various types of capacitors.

Aluminum oxide has excellent withstand voltage, per of thickness, and the thickness of the dielectric is controlled by the rated voltage of the aluminum electrolytic capacitor.

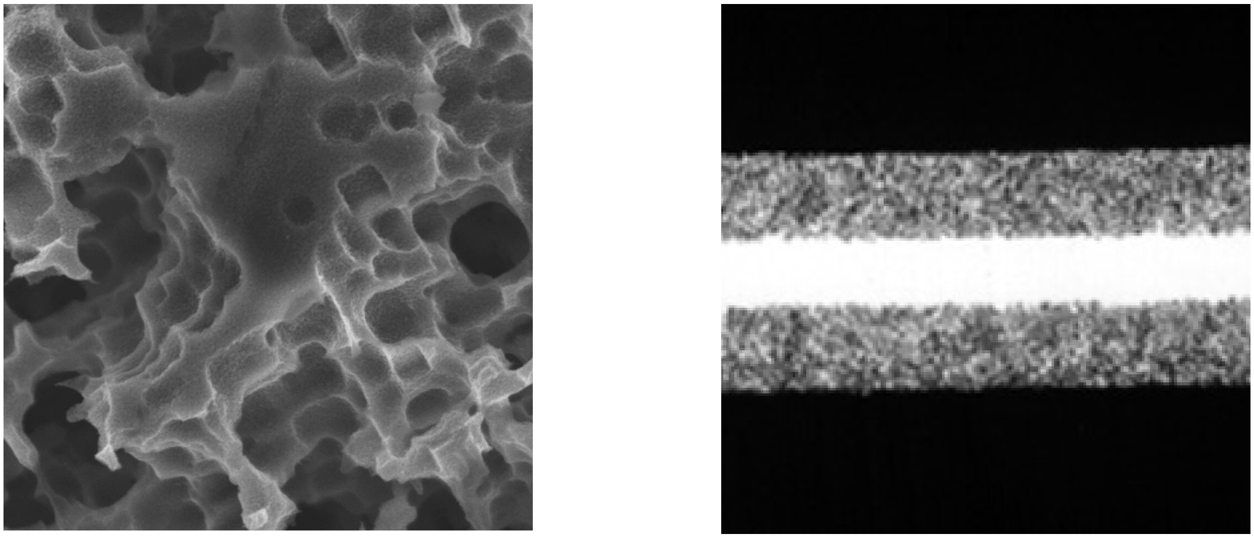
In comparison to other dielectric, similar voltage endurance is provided by dielectrics even if thickness ("d" in the above formula) is thin.

By etching the surface of aluminum foil, the effective area of the foil can be enlarged 80~100 times for low voltage capacitors and 30~40 times for middle / high voltage capacitors. Aluminum electrolytic capacitors have a higher capacitance for a unit area than other types of capacitors.

High purity aluminum foil for the anode is etched by electrochemical process in a chloride solution with DC, AC, or an alteration of DC and AC, or a concurring AC and DC current. Fine surface etching (photo 1-1) is accomplished by AC electrolysis and is generally used for foil with a low voltage rating. Tunnel etching (photo 1-2) is accomplished by DC electrolysis and is used for middle / high voltage foil. The etching of the cathode foil is mainly accomplished by AC electrolysis to increase the surface area.

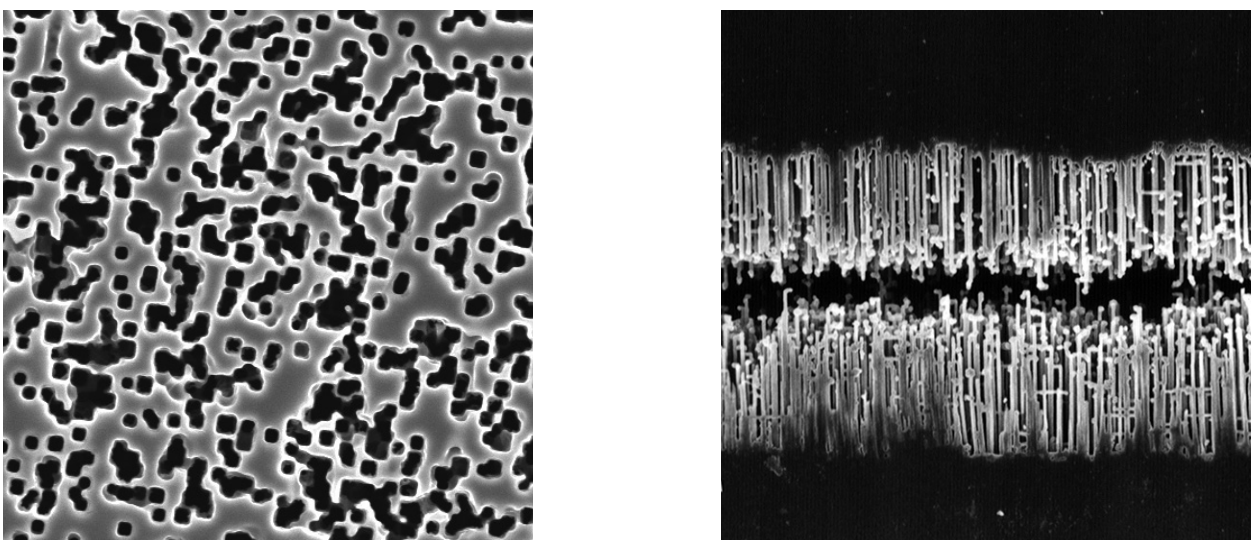
Table 1-1 Dielectric constants and minimum thickness of dielectrics used in various types of capacitors

Type of Capacitor	Dielectric	Dielectric Constant ε	Dielectric Thickness d (m)
Aluminum Electrolytic Capacitor	Aluminum Oxide	7～10	1.3×10^{-9}/V ～ 1.5×10^{-9}/V
Film Capacitor (Metallized)	Polyester Film	3.2	0.5×10^{-6} ～ 2×10^{-6}
Tantalum Electrolytic Capacitor	Tantalum Oxide	24	1.0×10^{-9}/V ～ 1.5×10^{-9}/V
Ceramic Capacitor (High Dielectric Constant Type)	Barium Titanate	500～20,000	2×10^{-6} ～ 3×10^{-6}
Ceramic Capacitor (Temp. Compensation Type)	Titanium Oxide	15～250	2×10^{-6} ～ 3×10^{-6}



Surface   Section

Photo 1-1 Surface and section photo of etched aluminum foil for low voltage capacitors.



Surface   Section (Replica)

Photo 1-2 Surface and section photo of etched aluminum foil for middle / high voltage capacitors.

1-3 Dielectric (Aluminum Oxide Layer)

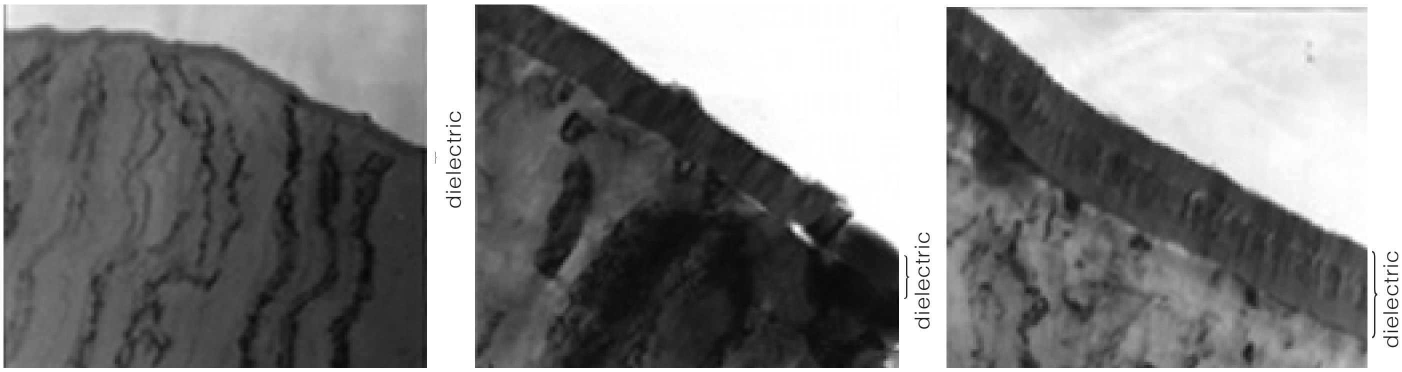
A high purity etched aluminum foil is anodized in a boric acid-ammonium water type solution, to form an aluminum oxide film on its surface. This aluminum oxide film is called the dielectric of the aluminum electrolytic capacitor. The DC voltage that is applied to the foil to oxidize the anode foil is called "Forming Voltage".

The thickness of the dielectric is proportional to the forming voltage and measures approximately 1.3×10^{-9} ～ 1.5×10^{-9} m/V.

Expanded photography of the dielectric (aluminum oxide layer) on the foil that has not been etched (plain foil) is shown in photo1-3.

The fabrication of the dielectric (aluminum oxide layer) can be expressed as follows:

$$2AL + 3H_2O \Rightarrow Al_2O_3 + 6H^+ + 6e^- \text{ (Electron)}$$
$$6H^+ + 6e^- \Rightarrow 3H_2 \uparrow \text{ (Gas)}$$



20V Formed 100V Formed 250V Formed

Photo 1-3 Enlarged photo of oxide layer formed on a non-etched plain aluminum foil.

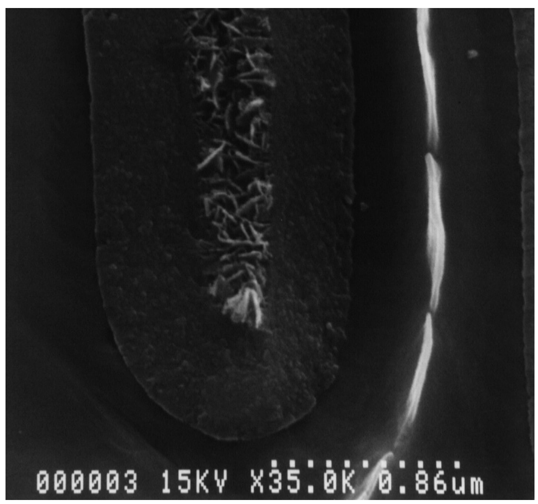


Photo 1-4 Enlarged photo of middle / high voltage formed foil.
(State of oxide layer formed in a pit)

1-4 Electrolyte

Anode foil and a cathode foil are interleaved with separator and wound into a cylindrical shape. This is called a "capacitor element." At this stage, it has the configuration of a capacitor. However, the unit has little capacitance.

When this capacitor element is impregnated with liquid electrolyte, the anode foil and cathode foil become electrically connected. A capacitor with a high value of capacitance has been achieved. The electrolyte is now functioning as a cathode. The basic characteristics required of an electrolyte are:

(1) It must be electrically conductive.
(2) It must have a forming property to heal any flaws on the dielectric oxide of the anode foil.
(3) It must be chemically stable with the anode and cathode foils, sealing materials, etc.
(4) It must have superior impregnation characteristics.
(5) Its vapor pressure must be low.

The above characteristics of electrolyte greatly influence the various characteristics of aluminum electrolytic capacitors. For this reason, the proper electrolyte is determined by the electrical ratings, operating temperatures and the application of the capacitor.

1-5 Manufacturing Process of Aluminum Electrolytic Capacitors

Process	Main Materials	Contents
Etching (Enlargement of the Surface Area)	High purity aluminum Chloride Deionized water	A 0.05~0.11 mm thick anode foil and a 0.02~0.05 mm thick cathode foil are continuously etched electrochemically in a chloride solution with an AC or DC current. This enlarges the effective surface area of the aluminum foils to attain smaller capacitor sizes.
Forming (Formation of the Dielectric)	Etched foil Borate, etc. Deionized water	The process develops aluminum oxide (Al_2O_3) to form a capacitor dielectric. A high purity etched aluminum foil is anodized in a boric acid - ammonium water type solution, for example, to form an aluminum oxide layer on the surface of the anode foil. As for the cathode foil, a low DC voltage is sometimes used for formation, but there are also situations where formation is not conducted.
Slitting	Anode foil Cathode foil	The foil is slit into specified widths according to capacitor case sizes.
Stitching & Winding	Slit foils (anode/cathode) Separator Lead Winding affixing material	Anode and cathode foils interleaved with a separator are wound into a cylindrical capacitor element, with leads being stitched onto both foils.

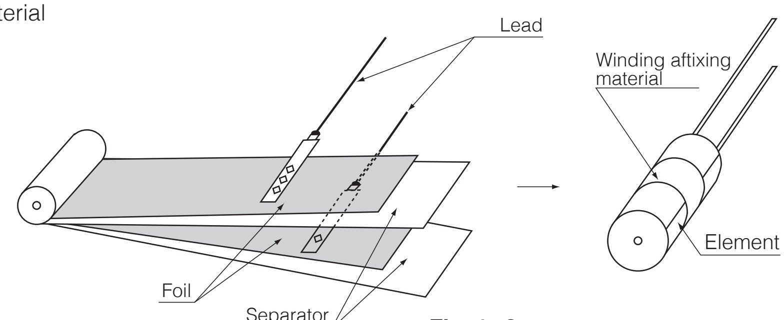


Fig. 1 - 2

Process	Main Materials	Contents
Element Impregnation Electrolyte	Elements Electrolyte	Elements are impregnated with liquid electrolyte. The clearance between the two electrode foils is filled with liquid electrolyte. With this impregnation, an element can function as a capacitor.
Assembly & Finishing	Impregnated elements Case (usually aluminum) End seal (Rubber packing Rubber-Bakelite with terminals Mold plastic with terminals) Exterior housing material (Sleeving, Bottom plate, etc.)	The impregnated element, case and end seal are assembled. For the end seal, a rubber packing, a rubber-lined bakelite (with terminals) or a molded plastic plate (with terminals) are used. After assembly, the capacitors are covered with exterior housing material. Sleeving is not used for laminated case products, such as surface mount capacitors.

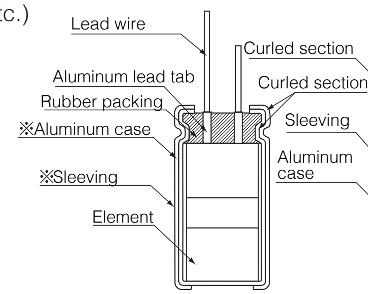


Fig. 1 - 3

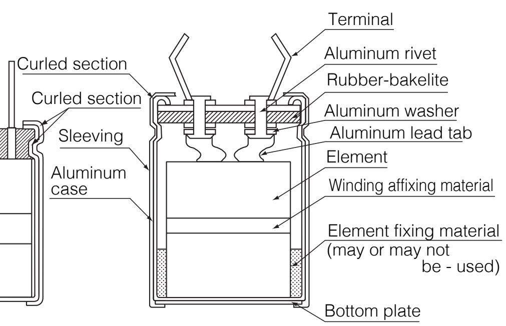


Fig. 1 - 4

※ laminate casing for laminate products (sleeveless)

Process	Main Materials	Contents
Aging	Assembled products	DC voltage is applied under high temperature conditions to reform the oxide film.
		All quantity Electric characteristic inspection
Processing	Plastic platform Taping material Accessories (Capacitor mounting band, Terminal screws, etc.)	Leads are processed and the plastic platform is attached to surface mount capacitors. Depending on customer specification, the lead cutting, forming, snap-in and taping are processed. Accessories, such as mounting bracket, are attached.

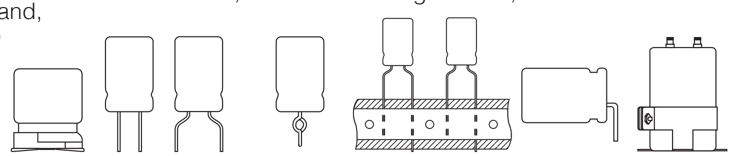


Fig. 1 - 5

Process	Main Materials	Contents
Inspection		Inspection based on the standard specification and test requirements is performed to guarantee the quality of products.
Packaging	Packaging materials	Packing
Shipping		

1-6 Characteristic

1-6-1 Capacitance

The capacitance (Ca) of the dielectric portion of the anode aluminum foil can be calculated with the following formula (discussed in 1-1):

$$Ca = 8.854\times10^{-12}\frac{\varepsilon S}{d} \ (F)$$

The cathode foil has a capacitance (Cc) that uses the oxide layer, which formed by the forming voltage or formed naturally during storage (generally 1V or less), as a dielectric. According to the construction of aluminum electrolytic capacitors, Ca and Cc are connected in series. Therefore, the capacitance can be determined by the following formula:

$$C = \frac{Ca\times Cc}{Ca + Cc}$$

The standard capacitance tolerance is ±20%(M); capacitors with a capacitance tolerance of ±10%(K), etc. are also manufactured for special usage. The capacitance of aluminum electrolytic capacitors changes with temperature and frequency of measurement, so the standard has been set to a frequency of 120Hz and temperature of 20°C.

1-6-2 Equivalent Series Resistance (R), Dissipation Factor (tanδ), Impedance(Z)

The equivalent circuit of an aluminum electrolytic capacitor is shown below. The equivalent series resistance is also known as "ESR".

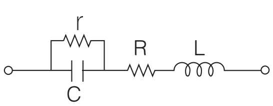
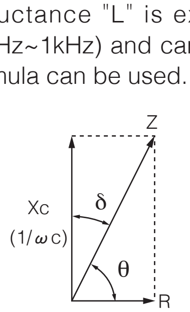


Fig. 1 - 6

C : Capacitance (F)
r : Equivalent parallel resistance of anode oxide film (Ω)
R : Equivalent series resistance (Ω)
L : Equivalent series inductance (H)

A reactance value due to the equivalent series inductance "L" is extremely small at low frequencies (50Hz~1kHz) and can be regarded as zero. The following formula can be used.



$$\tan\delta = \frac{R}{Xc} = \omega CR \quad \cdots(1-2)$$

$$DF = \tan\delta \times 100\ (\%) \quad \cdots(1-3)$$

$$PF = \cos\theta = \frac{R}{Z} = \frac{R}{\sqrt{R^2 + \left(\frac{1}{\omega C}\right)^2}} \quad \cdots(1-4)$$

$$Q = \frac{1}{\tan\delta} = \frac{Xc}{R} \quad \cdots(1-5)$$

$(\omega = 2\pi f)$

Fig. 1 - 7

The impedance can be expressed by:

$$Z = \frac{1}{j\omega C} + j\omega L + R$$

Its absolute value can be expressed by:

$$|Z| = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}$$

Its relation with frequencies is shown by a model curve (Fig. 1-8).

The inductance "L" is mainly from the wound electrode foils and the leads.

ESR "R" is from resistance of the electrode foils, the electrolyte, the leads and each connection.

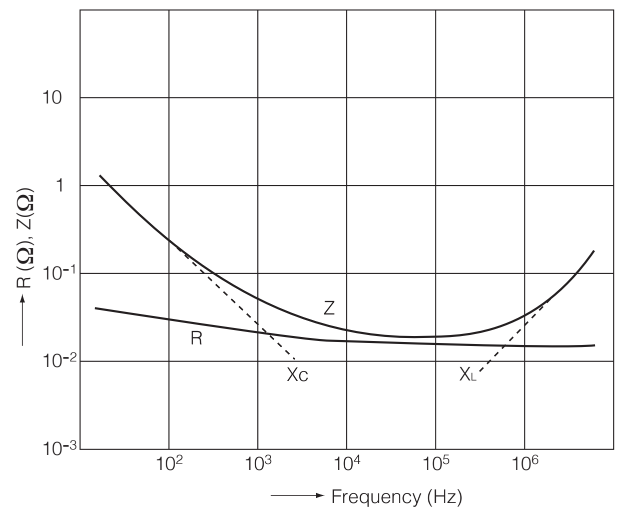


Fig. 1 - 8

1-6-3 Leakage Current

The causes of leakage current in aluminum electrolytic capacitors are:

(1) Distorted polarization of the dielectric (aluminum oxide layer)
(2) Resolution and formation of the dielectric
(3) Moisture absorption by the dielectric
(4) Breakdown of the dielectric due to the existence of chlorine or iron particles.

The leakage current value can be decreased by proper selection of materials and production methods; but it cannot be totally eliminated.

Leakage current is also dependent upon time, applied voltage and temperature.

The specified leakage current value is measured after the rated voltage of the capacitor is applied at room temperature for a specified time period. When selecting a capacitor for a particular application, characteristics such as temperature dependency, aging stability and etc. must be taken into account.

1-6-4 Temperature Characteristics

Aluminum electrolytic capacitors have liquid electrolyte. This electrolyte has properties (conductivity, viscosity, etc.) that have conspicuous temperature characteristics.

Electrical conductivity increases as the temperature increases and reduces as the temperature decreases. Therefore, the electrical characteristics of aluminum electrolytic are affected by temperature more than other types of capacitors. The following section explains the relationship between temperature and capacitance, tangent delta, ESR, impedance and leakage current.

1) Capacitance

The capacitance of aluminum electrolytic capacitors increases as the temperature increases and decreases as the temperature decreases. The relationship between temperature and capacitance is shown in Fig. 1-9.

2) Tanδ, Equivalent Series Resistance(ESR), Impedance

Tanδ, equivalent series resistance (ESR) and impedance changes with temperature and frequency. An example of the general characteristics is shown in Fig. 1-10 and 1-11.

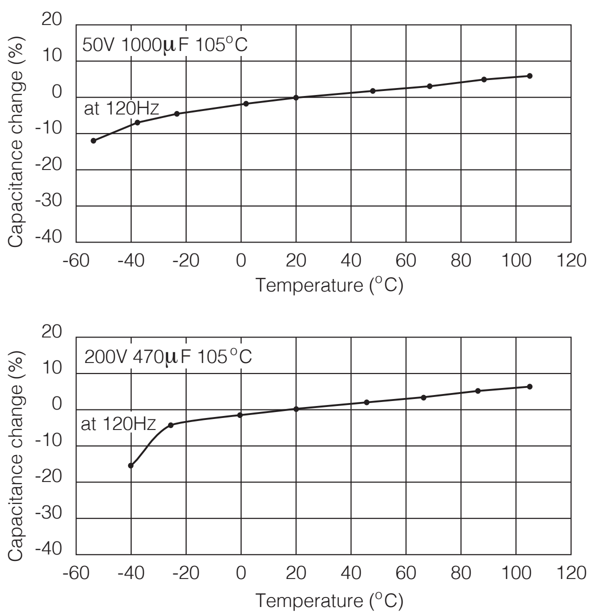


Fig. 1 - 9 Capacitance vs. Temperature Characteristics

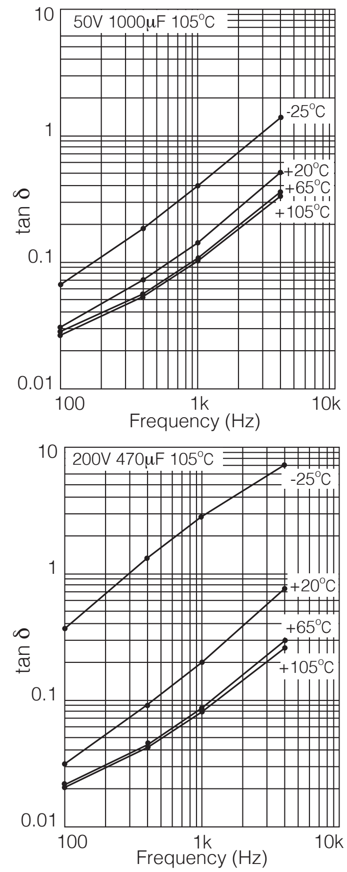


Fig. 1 - 10 Tanδ vs. Frequency Characteristics

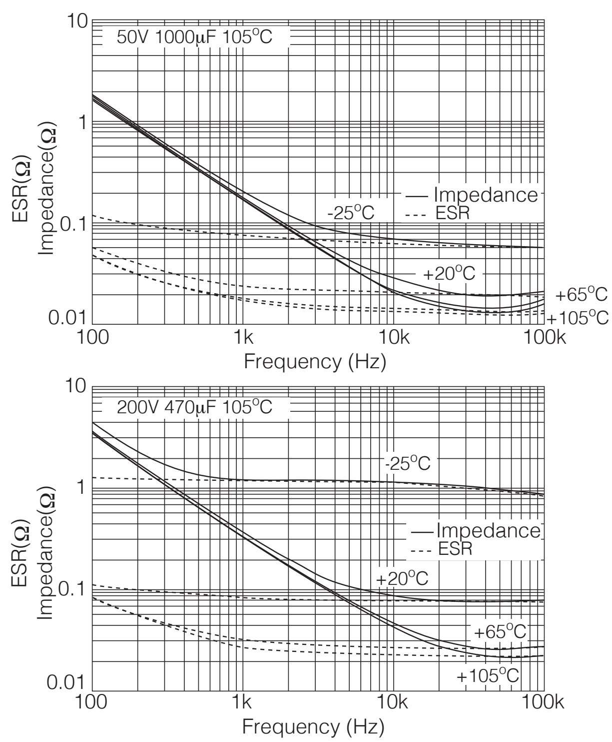


Fig. 1 - 11 Impedance, ESR vs. Frequency Characteristics

3) Impedance Ratio

The ratio between the impedance at 20°C and the impedance at various temperatures is called the impedance ratio. Impedance ratio becomes smaller as the smaller the change of ESR and capacitance with temperature. The performance at low temperatures is expressed with the impedance ratio at 120Hz.

4) Leakage Current

The leakage current increases as the temperature increases and decreases as the temperature decreases. Fig.1-12 shows the relationship between temperature and leakage current.

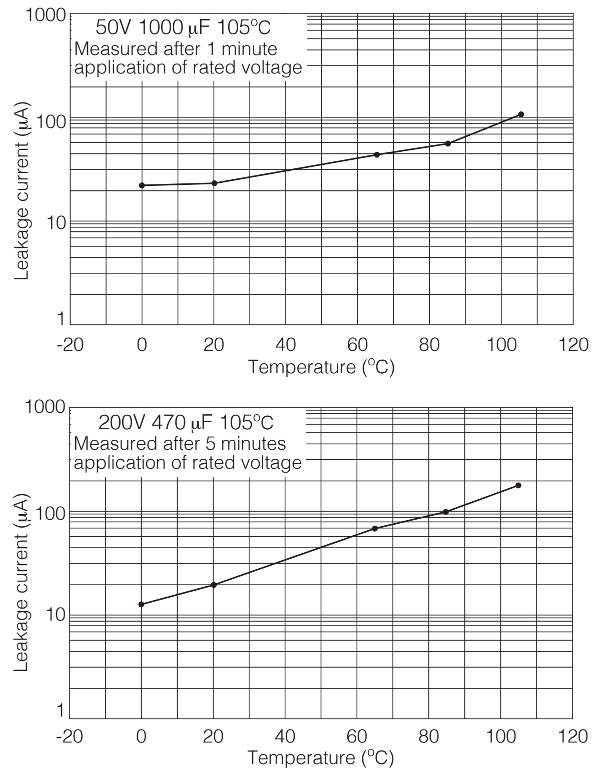


Fig. 1 - 12 Leakage current vs. Temperature Characteristic

2. Application Guidelines for Aluminum Electrolytic Capacitors

2-1 Application Guidelines

In the worst case, aluminum electrolytic capacitors may cause rupture, fire, smoke, short circuit, open circuit, or other failures, so use them with extreme caution.

2-1-1. Circuit Design

(1) Make sure the application and mounting conditions are within the conditions specified in the catalog or alternate product specification (Referred to as specification hereafter)

(2) Operating temperature and applied ripple current shall be within specification.
①The capacitor shall not be used in an ambient temperature which exceeds the operating temperature specified.
②Do not apply ripple current which exceeds the allowable ripple current.

(3) Appropriate capacitors which comply with the life requirement of the products should be selected when designing the circuit.

(4) Aluminum electrolytic capacitors are polarized. Make sure no reverse voltage or AC voltage is applied to the capacitors. Please use bi-polar capacitors in a circuit that can possibly see reversed polarity.
Note: Even bi-polar capacitors cannot be used for AC voltage application.

(5) For a circuit that repeats rapid charging/discharging, a capacitor that is capable of enduring such conditions must be used. Welding machines and photo flash are a few examples of products that contain such a circuit. In addition, rapid charging/discharging may be repeated in control circuits for servomotors, in which the circuit voltage fluctuates substantially.
Selecting capacitors for circuits that have repeated rapid charging/discharging, please consult Nichicon.

(6) Make sure no voltage (higher than the rated voltage) is applied to the capacitor.
①The peak voltage, which is the DC voltage overlapped by ripple current, does not exceed the rated voltage.
②Where more than 2 aluminum electrolytic capacitors are used in series, make sure the applied voltage will be lower than rated voltage and voltage will be applied to each capacitor equally using a balancing resistor in parallel with the capacitors.

(7) Aluminum electrolytic capacitors must be electrically isolated as follows:
(The aluminum case and the cathode foil are connected by the unstable resistance of a naturally formed oxide layer inside the aluminum case and the electrolyte.)
①(a) Case and negative terminal (except axisl leaded part such as JIS configuration 02 type)
(b) Case and positive terminal
(c) Case and circuit pattern
②Auxiliary terminal of can type such as JIS style symbol 693, 694 or 695 and negative and positive terminal, including the circuit pattern.
③Case and both terminals of a bi-polarized capacitor.

(8) Outer sleeve of the capacitor is not guaranteed as an electrical insulator. Do not use a standard sleeve on a capacitor in applications that require the electrical insulation. When the application requires special insulation, please contact our sales office for details.

(9) Capacitors may fail if they are used under the following conditions:
①Environmental (climatic) conditions
(a) Being exposed to water, high temperature & high humidity atmosphere, or condensation of moisture.
(b) Being exposed to oil or an atmosphere that is filled with particles of oil.
(c) Being exposed to salty water or an atmosphere that is filled with particles of salt.
(d) In an atmosphere filled with toxic gasses (such as hydrogen sulfide, sulfurous acid, nitrous acid, chlorine, bromine, methyl bromide, ammonia, etc.)
(e) Being exposed to direct sunlight, ozone, ultraviolet ray, or radiation
(f) Being exposed to acidic or alkaline solutions
②Under severe conditions where vibration and/or mechanical shock exceed the applicable ranges of the specifications.

(10) When designing a P.C. board, pay attention to the following:
①Have the hole spacing on the P.C. board match the lead spacing of the capacitor.
②There should not be any circuit pattern or circuit wire above the capacitor pressure relief vent.
③Unless otherwise specified, following clearance should be made above the pressure relief vent.

Case Diameter	Clearance Required
ϕ6.3~16mm	2mm or more
ϕ18~35mm	3mm or more
ϕ40mm or more	5mm or more

④In case the vent side is placed toward P.C. board (such as end seal vented parts), make a corresponding hole on the P.C. board to release the gas when vent is operated. The hole should be made to match the capacitor vent position.
⑤Screw terminal capacitors must be installed with their end seal side facing up. When you install a screw terminal capacitor in a horizontal position, the positive terminal must be in the upright position.

(11) The main chemical solution of the electrolyte and the separator used in capacitors are combustible. The electrolyte is conductive. When it comes in contact with the P.C. board, there is a possibility of smoking or fire. Do not locate any circuit pattern beneath the capacitor end seal.

(12) Do not design a circuit board where heat generating components are placed near an aluminum electrolytic capacitor or reverse side of P.C. board (under the capacitor).

(13) Refer to the pad size layout recommendations in our catalog when designing in surface mount capacitors.

(14) Electrical characteristics may vary depending on changes in temperature and frequency. This variation needs to be takin into consideration when you design circuits.

(15) When you mount capacitors on a double-sided P.C. boards, do not place capacitors on circuit patterns or over unused holes.

(16) The torque for terminal screw or brackets screws shall be within the specified value.

(17) When you install more than 2 capacitors in parallel, consider the balance of current flowing though the capacitors. Especially, when a solid conductive polymer aluminum electrolytic capacitor and a standard aluminum electrolytic capacitor are connected in parallel, special consideration must be given.

(18) If more than 2 aluminum electrolytic capacitors are used in series, make sure the applied voltage will be lower than the rated voltage and that voltage will be applied to each capacitor equally using a balancing resistor in parallel with each capacitor. If one side is shorted, the other side may be applied an overvoltage.

(19) When capacitors are connected in series or parallel, an imbalance current may cause to a short circuit on one side and an overvoltage on the other side.

2-1-2. Mounting

(1) Once a capacitor has been assembled onto a PC board and power applied, do not use it again even if the capacitor is discharged, because an electric potential (restriking voltage) may exist between the terminals. (Excluding capacitors removed to measure electrical performance during periodic inspection)

(2) Electric potential between positive and negative terminal may exist as a result of returned electromotive force, discharge the capacitor using a 1kΩ resistor.

(3) Leakage current of the parts that have been stored for more than 2 years may increase. If leakage current has increased, please perform a voltage treatment using 1kΩ resistor.

(4) Confirm ratings before installing capacitors on the P.C. board.

(5) Confirm polarity before installing capacitors on the P.C. board.

(6) Do not drop capacitors on the floor, nor use a capacitor that was dropped.

(7) Do not damage the capacitor while installing.

(8) Confirm the lead spacing of the capacitor matches the hole spacing of the P.C. board prior to installation.

(9) Snap-in can type capacitor such as JIS style symbol 692, 693, 694 and 695 type should be installed tightly to the P.C. board (allow no gap between the P.C. board and bottom of the capacitor).

(10) Make sure the clinch force is not too strong when capacitors are placed and fixed by an automatic insertion machine.

(11) Pay attention to the mechanical shock to the capacitor by suction nozzle of the automatic insertion machine or automatic mounter, or byproduct checker, or by centering mechanism.

(12) Hand soldering.
①Soldering condition shall be confirmed to be within specification.
②If the leads must be formed due to a mismatch of the lead spacing to hole spacing on the board, bend the lead before soldering without applying too much stress to the capacitor.
③If you need to remove parts which were soldered, please melt the solder enough so that stress is not applied to lead.
④Solder iron should not touch any portion of capacitor body.

(13) Flow soldering (Wave solder)
①Aluminum capacitor body must not be submerged into the solder bath. Aluminum capacitors must be mounted on the "top side" of the P.C. board and only allow the bottom side of the P.C. board to come in contact with the solder.
②Soldering condition must be confirmed to be within Nichicon specification.
③Avoid having flux adhere to any portion of the capacitor except the terminal.
④Avoid contact between other components and the aluminum capacitor.

(14) Reflow soldering (SMD only)
①Soldering condition must be confirmed to be within Nichicon specification.
②When an infrared heater is used, pay attention to the extent of heating since the absorption rate of infrared may vary due to the differences of the color of capacitor body, material of the sleeve and capacitor size.

(15) Soldering flux
There are non-halogen types of flux that do not contain ionic halides, but contain many non-ionic halides. When these non-ionic halides penetrate into the capacitor, they cause a chemical reaction that is just as harmful as the use of cleaning agents. Use soldering flux that does not contain non-ionic halides.

(16) Shrinkage, bulging and/or cracking could be seen on the outer sleeve of the capacitor when the capacitors are kept in for more than 2 minutes at 150°C ambient temperature during soldering process or resin curing process. Applying high temperature gas or heat ray to capacitor can cause the same phenomenon.

(17) Do not tilt, lay down or twist the capacitor body after soldering the capacitor to the P.C. board.

(18) Do not carry the P.C. board by grasping the soldered capacitor.

(19) Do not allow anything to touch the capacitor after soldering. If the P.C. boards are stored in a stack, please make sure the P.C. boards or the other components do not touch the capacitor. The capacitors shall not be effected by any radiated heat from the soldered P.C. board or other components after soldering.

(20) Cleaning Agent, Fixing material, Coating material
Please refer to the section 2-10-2, -3 for details.

(21) Fumigation
Please refer to the section 2-10-4 for details.

2-1-3. In the equipment

(1) Do not directly touch terminal by hand.

(2) If the capacitor becomes hot or the pressure valve is activated the capacitor has failed, high-temperature steam over 100°C will be expelled. Keep your hands and face away from the capacitor and do not approach any places where steam is exposed, it may causes burns.

(3) Do not short the terminals with a conductor, or spill conductible liquid such as alkaline or acidic solution on or near the capacitor.

(4) Make sure the ambient conditions where the capacitor is installed does not have any of the following conditions:
①Capacitors are exposed to water, high temperature & high humidity atmosphere, or condensation of moisture.
②Capacitors are exposed to oil or an atmosphere that is filled with particles of oil.
③Capacitors are exposed to salty water, or an atmosphere that is filled with salt.
④Atmosphere is filled with toxic acid gasses (e.g. hydrogen sulfide, sulfurous acid, nitrous acid, chlorine, bromine, methyl bromide, etc.)
⑤Atmosphere is filled with toxic alkaline gasses (e.g. ammonia)
⑥Capacitors are exposed to acidic or alkaline solutions.
⑦Shrinkage, bulging and/or cracking could be seen on outer sleeve of the capacitor when the capacitors are used in an atmosphere where condensation of moisture occurs, please confirm their adaptation before use.
The condensation of moisture could occur when the Temperature Cycling Test / Rapid Change of Temperature Test is performed, in this case, the above sleeve problem could be seen.

2-1-4. Maintenance Inspection

(1) Periodically inspect the aluminum capacitors that are installed in industrial equipment. The following items should be checked:
①Appearance : Remarkable abnormality such as vent operation, leaking electrolyte etc.
②Electrical characteristic: Capacitance, dielectric loss tangent, leakage current, and items specified in the specification.

2-1-5. In an Emergency

(1) Capacitors of certain sizes have a pressure relief vent to release abnormal pressure. If you see smoke due to operation of pressure relief vent, turn off the power. The steam coming out from the pressure relief vent is the vaporization of hydrogen gas and electrolyte, it is not smoke due to combustion.

(2) Do not bring your face near the capacitor when pressure relief vent operates. The gasses emitted are over 100°C and it may cause burns.
If the gas gets into your eyes, flush your eyes with water immediately.
If you breathe in the gas, immediately wash out your mouth and throat with water.
Do not ingest electrolyte. If your skin is exposed to electrolyte, please wash it with soap and water.

(3) The temperature of capacitor could be high even if the steam is not visible from the pressure relief vent. Touching it may causes burns.

2-1-6. Storage

(1) It is recommended to keep capacitors between the ambient temperatures of 5°C to 35°C and a relative humidity of 75% or less.

(2) Make sure the ambient storage condition will be free from the conditions that are listed in clause 3. "In the equipment" at (4).

2-1-7. Disposal

(1) Use either of the following methods for disposing of capacitors.

①Make a hole in the capacitor body or crush the capacitors and incinerate them.

②If incineration is not applicable, hand them over to a waste disposal agent and have them buried in a landfill.

(2) When removing a capacitor from the circuit board or when disposing the capacitor, please ensure the capacitor is properly discharged.

The above guidelines are made according to the "Guideline of Nota Bene for Aluminum Electrolytic Capacitors for the Use in Electronic Equipment" which issued by EIAJ RCR- 2367D in March, 2019.
Please refer to the book for more details.

2-2 Failure Modes of Aluminum Electrolytic Capacitors

2-2-1. Definition of Failure

The following two conditions must be considered in defining "failure."

1) Catastrophic failure

When a capacitor has completely lost its function due to a short or open circuit.

2) Degradation failure

Caused by the gradual deterioration of a capacitor. The criteria for degradation failure differs according to the use of a capacitor. Follow the standard values that are specified in the specification as the judging criteria.

2-2-2 Failure Mode in the Field

1) Short Circuit

Short circuits in the field are very rare. A short circuit between the electrodes can be caused by vibration, shock or stress on leads. It can also be caused by the application of voltages above the rated voltage, application of extreme ripple or by application of pulse current.

2) Open Circuit

- An open circuit can be caused if extreme force is applied to the capacitor at the time of mounting and if vibration / shock is then applied during usage. In such cases, the connection between the lead wire and tab could be distorted or twisted which eventually leads to an open circuit.
- If the cleaning agent for P.C. boards or the fixing agent (including conformal materials) for capacitors which contains halogen infiltrates the capacitor, the operation of the product may be affected by an increased leakage current as a result of an open circuit due to corrosion of lead wires, foils and tabs.
- The electrolyte may vaporize and cause an open circuit if the sealing part cannot be maintained. Sealing material deterioration can be caused by use under temperatures that exceed the rated maximum operating temperature, or by the exposure to high heat transmitted through the P.C. board patterns, or by prolonged usage.
- If an improper amount of ripple is applied, the electrolyte vaporizes and permeates through the end seal material due to the rise in the temperature inside the capacitor. As a result, the electrolyte will dry up and open circuit will occur.

3) Capacitance Drop, High Loss (High ESR)

If the capacitor is subjected to the following conditions, capacitance drop and high loss will occur:
1)reverse voltage is continuously applied,
2)current exceeding the maximum rated ripple is continuously applied,
3)if the capacitor is subjected to extreme charge and discharge.

4) Destruction (Pressure relief vent Operation)

The pressure relief vent may operate due to generation of gas caused by reverse voltage, over-voltage, extreme ripple or AC voltage.

2-2-3 Analysis of Failure Mode

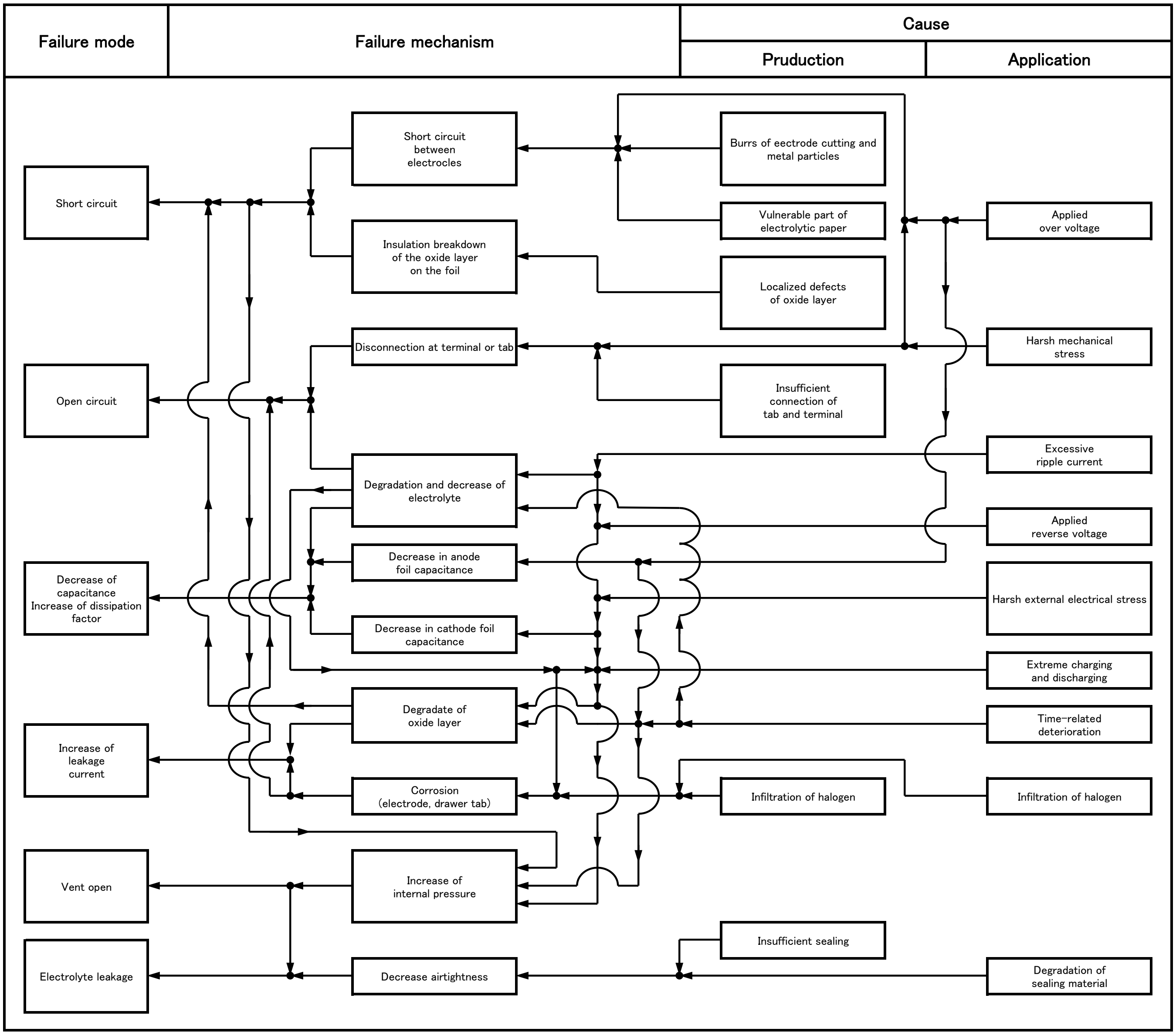


Fig. 2 - 1 Analysis of Failure Mode

2-3 Operating Voltage and Safety

2-3-1 Foreword

The relationship between the voltage and leakage current when voltage is applied to the aluminum electrolytic capacitor is shown in Fig. 2-2. From Fig. 2-2, the following can be observed:

- If voltage is applied in the direction of the polarity of the capacitor, the leakage current will rapidly start to rise if the applied voltage exceeds the rated voltage.
- If voltage is applied in reverse direction of the polarity of the capacitor, a large amount of current begins to run through with a low voltage.

The behavior and safety test method of the aluminum electrolytic capacitor which withholds the above nature under the below conditions, is expressed in the following section.

1) Under reverse polarity
2) Under excess voltage application.
3) Under AC voltage application

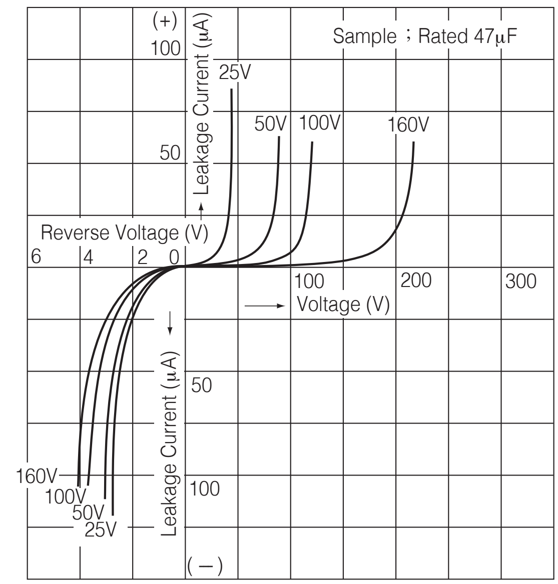


Fig. 2 - 2 V - I Characteristics (Voltage - Current Characteristics)

2-3-2 Reverse Voltage

The state of the capacitor changes according to the degree of reverse voltage being applied.

1) If a high reverse voltage is applied, the current will increase. Heat will be generated due to the power loss (W=Vc×Ic) caused by the reverse voltage (Vc) and current (Ic). Heat caused by the current generates gas due to the electrolytic dissociation of the electrolyte. This will increase the pressure inside the capacitor and activate the pressure relief vent in a short period of time.
2) In case of a low reverse voltage and a low leakage current, a capacitor will initially generate heat due the power loss. But the progressing formation of an oxide layer on the cathode electrode causes a decrease in current. Fig. 2-3 shows how the capacitance changes relative to the application of reverse voltage. The results shown in the figure is due to the decrease in cathode foil capacitance caused by oxide layer formation on the surface of the cathode aluminum foil. Again due to the consumption of electrolyte, the tan δ increases.

Normally a cathode foil has a withstand voltage of about 1V because of the natural oxide layer formed on its surface. This is as much as a diode's withstand reverse voltage. If the capacitor is exposed to a reverse voltage over the withstand voltage, the internal pressure will rise and activate the pressure relief vent. Make sure to check the polarity of the capacitors before usage.

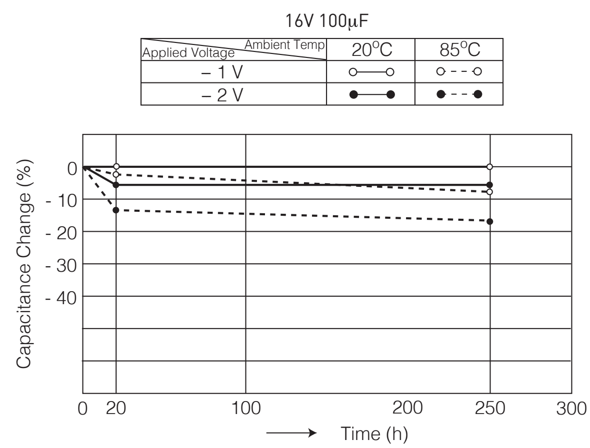


Fig. 2 - 3 Capacitance vs. Reverse Voltage Characteristics

2-3-3 Excess Voltage Application

Fig. 2-4 shows, the leakage current rises sharply when voltages above the rated voltage applied. When the withstand voltage of the anode foil decreases due to the generation of heat and the anode foil undergoes insulation breakdown, a large amount of current will flow and cause the internal pressure to rise within a short period of time. If the pressure relief vent is activated, the electrolyte that has changed to a gas is released from the opened vent. The energy of the capacitor is proportional to the second power of the voltage ($J=\frac{1}{2}CV^2$). The higher the applied voltage, the more severe the condition of the activated vent, and the more likely that a short between the foils will occur.

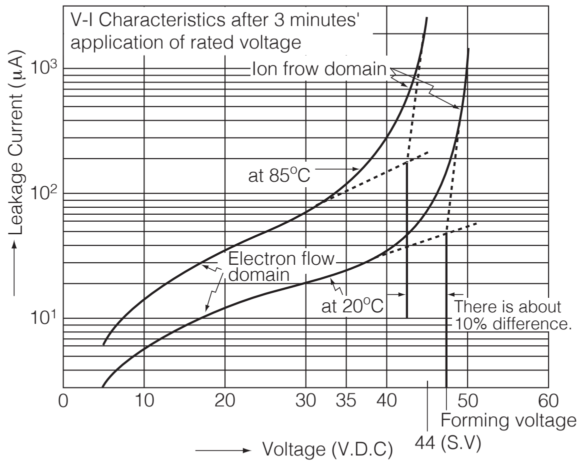


Fig. 2 - 4 V - I Characteristics (ex. Rated at 35V)

2-3-4 AC Voltage Application

If AC voltage is applied to an aluminum electrolytic capacitor, an electric current of $I = \omega CE$ (A) flows.

(Fig. 2-2 V-I Characteristics) shows, the aluminum electrolytic capacitor does not have a withstand voltage in the reverse direction. If the capacitor is used in an AC circuit, the electric current flowing is larger than that calculated from $I = \omega CE$. If the internal resistance of the aluminum electrolytic capacitor is labeled R (Ω), heat will be generated due to the wattage loss $W = I^2R$ (W) according to the current. The amount of heat is large because the internal resistance of the capacitor is large. The pressure relief vent is activated when heat is generated. This causes the electrolyte to evaporate, and the internal pressure to rise. Even bipolar capacitors (non-polar), cannot be used in continuous AC applications.

2-3-5 Pressure Relief Vent Structure

The internal pressure of the capacitor will rise due to gas generation caused by heat generation, evaporation of the electrolyte or electrolytic dissociation if the following is applied: extreme voltage, reverse voltage, AC current or extreme ripple. The pressure relief vent is provided to release the internal pressure.

There are two types of pressure relief vents classified by their location on the capacitor: 1) end seal, 2) aluminum case.

Testing Method (For example)

a. AC Voltage Method (JIS C5101-1, 4.28.1)

(1)In the circuit shown in Fig.2-5 a series resistance "R" is selected from Table 2-1 in accordance with the rated capacitance of the capacitor to be tested.

Table 2-1

Rated Capacitance (μF)	Series Resistance (Ohm)	Rated Capacitance (μF)	Series Resistance (Ohm)
1 or below	1000±100	Over 100～1000	1±0.1
Over 1～10	100±10	Over 1000～10000	0.1±0.01
Over 10～100	10±1	Over 10000	Note 1

Note 1 : A resistance value equivalent to 1/2 of impedance at testing frequency.

(2)The capacitor is connected and AC voltage is applied as high as 70% of the rated voltage or 250Vrms, whichever is smaller. When 30Arms or more is applied, the voltage must be adjusted so the maximum applied current is 30 Arms. The power source frequency is either 50Hz or 60Hz.

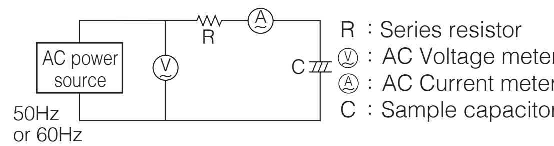


Fig. 2 - 5

b. DC Reverse Voltage Method (JIS C5101-1, 4.28.2)

(1)For the circuit shown in Fig.2-6, DC current is selected from Table 2-2 according to the nominal diameter of the capacitor to be tested.

Table 2-2

Nominal Diameter (mm)	DC Current (A)
22.4mm or less	1A constant
Over 22.4mm	10A constant

(2)The capacitor is connected with its polarity reversed to a DC power source. Then the current selected from Table 2-2 is applied.

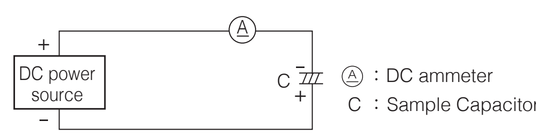


Fig. 2 - 6

Judging Criteria

If the results of the prior tests show the following conditions, the pressure relief vent has passed the test.

(1) The vent operates with no dangerous conditions such as flames or dispersion of pieces of the capacitor element and/or case.

(2)Nothing abnormal takes places even if the test voltage has been applied to the capacitor for 30 minutes.

2-4 Charging and Discharging

2-4-1 Effect of Charging and Discharging

Following are the phenomenon that occurs in the aluminum electrolytic capacitor, when used in a frequent charge/discharge circuit such as shown in Fig. 2-7.

In the circuit shown in Fig. 2-7, when a polarized aluminum electrolytic capacitor, which consists anode foil capacitance (Ca) and cathode foil capacitance (Cc), is charged with voltage (V), the anode foil dielectric is charged with an electrical charge of Q = Ca×V (C: coulomb). Next when the capacitor discharges its electrical charge through a discharge resistance, the electrical charge of the anode foil moves and charges the cathode foil. Since the withstand voltage of the cathode foil dielectric is low, the cathode foil reaches its withstand voltage by absorbing part of the electrical charge. When electrical charge moves continuously, electro-chemical reactions occur between cathode foil surface and electrolyte. If charge and discharge are repeated, another dielectric layer is formed on the dielectric layer of the cathode foil. Cathode foil capacitance gradually decreases as additional dielectric layer is formed. Capacitance value of the capacitors decreases as the cathode foil capacitance decreases. The gas generated during oxide layer formation accumulates inside of the capacitor, and rises internal pressure. Depending upon the charge and discharge conditions, pressure relief vent may activate.

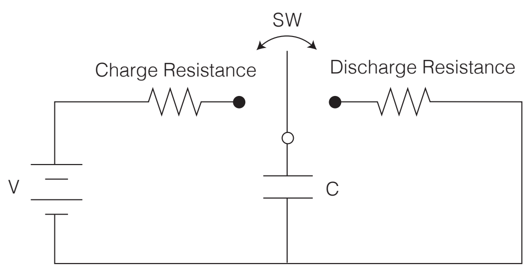


Fig. 2 - 7

2-4-2 Formation of the Oxide Layer

The voltage applied to the cathode foil during discharge is explained as follows.

Electrical charge of the anode foil moves until the anode foil voltage and cathode foil voltage become equal (direction of voltage are opposite to each other and the voltage between the terminals is zero).

The following formula can be developed, using anode foil capacitance (Ca), the initial cathode foil capacitance (Cc),discharge voltage (V), and the voltage applied to anode and cathode foil after discharging (Vc).

$$Ca \times V = Ca \times Vc + Cc \times Vc$$

$$\therefore Vc = \frac{Ca}{Ca + Cc} \times V \quad \cdots\cdots\cdots (2 - 1)$$

From the above, when considering usage of an aluminum electrolytic capacitor in a circuit that has frequent charge and discharge, it is recommended to use capacitors designed to specifically meet conditions of frequent charge/discharge.

2-4-3 Measures Taken Against frequent Charge / Discharge

The following measures are taken to prevent an oxide layer formation on the cathode foil.

① Using a cathode foil with a formation of dielectric layer over the Vc voltage expected.

② The following Equation 2-2 led from Equation 2-1; Equation 2-2 shows that the greater the ratio between the capacitance of anode and capacitance of cathode foil, which is Cc / Ca, the smaller the Vc. From this, the Vc is made smaller than the forming voltage of the cathode foil by using a cathode foil with a sufficient(big enough) capacitance against the anode foil capacitance.

$$Vc = \frac{V}{1 + \frac{Cc}{Ca}} \quad \cdots\cdots\cdots (2 - 2)$$

Fig.2-8 shows examples of results, after the charge/discharge test, found in the charge / discharge type capacitor and standard capacitor.

Capacitance: 63V 10000uF
Charge resistance: 2Ω
Discharge resistance: 100Ω
Charge/discharge cycle: 1 second of charge, 1second of discharge is 1 cycle.
Temperature : 70°C

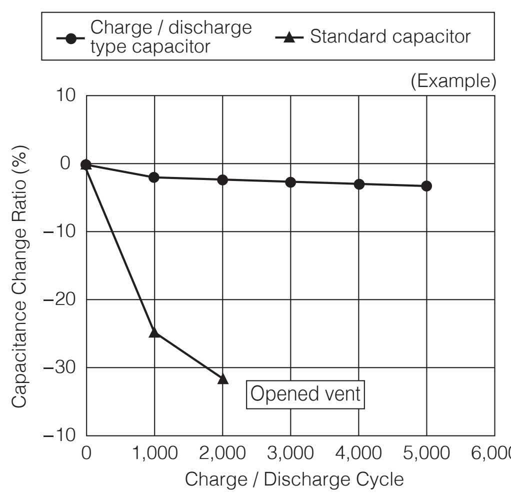


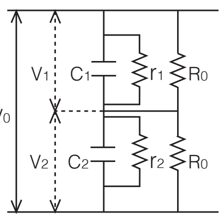
Fig. 2 - 8

If the application is a circuit that has large fluctuations in voltage, such as a power supply for an AC servo amplifier or an inverter, select a LQS, LQR, LNC, LNU series of capacitors that allows rapid charging and discharging. LQS, LQR, LNC, LNU series capacitors employ a special structure to increase their durability against rapid charging and discharging. (Patent pending)

2-5 Method of Setting the Balance Resistance in a Series Connection

2-5-1 Equivalent Circuit and Leakage Current

The relationship between the balance resistance and leakage current resistance of aluminum electrolytic capacitors used in a series circuit, expressed in an equivalent circuit, is shown in Fig. 2-9.



C_1 : Aluminum Electrolytic Capacitor No.1
C_2 : Aluminum Electrolytic Capacitor No.2
r_1 : Leakage Current resistance of Capacitor No.1
r_2 : Leakage Current resistance of Capacitor No.2
V_1 : Voltage between terminals in Capacitor No.1
V_2 : Voltage between terminals in Capacitor No.2
R_0 : Balance Resistance
V_0 : Line Voltage

Fig. 2 - 9

If the leakage current of C_1 and C_2 are expressed as i_1 and i_2:

$$i_1 = \frac{V_1}{r_1}, \quad i_2 = \frac{V_2}{r_2} \cdots\cdots\cdots (2-3 \cdot 2-4)$$

$$V_0 = V_1 + V_2, \quad V_1 - V_2 = R_0 \times (i_2 - i_1)$$

$$R_0 = \frac{V_1 - V_2}{i_2 - i_1} \cdots\cdots\cdots\cdots\cdots (2-5)$$

2-5-2 Leakage Current of the Aluminum Electrolytic Capacitor

If the rated voltage is expressed as V (V) and the capacitance as C (μF), variation of the leakage current in a PC board mounting type capacitor at room temperature (20°C) can be generally expressed by the following equation:

$$i_{max} - i_{min} = \frac{\sqrt{C \times V}}{2} - \frac{\sqrt{C \times V}}{5}$$

$$= \sqrt{C \times V}\left(\frac{1}{2} - \frac{1}{5}\right)$$

$$= \frac{3}{10}\sqrt{C \times V} \cdots (\mu A) \cdots\cdots\cdots (2-6)$$

The leakage current of aluminum electrolytic capacitors increases as the temperature rises.

Generally if the leakage current at 20°C is referred to as 1, it becomes 2~3 times at 65°C and 3~5 times at 85°C. The leakage current also differentiates depending on the applied voltage and storage conditions, so it is necessary to multiply the leakage current variation coefficient to give a little leeway.

2-5-3 Example of Setting the Balance Resistance

The following shows the equation for setting the balance resistance in using 2 (pcs) of 400V, 470μF aluminum electrolytic capacitors in a series circuit in an ambient temperature of 60°C.

Temperature coefficient for leakage current at 60°C: 2.0
Voltage balance rate: 10%
Coefficient for variation of leakage current: 1.4

Voltage balance

$$V_1 - V_2 = 400 \times 0.1 = 40 \text{ (V)}$$

Range of leakage current variation:

$$i_{max} - i_{min} = \frac{3}{10}\sqrt{C \times V} \times 2 \times 1.4$$

$$= \frac{3}{10}\sqrt{470 \times 400} \times 2 \times 1.4$$

$$= 364 \ (\mu A)$$

$$\therefore R_0 = \frac{40}{364 \times 10^{-6}} \approx 109000 \cdots\cdots 100k\Omega$$

2-6 Storage Performance

When an aluminum electrolytic capacitor is stored under no load conditions for a long period of time, its leakage current tends to increase slightly. This is due to a drop in the withstand voltage of the dielectric caused by the reaction of the anode oxide layer with the electrolyte. When voltage is applied to the capacitor, the leakage current returns to its initial level because of the re-forming action of the electrolyte (called voltage treatment). If the storage temperature is high, the leakage current will increase substantially. It is desirable to store capacitors at normal temperature level with no direct sunlight. A voltage treatment is recommended when using a capacitor that's been stored for a long period of time. The treatment for an individual capacitor is accomplished by charging it up to its rated voltage through a resistance of about 1kΩ and applying the voltage for approximately 30 minutes. When a capacitor is already built into a the circuit it must undergo aging. If the input voltage is adjustable or the power supply that supplies power to a module, first set the voltage to a low value (approximately half the rated voltage) and let it run for about ten minutes. Then, increase the voltage to the appropriate value little by little while monitoring the working of a device. If the voltage is not adjustable, turn on the switch and let it run for about thirty minutes while confirming if the device complies with the specifications. Then turn off the switch.

Generally, if the capacitor has been stored less than 2 years in the temperature range of 5 to 35°C, the capacitor can be used without voltage treatment.

Fig. 2-10 shows an example of the characteristic change in capacitors that were stored at normal temperatures.

Mark	Ratings	Case Size	Temperature	Test Condition
—●—	25V 4700μF	φ22×25L	Room Temperature	No load storage
--○--	400V 150μF	φ25×30L	Room Temperature	No load storage

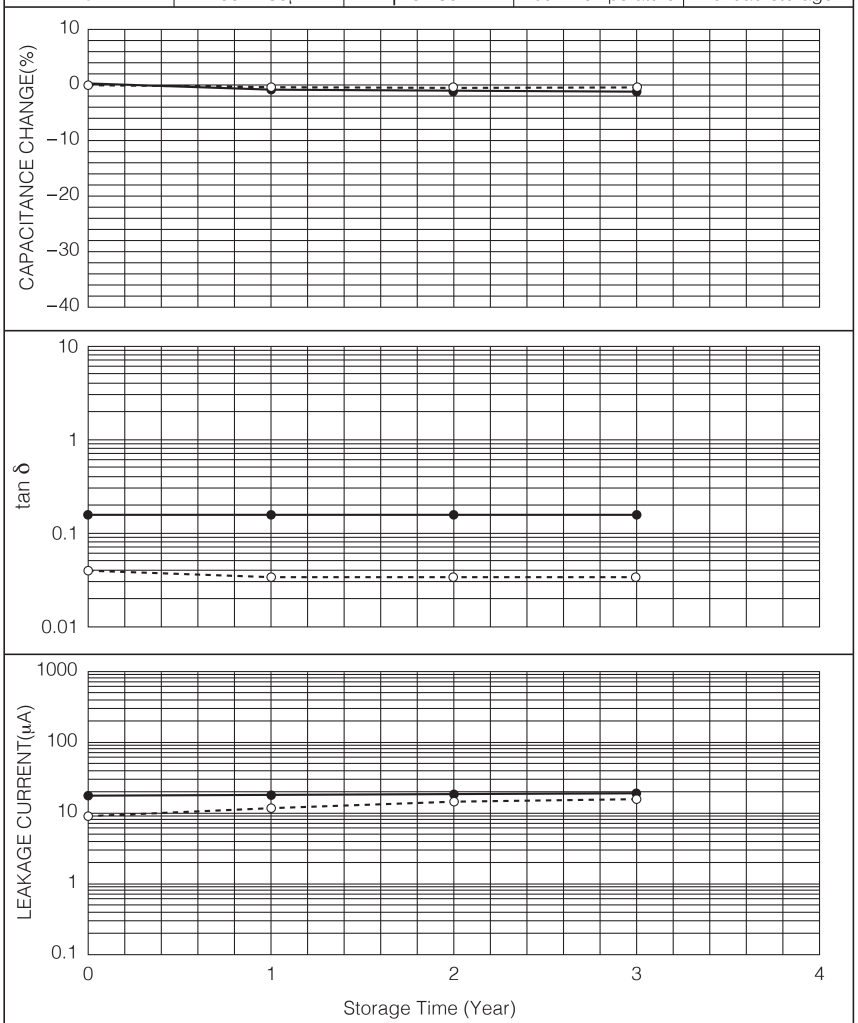


Fig. 2 - 10

2-7 Restriking voltage

Aluminum electrolytic capacitors are discharged completely after inspection before shipping. Even if the capacitor has been discharged, voltage still appears between the terminals. This voltage is called restriking-voltage or remaining voltage.

By polarization phenomena, the surface of the dielectric is charged positively and negatively respectively when voltage is applied to the capacitor. When terminals are shorted, electrical charge at the surface discharges, When the terminals are opened, some voltage appears between the terminals because dipoles that were polarized remained in the polarized position. This is what is referred to as the restriking-voltage. Restriking-voltage relates to the thickness of the dielectric. So it increases as the rated voltage becomes larger. When restriking-voltage occurs, electrical sparks may occur when a capacitor is installed into the circuit and surprise the operator or destroy other low voltage disturbance elements. To prevent this, it is recommended to discharge the accumulated electricity by connecting the terminals with a resistor that has a resistance of 100Ω to 1kΩ before usage. Capacitors with high voltage and large capacitance, have packaging that create a short between terminals by use of aluminum foil or electrical conductive rubber is available. If you need such packaging, please contact our sales offices.

2-8 Usage at High Altitudes

Here are precautions in using aluminum electrolytic capacitors at high altitudes, such as in mountainous regions and in aircrafts.

If the capacitor is used at high altitudes, the atmospheric pressure will become lower than the internal pressure of the capacitor. The aluminum electrolytic capacitor can be used at altitudes below 10,000 (m) .

The temperature decreases as the altitude rises. If the temperature of the capacitor decreases, the capacitance will drop and the tangent delta will increase. We recommend checking the performance of the electrical equipment as temperature changes.

Table 2-3 Relationship Between Altitude, Temp. and Air Pressure

Altitude (m)	Temp.(°C)	Air Pressure (hPa)
0	15.0	1013.3
2,000	2.0	795.0
4,000	- 11.0	616.4
6,000	- 24.0	471.8
8,000	- 37.0	356.0
10,000	- 50.0	264.4
20,000	- 56.5	54.7

For more details, please contact our sales offices.

2-9 Life and Reliability

2-9-1 Foreword

The failure rate (λ) for electronic applications and components which require no particular maintenance follows their time transition (t) and shows a curve as shown in Fig.2-11. Because this curve resembles the shape of a western bathtub, it is called "Bathtub Curve". The failure mode of aluminum electrolytic capacitors also forms a "Bathtub Curve." If the results of the life evaluation test of aluminum electrolytic capacitors is analyzed by "Wei bull Probability Paper" as in Fig. 2-12, the shape parameter "m" will be larger than 1, which shows that the failure mode is a wear-out failure.

Although the failure rate or the life estimation is generally used in designing a device, the reliability of an aluminum electrolytic capacitor is generally measured by its life (the expected life in practical use) rather than failure rate, since the failure mode of aluminum electrolytic capacitors is wear-out. In other words, when ascertaining the failure rate in the life test, the results may vary greatly even for the same total test time because of the different combination of the number of specimens and the test time (e.g. 100 capacitors x 10^3 hours... zero failures is expected, 10 capacitors x 10^4 hours... 100% will be failed.) The factors that most effect the life of aluminum electrolytic capacitors are acceleration according to the ambient temperature (F_T), acceleration according to the ripple current (F_I) and acceleration according to the applied voltage (F_U). The expected life is calculated by multiplying the specified life time on Nichicon catalog, F_T, F_1, and Fu. The life of aluminum electrolytic capacitors is discussed in the following.

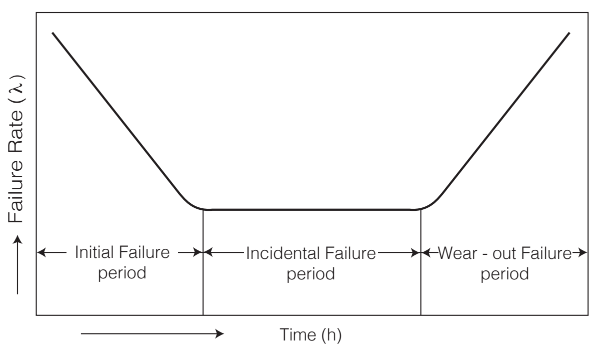


Fig. 2 - 11 Failure Rate Curve (Bathtub Curve)

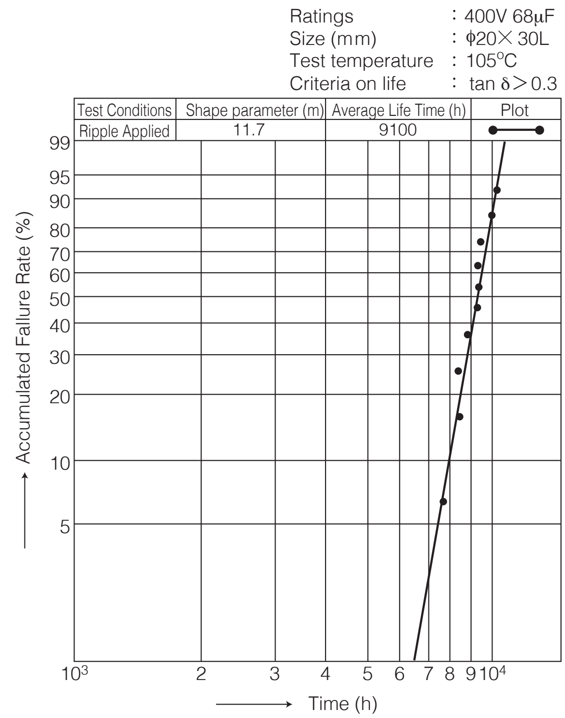


Fig. 2 - 12 Failure Analysis by Weibull Probability Paper

2-9-2 Life Evaluation Method

An aluminum electrolytic capacitor is determined to have reached its end of life when the capacitance change, tan δ and leakage current have exceeded the specified value or when a noticeable external abnormality occurs. Factors that affect the life of aluminum electrolytic capacitors are temperature, humidity and vibration, etc. but the factor that has the most effect is the temperature. The life of capacitors shortens as the temperature rises. Endurance ratings are determined by applying the DC voltage or by applying ripple superimposed upon DC voltage at the specified maximum operating temperature of the capacitor. Examples of the test results are shown in Fig.2-13 and 2-14.

Mark	Ratings	Size	Temp.	Test Condition
—●—	200V 220μF	φ20×25L	105°C	120Hz 1.00Arms+DC191V
- ○ -	400V 68μF	φ20×30L	105°C	120Hz 0.56Arms+DC384V

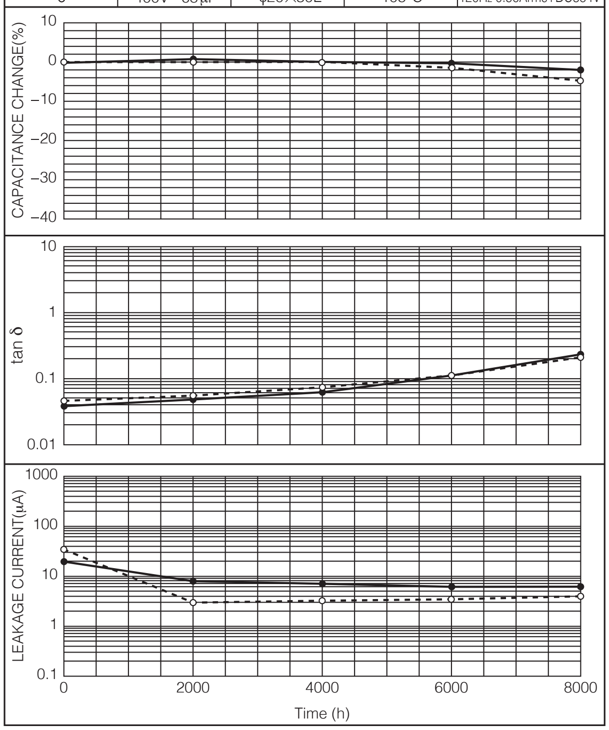


Fig. 2 - 13 High Temperature Life Evaluation Test

Mark	Ratings	Size	Temp.	Test Condition
—●—	50V 1000μF	φ16×25L	105°C	100kHz 2235mArms+DC48V
- ○ -	16V 4700μF	φ16×31.5L	105°C	100kHz 3010mArms+DC15V

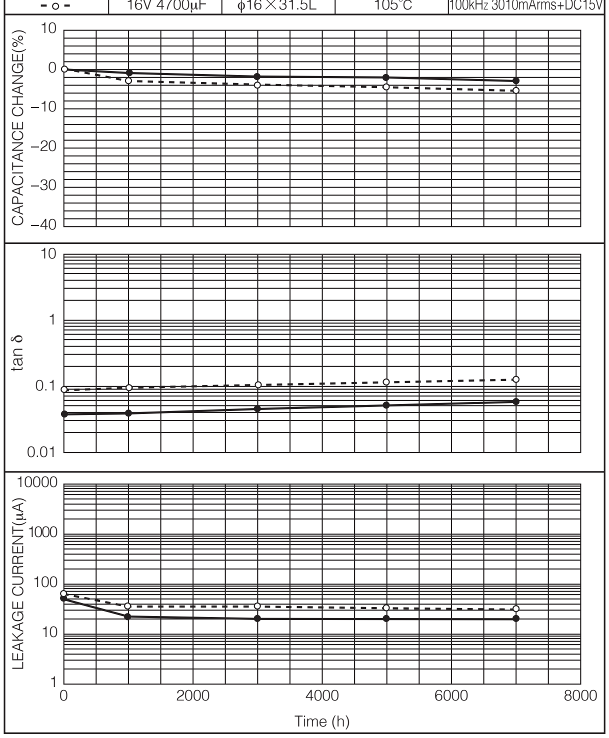


Fig. 2 - 14 High Temperature Life Evaluation Test

2-9-3 Ambient Temperature and Life

In general, if a capacitor is used at the maximum operating temperature or to a minimum of 40°C operating temperature the life expectancy can be calculated according to Arrhenius theory in which the life doubles for each 10°C drop in temperature (Fig 2-15).

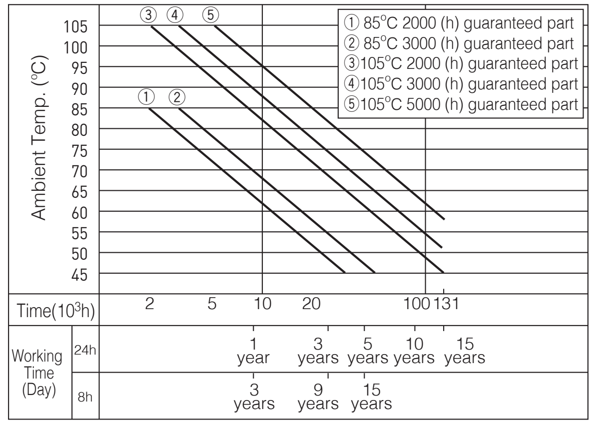


Fig. 2 - 15 Life Estimation Table

2-9-4 Applied Voltage and Life

Compared to how ambient temperature and ripple current effect life, the applied voltage effects the life of the capacitor when used below the rated voltage is small. Therefore, when estimating the life of a capacitor, the voltage coefficient to the applied voltage (Fu) is calculated as 1. An example of the test results is shown in Fig.2-16.

Mark	Ratings	Size	Temp.	Test Condition
—●—	50V 12000μF	φ35×45L	105°C	DC 50V
- ○ -	50V 12000μF	φ35×45L	105°C	DC 40V
—×—	50V 12000μF	φ35×45L	105°C	DC 30V

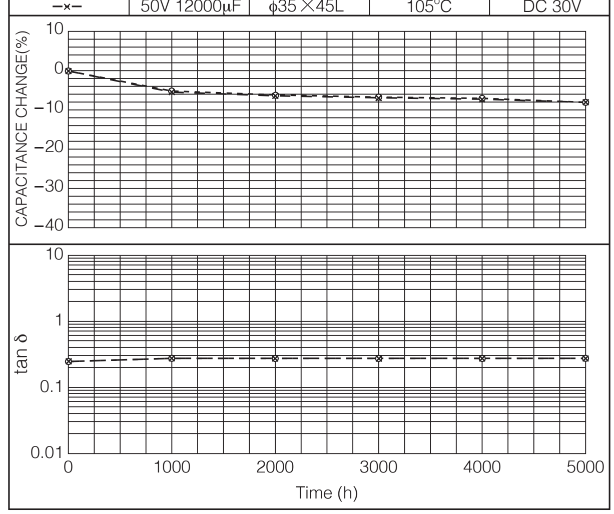


Fig. 2 - 16 High Temp. Evaluation Test When Applied Voltage is Charge

High voltage capacitors used in smoothing circuits for power electronic equipment, as the leakage current decreases the voltage drops and decreases the consumption of electrolyte. The life of the capacitor may be extended as a result. For more details, please contact our sales offices.

2-9-5 Ripple Current and Life

The tan δ of an aluminum electrolytic capacitor is larger than other types such as film capacitors, and heat generates inside electrolytic capacitors due to power loss when ripple current is applied. Heat generation effects the life of the capacitor significantly because it causes temperature rise.

1) Ripple Current and Heat Generation

The power loss due to ripple current being applied along with a DC voltage can be calculated by the following formula:

$$W = W_{AC} + W_{DC}$$

$$W = I_{AC}^2 \times Re + V_{DC} \times I_{DC} \quad \cdots\cdots\cdots (2-7)$$

- W : Consumption of electricity by the capacitor (W)
- W_{AC} : Power loss due to ripple current (W)
- W_{DC} : Power loss due to DC (W)
- I_{AC} : Ripple current (A)
- R_e : E.S.R. of the capacitor
- V_{DC} : DC Voltage (V)
- I_{DC} : Leakage Current (A)

If the DC voltage is below the rated voltage, the leakage current will be extremely small and becomes $W_{AC} >> W_{DC}$.
From this, power loss can be calculated by the following formula:

$$W = I_{AC}^2 \times Re \quad \cdots\cdots\cdots (2-8)$$

The temperature of the capacitor rises to a point where the internal heat generation balances with the heat radiation (2-9). The internal temperature rise can be expressed by formula 2-10:

$$I_{AC}^2 \times Re = \beta \times A \times \Delta t \quad \cdots\cdots\cdots (2-9)$$

$$\Delta t = \frac{I_{AC}^2 \times Re}{\beta \times A} \quad \cdots\cdots\cdots (2-10)$$

β : Heat Radiation Constant (10^{-3}W / °C·cm^2)
A : Surface Area (cm^2)

When the size of the capacitor is φD × L :

$$A = \frac{\pi}{4} D(D + 4L) \quad \cdots\cdots\cdots (2-11)$$

The surface area can be calculated from the above equation.
Δt = Temperature rise of ripple (°C)

The relationship between internal resistance "Re," capacitance "C" and tan δ is as follows :

$$Re = \frac{\tan\delta}{\omega C} \quad \cdots\cdots\cdots (2-12)$$

However, according to $\omega = 2\pi f$, ········· (2 - 13)

$$\Delta t = \frac{I_{AC}^2 \times Re}{\beta \times A} = \frac{I_{AC}^2 \times \tan\delta}{\beta \times A \times \omega C}$$

The heat radiation constant (β) and temperature rise multiplier, which is temperature rise ratio calculated by the temperature rise at the surface Δts divided by at the core of element Δtc and is expressed as α, is as shown in Table 2-4.

Table 2-4

Case dia (mm)	5 or less	6.3	8	10	12.5	16	18	20	22	25	30	35	40
β	2.18	2.16	2.13	2.10	2.05	2.00	1.96	1.93	1.88	1.84	1.75	1.66	1.58
α	1.0		0.94	0.90	0.85	0.80	0.77	0.75	0.74	0.71	0.67	0.64	0.62

α :Temperature rise ratio calculated $\alpha = \Delta ts / \Delta tc$

β : Heat radiation constant (10^{-3} W / °C·cm^2)

2) Frequency Coefficient of Allowable Ripple Current

Equivalent series resistance of aluminum electrolytic capacitor (Re) is frequency dependent. Higher the frequency, lower the ESR. Assuming that temperature rise due to ripple current at a frequency of (fx) and at a frequency of (fo) are the same, when (Ro) is ESR at a frequency of (fo) and (Rx) is ESR at a frequency of (fx). The following equation would be set.

$$I_0^2 \times R_0 = I_x^2 \times R_x$$

$$\therefore I_x = \sqrt{\frac{R_0}{R_x}} \times I_0 \quad \cdots\cdots\cdots (2-14)$$

Thus, $\sqrt{R_0/R_x}$ becomes the frequency coefficient Kf.
Table 2-5 shows examples of frequency coefficients.

Table 2-5 Frequency coefficient of allowable ripple current <Example>

・Snap - in terminal type capacitors (For input smoothing circuit)

Frequency (Hz)		50	60	120	300	1k	10k	50k~
Frequency coefficient (Kf)	16~100V	0.88	0.90	1.00	1.07	1.15	1.15	1.15
	160~250V	0.81	0.85	1.00	1.17	1.32	1.45	1.50
	315~450V	0.77	0.82	1.00	1.16	1.30	1.41	1.43

・Lead type capacitors (For output smoothing circuit)

Rated voltage(V)	Frequency (Hz) / Cap.(μF)	50	120	300	1k	10k~
6.3~100V	~56	0.20	0.30	0.50	0.80	1.00
	68~330	0.55	0.65	0.75	0.85	1.00
	390~1000	0.70	0.75	0.80	0.90	1.00
	1200~15000	0.80	0.85	0.90	0.95	1.00

3) Temperature Coefficient of Allowable Ripple Current

The applicable ripple current value below the maximum operating temperature must be limited by specified ripple temperature rise at the center of element per ambient temperature.(Table 2-6.)

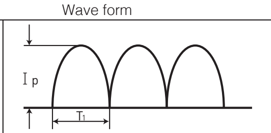
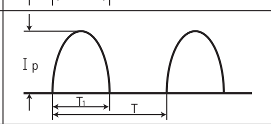
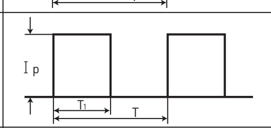
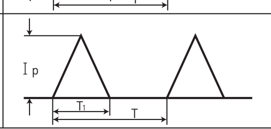
Table 2-6 Limit of element core temperature rise (Over 315 Voltage with Snap-in terminal type capacitors)

Ambient Temperature (°C)	40	55	65	85	105
Δtc (°C)	30	30	25	15	5

4) The method which seeks for effective current value from Ripple current wave form

When a ripple current at high frequency switching is superimposed upon commercial frequency ripple, is applied, such as in switching power supplies, inverter type supplies and active filter circuits, there is a method to obtain the effective value from the waveform pattern in Table 2-7 by finding the similar waveform observed in actuality.

Table 2-7 Current Wave and Caluculation Expression for Effective Value

	Wave form	Formula of effective value
①		$I_{rms} = \frac{I_P}{\sqrt{2}}$
②		$I_{rms} = I_P\sqrt{\frac{T_1}{2T}}$
③		$I_{rms} = I_P\sqrt{\frac{T_1}{T}}$
④		$I_{rms} = I_P\sqrt{\frac{T_1}{3T}}$

Effective ripple value is calculated from the wave form of ripple, which ripple current of high frequency switching (I_H) is superposed upon ripple current of commercial frequency (I_L) (as in Figure 2-17), by dividing it into each frequency component.

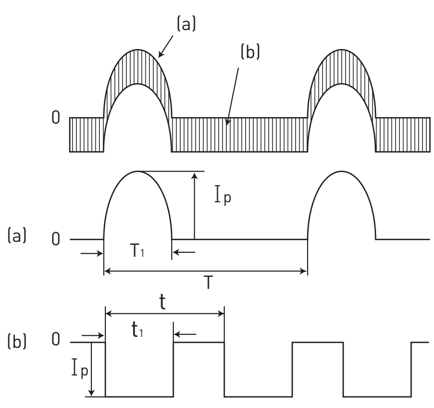


Fig. 2 - 17

Setting Model ② as the ripple current for a low frequency component (I_L):

$$I_L = I_P \times \sqrt{\frac{T_1}{2T}} \quad \cdots\cdots\cdots (2 - 15)$$

Setting Model ③ as the ripple current for a high frequency component (I_H):

$$I_H = I_P \times \sqrt{\frac{t_1}{t}} \quad \cdots\cdots\cdots (2 - 16)$$

The equivalent series resistance of aluminum electrolytic capacitors has frequency characteristics; so if the frequency is different from the standard, it is converted to meet the standard frequency. If the frequency coefficient for low frequency components is labeled as "K_{fL}" and the frequency coefficient for high frequency components labeled as "K_{fH}, " the synthetic ripple "In" converted to the standard frequency is :

$$I_n = \sqrt{\left(\frac{I_L}{K_{fL}}\right)^2 + \left(\frac{I_H}{K_{fH}}\right)^2} \quad \cdots\cdots\cdots (2 - 17)$$

5) Estimating Temperature Rise due to Ripple Current

Since the power loss is proportional to the square of the ripple current, if the rise in temperature at the center of the element when the rated ripple current I_o (A) flows is labeled as Δt_o, the rise in temperature when the ripple current I_n (A) flows, which labeled as Δt_n, can be obtained as 2-18: $\Delta t_n = \left(\frac{I_n}{I_0}\right)^2 \times \Delta t_0$ ········· (2 - 18)

The rise in temperature "Δt_o" for a 105°C snap-in terminal type capacitor is approximately 5°C. Since the equivalent series resistance "R_e" of aluminum electrolytic capacitors differs according to the temperature and because the ripple current waveform is complex and has many frequency components in actuality, we recommend to measure the rise in temperature with thermocouples.

2-9-6 Estimated Life

The estimated life of an aluminum electrolytic capacitor represented multiplying the specified life time on F_T, F_1, and Fu as explained in 2-9-1. Shown below are the formulas for obtaining the expected life for the large can type aluminum electrolytic capacitors and the miniature aluminum electrolytic capacitors. For further details, please consult Nichicon.

(Large can type)

Formula 2-19 is for obtaining the estimated life of a large can type electrolytic capacitor.

For the formula for screw terminal capacitors, please consult Nichicon.

$$L_n = L_o \times 2^{\frac{T_0 - T_n}{10}} \times 2^{1-\frac{\Delta t_n}{K}} \quad \Delta t_n = t_0 \times \left(\frac{I_n}{I_m}\right)^2 \cdots\cdots (2 - 19)$$

L_n : Estimated life (h) at ambient temperature Tn (°C) with a ripple current In (Arms) applied.

L_o : Specified life time (h) at maximum operating temperature To (°C) with rated ripple current Im (Arms)at To (°C) applied

T_o : Maximum operating temperature of the capacitor (°C)
T_n : Ambient temperature of the capacitor (°C)
t_o : The internal temperature rise (°C) of the capacitor at ambient temperature To (°C) with rated ripple current Im (Arms) applied
Δt_n : The internal temperature rise (°C) of the capacitor at ambient temperature Tn (°C) with the actually applied ripple current In (Arms)
K : Acceleration coefficient of temperature rise due to ripple [refer to the chart below (Fig. 2-18); applicable coefficient is for the range below the maximum operating temperature To (°C)]

※ The formula is applicable for the range of ambient temperature Tn of 40°C and the maximum operating temperature To. Note that fifteen years is generally considered to be the maximum for the estimated life obtained by the above formula.

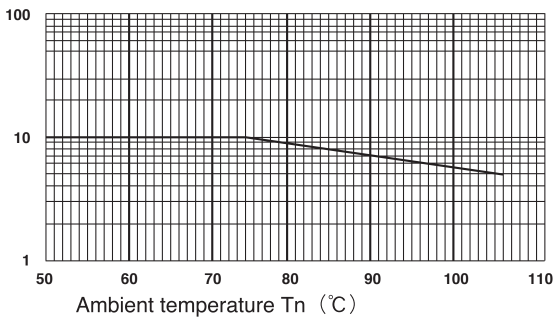


Fig 2-18 Acceleration coefficient of temperature rise due to ripple; K

(Miniature type)
There are two formulas for obtaining the estimated life of a miniature aluminum electrolytic capacitor, depending on the life specification of each series in the Nichicon catalog. These formulas are shown in 2-20 and 2-21.

(1) Capacitors life time is specified with rated DC voltage applied only

$$L_n = L \times 2^{\frac{T_0-T_n}{10}} \times \frac{1}{B_n} \quad \cdots\cdots\cdots \quad (2\text{-}20)$$

$$\text{Where } B_n = 2^{\alpha \times \left(\frac{I_n}{I_m}\right)^2 \times 2^{-\left(\frac{T_0-T_n}{30}\right)}}$$

(2) Capacitors life time is specified with D.C. bias voltage plus rated ripple current.

$$L_n = L_o \times 2^{\frac{T_0-T_n}{10}} \times 2^{\alpha\left\{1-\left(\frac{I_n}{I_m}\right)^2 \times 2^{-\left(\frac{T_0-T_n}{30}\right)}\right\}} \quad \cdots\cdots\cdots \quad (2\text{-}21)$$

(2-20) , (2-21) :

$2^{\frac{T_0-T_n}{10}}$ Tn(℃)≦40 : $2^{\frac{T_0-40}{10}}$

$2^{-\left(\frac{T_0-T_n}{30}\right)}$ Tn(℃)≦50 : $2^{-\left(\frac{T_0-50}{30}\right)}$

L_n : Estimated life time (h) at ambient temperature of Tn (°C) with a ripple current In (Arms) applied.
L : Specified life time (h) at maximum operating temperature T (°C) with the rated DC voltage applied.
L_o : Specified life time (h) at maximum operating temperature T (°C) with rated ripple current Im (Arms) at T (°C) applied.
T_o : Maximum operating temperature of the capacitor (°C)
T_n : Ambient temperature of the capacitor (°C)
I_m : Rated ripple current (Arms) at maximum operating temperature T (°C)
Im need to be valued in the same frequency as that of the ripple current being used by multiplying specified ripple-frequency coefficient in Nichicon catalog.
I_n : Ripple current (Arms) actually applied at ambient temperature Tn (°C)
B_n : Acceleration coefficient when ripple In (Arms) is applied at ambient temperature Tn (°C)
α : Life constant
Please contact us for details regarding the life constant.

The formula is based on life test results at high temperatures. Please note that calculated life time is for reference only and judgement should be done after sufficient testing before using. Typically, fifteen years is generally considered to be the maximum for the estimated life obtained by the above formula.

2-10 Effects of halogen

2-10-1 Foreword

When a halide substance seeps into the aluminum electrolytic capacitor:

The halide dissolves and frees halogen ions.

$RX + H_2O \Rightarrow ROH + H^+ + X^-$

Also, the following reaction (Electricity cauterization reaction) can occur

$AL + 3X^- \Rightarrow ALX_3 + 3e^-$

$ALX_3 + 3H_20 \Rightarrow AL(OH)_3 + 3H^+ + 3X^-$

When this reaction is repeated, the leakage current increases and the pressure relief vent will be activated and may lead to open vent. For this reason, the usage of halogen type cleaning agents or adhesive material and coating material is not recommended. The following explains the recommended conditions for using cleaning agents, adhesive material and coating material. Besides, if the halogen solvent must be used due to the cleaning ability, please refer to section 2-10-3.

2-10-2 Recommended Cleaning Condition

Applicable : Any type, any ratings.

Cleaning Agents : Alcohol solvent based cleaning agent
Isopropyl Alcohol
Water solvent based cleaning agent
• Premium alcohol solvent type
Pine Alpha ST-100S
(Arakawa Chemical Industries, Ltd.)
Sanelek B-12
(SANYO-KASEI)
• Surfactant type
Clean Through 750HS, 750HN, 750K, 750J (Kao Corporation)

Cleaning Conditions: Total cleaning time shall be no greater than 5 minutes by immersion, ultrasonic or other method. (Temperature of the cleaning agent shall be under 60°C.)
After the board cleaning has been completed, the capacitors should be dried using hot air for a minimum of 10 minutes.
If the cleaning solution has infiltrated between the case and the sleeve, the sleeve might soften and swell when the temperature of hot air is too high. Therefore, the temperature of hot air should not exceed the softening temperature (80°C) of the sleeve.
Insufficient dries after water rinse may cause appearance problems, such as sleeve shrinking, bottom-plate bulging.
In addition, a monitoring of the contamination of cleaning agents (electric conductivity, pH, specific gravity, water content, etc.) must be implemented. After the cleaning, do not keep the capacitors in an atmosphere containing the cleaning agent or in an air tight container.
When using jet spray, the sleeve may expand depending on the angle and strength of the spray. Other cleaning method may cause the marking on a capacitor to be erased or blurred.

The use of hydro-chlorofluorocarbon (HCFC) is expected to be banned in the future and Nichicon does not recommend the use of HCFC as a cleaning agent considering its impact on the environment. When it is absolutely necessary to use HCFC, cleaning is possible under the following conditions:

Applicable : Anti-solvent capacitors (listed in the catalogue)
Cleaning Agents : AK-225AES
Cleaning Conditions: Within 5 minutes total cleaning time by immersion, vapor spray, or ultrasonic and such. For SMD and ultra-miniature type, 2 minutes maximum of total cleaning time is required. (Temperature of agent: 40°C or below)

Notes: Monitoring of the contamination of cleaning agents (electric conductivity, pH, specific gravity, water content, etc.) must be implemented.
After cleaning, do not keep the capacitors in an atmosphere containing the cleaning agent or in an air tight container.

Consult Nichicon before using a cleaning method or cleaning agent other than those recommended.

2-10-3 Fixing and Coating Materials

1) Do not use any fixing or coating materials which contain halide substance.
2) Before using fixing or coating materials, remove flux and any contamination which remains in the gap between the end seal and PC board.
3) Please dry the cleaning agent on the PC board before using fixing or coating materials.
4) Do not cover the entire sealing part of the capacitor when using fixing or coating materials.

There are variations of fixing and coating materials, so please contact manufacture or our sales office to make sure the material selected would not cause any problem.

2-10-4 Others

Fumigation

Wooden packaging may be subjected to fumigation by halogen compounds (e.g. methyl bromide) as insect control measures at the time of export. If devices with aluminum electrolytic capacitors or capacitors themselves are directly fumigated or packed with the pallet that is fumigated, the halogen contained in the fumigant may cause corrosion reaction inside capacitors.

2-11 CR Timing Circuit

2-11-1 Foreword

The following shows precautions to be taken when considering usage of the aluminum electrolytic capacitor in a timing circuit and calculating out the timing for maintenance.

2-11-2 Recharge Circuit

The circuit shown in Fig. 2-19 considers the terminal voltage of the capacitor when charging the capacitor C through the resistor R with the power supply voltage V. (At the time of initial t = 0, the charge of the capacitor is set to zero.) With the start of charging, the voltage across the capacitor rises according to 2-22. According to 2-22, the time tn to reach the specified voltage Vn is shown in 2-23.

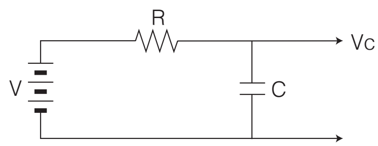


Fig. 2 - 19

$$V_C = V(1 - e^{-\frac{t}{CR}}) \quad \cdots\cdots\cdots (2-22)$$

$$t_n = CR\ln\left(\frac{V}{V - V_n}\right) \quad \cdots\cdots\cdots (2-23)$$

R : Series resistor (Ω)
C : Capacitance (F)
V : Applied voltage (V)

2-11-3 Discharge Circuit

Figure 2-20 shows the situation where capacitor C is discharged with resistance Rd when switch SW is moved toward 2, after it has been charged with applied voltage V by moving switch SW toward 1. The relationship between the terminal voltage Vc (V) and discharge time (t) may be expressed by formula 2-24. The time "tn" needed for the terminal voltage "Vc" (V) of a capacitor to reach voltage "Vn" can be expressed by formula 2-25.

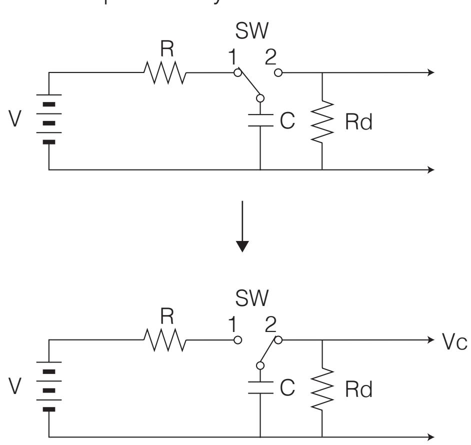


Fig. 2 - 20

$$V_C = V \times e^{-\frac{t}{CR_d}} \quad \cdots\cdots\cdots (2-24)$$

$$t_n = CR_d\ln\left(\frac{V}{V_n}\right) \quad \cdots\cdots\cdots (2-25)$$

Rd : Discharge resistor (Ω)
C : Capacitance (F)
V : Applied voltage (V)

2-11-4 Leakage Current Resistance of Capacitors

When DC voltage is applied, leakage current flows through the capacitors. The leakage current of aluminum electrolytic capacitors is larger than other types of capacitors; Leakage current changes according to the temperature, applied voltage and application time. If considering an equivalent circuit, the leakage current can be thought as the current flows through a resistance which is connected in parallel to a capacitor. Leakage current becomes the power loss when capacitors are charging, and the self-discharge source when capacitors are discharged. It increases the error for the theoretical formulas shown in 2-11-2 and 2-11-3.

The time constant when charging will become larger than theoretical value and the time constant during discharge will become smaller than theoretical value.

It is important to confirm when using an aluminum electrolytic capacitor in a timing circuit, the capacitor meets the necessary requirements within the operating temperature range of the equipment.

2-12 Setting Up Capacitors

2-12-1 Foreword

The aluminum electrolytic capacitor is the most commonly used type of capacitor in a smoothing circuit. The reason is aluminum electrolytic capacitors have higher capacitance/unit volume with lower price/unit capacitance compared to other types of capacitors.

In the electrical component market, surface mount (SMD) types of capacitors are progressing along with the demand for electronic devices to become smaller thinner and lighter, along with higher efficiency, higher frequency, higher reliability, and higher automation. Because PL (Product Liability) has been increased, safety is more important than before. Aluminum electrolytic capacitors that are used in power supplies therefore are required to have the following features: miniature, light in weight, thin, extended life and high reliability, chip type, and safety. The following discusses factors that will help in proficiently using aluminum electrolytic capacitors.

2-12-2 Characteristics of the Aluminum Electrolytic Capacitor Series

(1) Capacitor for input smoothing circuit of a power supply

Capacitors for input smoothing circuit of a power supply are placed after the diodes. They work to smooth the electrical current that is rectified by the diodes and are required to have characteristics such as high ripple, high reliability and safety. Table 2-8 shows the series matrix for Can Type (snap-in terminal type) capacitors.

Table. 2 - 8 Series Matrix for Can type (Snap-in Terminal type) Capacitors

Configuration \ Feature	85°C Type		105°C Type			
	Standard type	Miniature type	Standard type	Miniature type	Long life	Withstanding overvoltage
Standard type	LLS	LLG	LGU, LGN	LGG,LGL, LGM	LGY,LGX, LGR,LGZ	LAK,LAQ, LAS
Low type	–	–	LGJ	LGJ(15)	–	–

The standard type for 105°C capacitors is LGU series; LGN and LGG series are miniature type; LGJ series is recommended for low profile-type applications.; If a higher reliable capacitor is required, LGX series with guaranteed life of 5000 hours and LGY series with guaranteed life of 7000 hours are recommended. LAK and :LAQ series are designed when an overvoltage is applied, the safety vent will operate without causing a short circuit if there is a certain range of overvoltage (no danger of ignition). These series are recommended for information and communication equipment such as facsimile machines and copiers that are used 24 hours a day.

(2) Capacitors for Usage in Output Smoothing Circuit of a Power Supply

Output smoothing capacitors are important for obtaining a stable output voltage. As the power conversion frequency increases, capacitors with low impedance and low equivalent series resistance (ESR) are required in the high frequency range. Furthermore, Surface mount components (SMD) are often used in miniature switching power supplies and DC-DC converters. Table2-9 shows the series matrix for radial lead type capacitors, and Table 2-10 is the series matrix for surface mount devices.

Table. 2 - 9 Series Matrix for Lead type Capacitors

Configuration \ Feature	Standard type	105°C type	125°C or more	Bi-polarized type	Low impedance
11mml or more	UVK, URS	UVY,URZ	UBT,UBW, UBX,UBY	UVP	UPA,UPW, UHW

Table. 2 - 10 Series Matrix for Chip type Capacitors

Configuration \ Feature	Standard type	105°C type	125°C or more	Bi-polarized type	Low impedance	Long life (105°C 5000h)
3.95mml	UZR	UZG	–	–	–	–
4.5mml	UZS	UZT	–	–	–	–
5.5mml	UWX	UWT	–	UWP	UWF, UWG	–
5.8mml or more	UUR	UUT	UUB	UUP	UCD,UCL, UCM,UCV	UUL
Higher capacitance	UUG	UUJ,UCD	UUE,UCH, UCX,UCZ	UUN		UUJ

The standard series for usage in output smoothing circuit of a power supply is UPW series. UPA series is recommended if a low impedance, miniature type is required.

As for surface mount capacitors, UWT series is the standard series; for a capacitor with low height, UZT and UZG series are recommended; UCD series is recommended if a low impedance series is needed; UUX and UUJ series are designed to meet the requirements of a higher voltage and higher capacitance range.

(3) Capacitors for Usage in Control Circuits

Because of the downsizing, high capacity, and high-density mounting of electronic devices, in some cases, failures of capacitors for usage in control circuits may occur due to the rise of ambient temperatures which caused by heat-generating components near the capacitors. Nichicon has designed several capacitors for usage in control circuits, such as: UVY series (miniature type) with a maximum operating temperature of 105°C, Please check our catalogue for more details.

2-12-3 High density mounting and extension of product life

Ambient temperature of capacitors is increasing because of the miniaturization, higher capacity, and higher density mounting of electronic devices. Many of them are operated continuously, which requires characteristics of higher reliability and longer life. The life of an aluminum electrolytic capacitor decreases as the ambient temperature increases. Consider the following to extend the life of aluminum electrolytic capacitors.

①Avoid placing heat-generating components around the capacitor or on the back side of the printed wiring board (under the capacitor).

②Remove as much heat as possible inside the electrical equipment by using a heat radiator fan or other heat dissipation device.

③Make a hole in the housing to lower the temperature inside the electronic device, and arrange it at the proper place so the outside air taken in from the hole cools the capacitor.

④Electronic equipment using a double-sided circuit board may receive high heat from the circuit board pattern if it is mounted close to a power module or heat-generating component. Be careful when using a power supply with large power consumption.

⑤The inside of electronic equipment is hottest near the top. Place the capacitor at the lowest possible position. Take special care for electronic devices that are used upright.

2-12-4 In-rush current and Discharge Resistance

With a capacitor input type power supply, the in-rush current that charges the capacitor flows when the power supply is turned on. The inrush current differs according to the timing of input or the circuit, but it can be several tens of times the steady current. If the in-rush current is repeated only several times a day, there should be no problem. If the input and turn-off is repeated frequently or if the electromagnetic noise that occurs at input causes any interference to the equipment, add inductance or active filter to the circuit on the input side is recommended. In the case of a circuit system that automatically discharges the capacitor when the power is cut off, we recommend a discharge resistance of 1 kΩ or more.

2-12-5 Surface Mount Type Capacitors (Chip type aluminum electrolytic capacitor)

Surface mount parts are replacements for radial leaded parts, chip aluminum electrolytic capacitors are required to have good stability, solder ability and resistance to heat, in order to be reflow soldered onto PC boards. In order to meet such requirements, we convert the lead wiring into a flat lead and have attached a plastic platform that resists high heat; such capacitors are the mainstream in the vertical mount chip-type capacitors.

We are offer a wide range of vertical mount chip-type capacitors in case sizes φ3, 4, 5, 6.3, 8, 10, 12.5, 16 and 18mm, in rated voltages of 4V~500V with capacitance of 0.1~10000μF. Figure 2-21 shows the outward appearance of chip aluminum electrolytic capacitors. For more details, please check Nichicon's catalog

(Example)

φ3~φ10

φ12.5~φ20

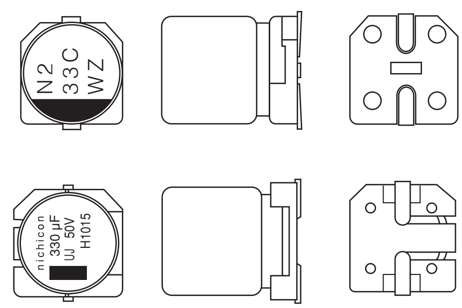


Fig. 2 - 21 Outward appearance of chip aluminum electrolytic capacitors