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 (electrolytic paper), electrolyte, and an aluminum oxide layer, which acts as the dielectric, formed on the anode foil surface.

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

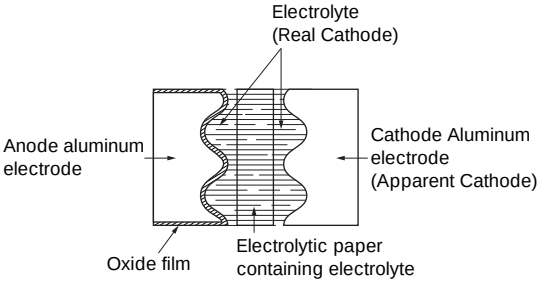


Fig. 1 - 1

Since the oxide layer has rectifying properties, a capacitor has polarity. If both the anode and cathode foils have an oxide layer, the capacitors would be bipolar (non-pola) type capacitor.

These technical notes refer to "non-solid" aluminum electrolytic construction in which the electrolytic paper is impregnated with liquid electrolyte. There is another type of aluminum electrolytic capacitor, which is the "solid" 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 same as for a parallel-plate capacitor.

$$C = 8.855 \times 10^{-8} \frac{\varepsilon S}{d} (\mu F) \quad \cdots\cdots\cdots (1 - 1)$$

ε : Dielectric constant of dielectric
S : Surface area (cm^2) of dielectric
d : Thickness (cm) of dielectric

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

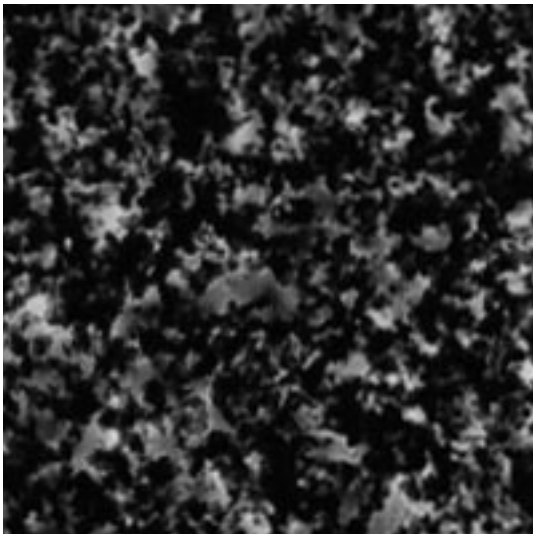
With aluminum electrolytic capacitors, since aluminum oxide dielectric has excellent withstand voltage per thickness. And the thickness of dielectric can be freely controlled according to the rated voltage of the aluminum electrolytic capacitor.
Therefore, in compare to other dielectric, similar voltage endurance is provided by aluminum oxide dielectric even if thickness ("d" in the above formula) is thin.

Furthermore, by etching the surface of aluminum foil, the effective area of the foil as compared to the apparent area can be enlarged 80~100 times for low voltage capacitors and 30~40 times for middle / high voltage capacitors. Therefore, aluminum electrolytic capacitors have a higher capacitance for a specified apparent area than other types of capacitors.

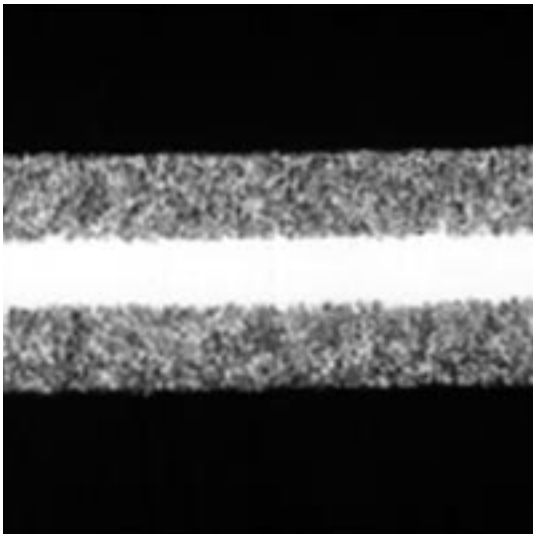
High purity aluminum foil for the anode is etched by electrochemical process in a chloride solution with DC, AC, or an alteration of DC and AC, or a concurring AC and DC current. Fine surface etching (photo 1-1) accomplished mainly by AC electrolysis is generally used for low voltage foil. Tunnel etching (photo 1-2) accomplished mainly by DC electrolysis is used for middle / high voltage foil. The ething 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 (μm)
Aluminum Electrolytic Capacitor	Aluminum Oxide	7~10	(0.0013~0.0015/V)
Tantalum Electrolytic Capacitor	Tantalum Oxide	24	(0.001~0.0015/V)
Film Capacitor (Metallized)	Polyester Film	3.2	0.5~2
Ceramic Capacitor (High Dielectric Constant Type)	Barium Titanate	500~20,000	5
Ceramic Capacitor (Temp. Compensation Type)	Titanium Oxide	15~250	5

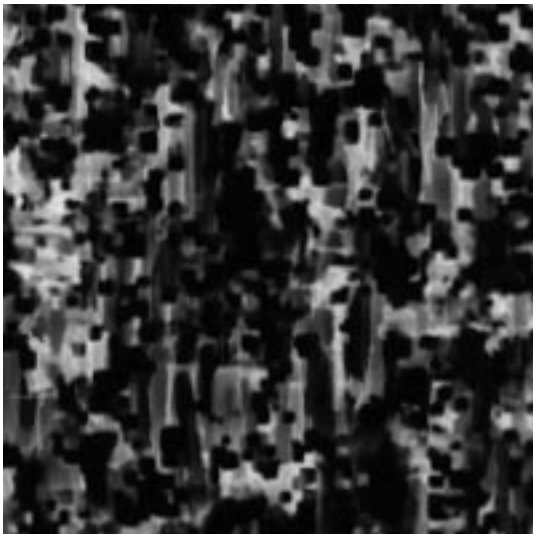


Surface

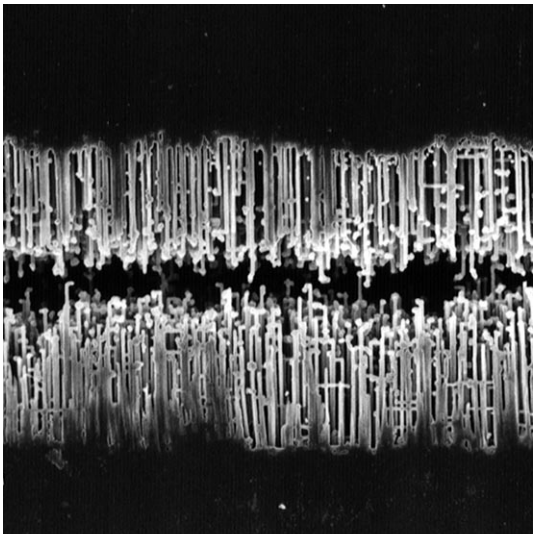


Section

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)

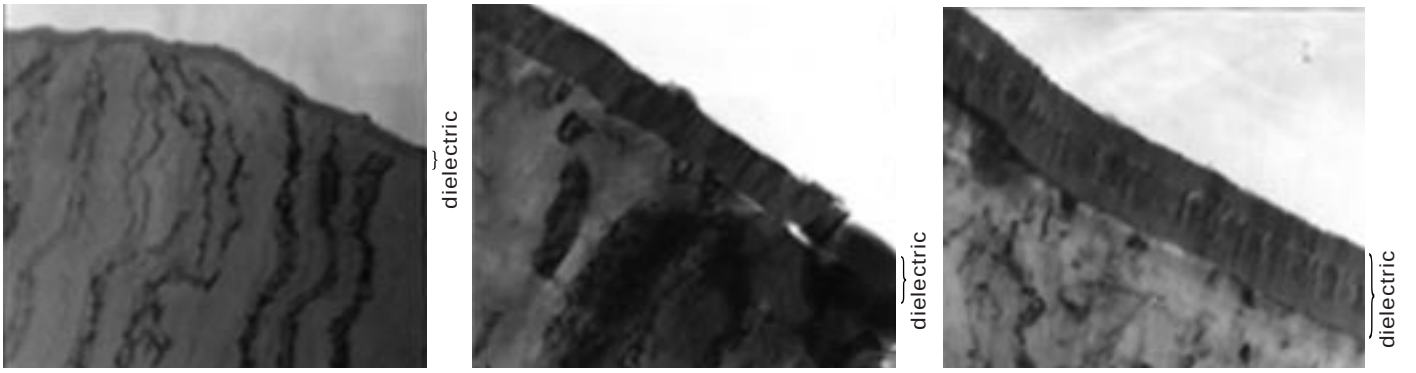
A high purity etched aluminum foil is anodized in a boric acid-ammonium water type solution, for exsample, to form an aluminum oxide layer on its surface. This aluminum oxide layer is what we call the dielectric of the aluminum electrolytic capacitor. The DC voltage that is applied to the foil to oxidize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

The thickness of the dielectric is nearly proportional to the forming voltage and measures approximately 0.0013~0.0015 (μm/ V).

Expanded photography of a dielectric (aluminum oxide layer) on the foil that has not been etched (plain foil) is shown in photo 1-3.

The fabrication reaction of the dielectric can be expressed as follows:

1) $Al^{3+}+6H_2O \rightarrow [Al(OH_2)_6]^{3+}$
2) $[Al(OH_2)_6]^{3+} \rightarrow Al(OH)_3+3H_2O+3H^+$
3) $2Al(OH)_3 \rightarrow Al_2O_3+3H_2O$



20V Fomed 100V Fomed 250V Fomed

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

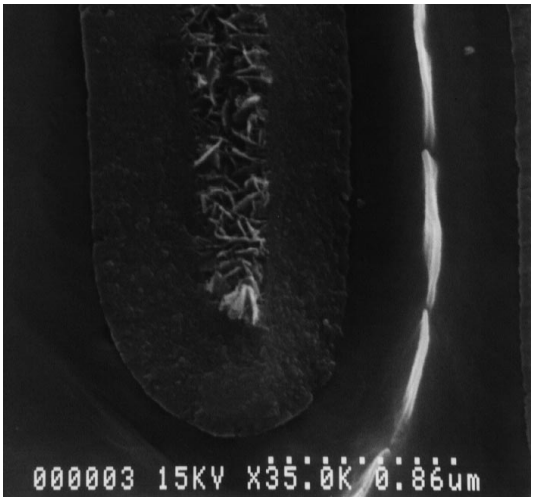


Photo 1-4 Enlarged photo of middle, high voltage formed foil.
(Condition of oxide layer formation in a pit)

1-4 Electrolyte

Anode foil and a cathode foil facing each other are interleaved with electrolytic paper and wound into a cylindrical shape. This is called a "capacitor element." At this stage, it has configuration of a capacitor when considers electrolytic paper and the aluminum oxide layer to be dielectric, however, the unit has few capacitance.

When this capacitor element is impregnated with liquid electrolyte, the anode foil and cathode foil are electrically connected. With the aluminum oxide layer formed on the anode foil acting as the sole dielectric, a capacitor with a high value of capacitance is now attainable. That is to say that the electrolyte is now functioning as a cathode. The basic characteristics required of an electrolyte are listed below:

(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 foil Chloride Pure 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. Pure 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 exsample, to form an aluminum oxide film on the surface of the cathode foil. As for the anode foil, an low DC voltage is sometimes used for formation, but there are also situations where formation is not conducted.
Slitting	Anode foil Cathode foil	A foli is slit into specified widths according to capacitor case sizes.
Winding	Slited foils (anode/cathode) Electrolytic paper Leade Winding aftixing material	Anode and cathode foils interleaved with an electrolytic paper are wound into a cylindrical capacitor element, with leads being connected to both foils.

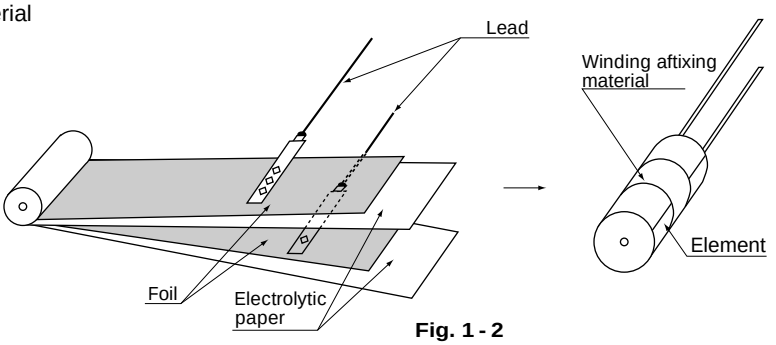


Fig. 1 - 2

Prosess	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. The impregnated element, case and end seal are assmbled.
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.)	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 laminate case products, such as surface mount capacitors.
Aging	Assembled products	DC voltage is applied under high temperature conditions to reform the oxide film.
Processing	Plastic platform Taping material Accessories (Capacitor mounting braket 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 braket, are attached.
Inspection		An inspection based on the standard specification and test requirements is performed to guarantee the quality of products.
Packaging	Packaging materials	
Shipping		

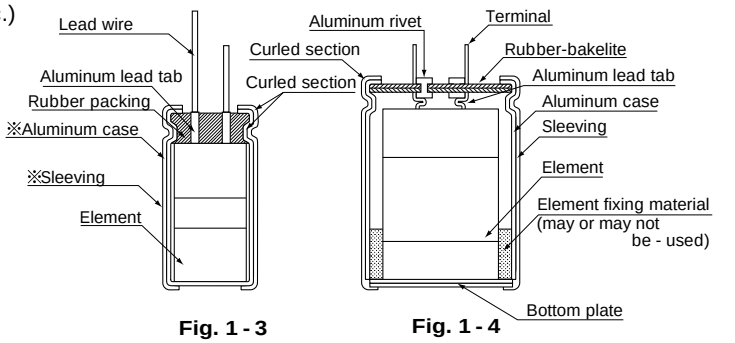


Fig. 1 - 3 **Fig. 1 - 4**

※Nylon laminate casing for laminate products (sleeveless)

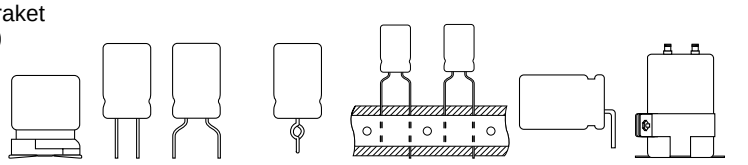


Fig. 1 - 5

1-6 Characteristics

1-6-1 Capacitance

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

$$Ca = 8.855\times10^{-8}\ \frac{\varepsilon S}{d}\ (\mu F)$$

The cathode foil has a capacitance (Cc) that uses the oxide film, which formed by the forming voltage or formed naturally during storage (generally it should be 1V or less), as a dielectric. According to the construction of aluminum electrolytic capacitors, Ca and Cc are connected in a 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); however, 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 Facter (tanδ), Impedance (Z)

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

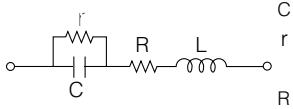
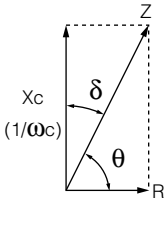


Fig. 1 - 6

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. Therefore, the following formula can be set up.



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

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

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

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

$(\omega = 2\pi f)$

Fig. 1 - 7

The impedance can be expressed by :

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

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.

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.

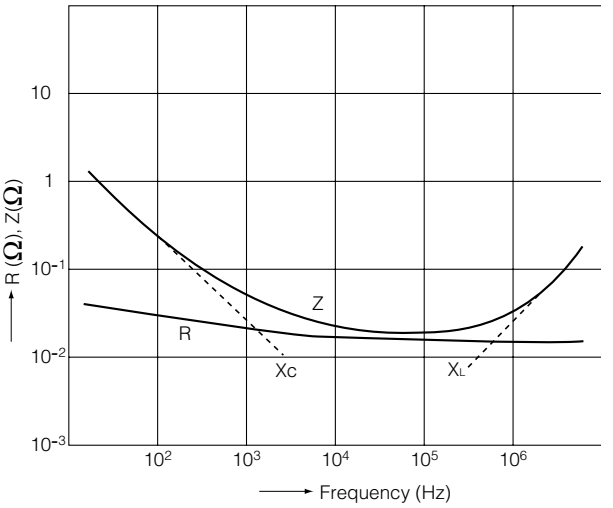


Fig. 1 - 8

1-6-3 Leakage Current

The causes of leakage current in aluminum electrolytic capacitors are listed below :

1)Distorted polarization of dielectric (aluminum oxide layer)
2)Resolution and formation of dielectric
3)Moisture absorption by dielectric
4)Breakdown of 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; however, 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 rather conspicuous temperature characteristics.

Electrical conductivity increases as the temperature increases and reduces as the temperature decreases. Therefore, the electrical characteristics of aluminum electrolytics 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

The 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.

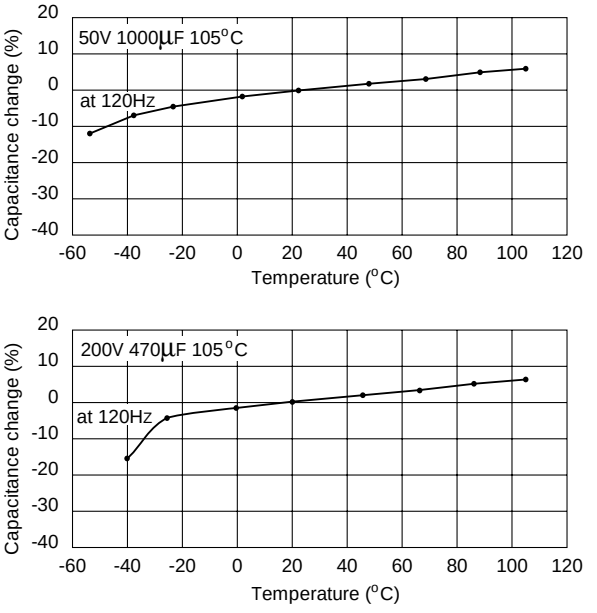


Fig. 1 - 9 Capacitance vs. Temperature Characteristics

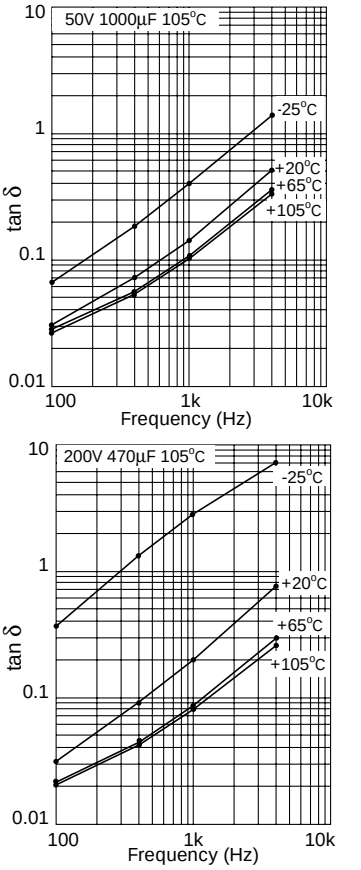


Fig. 1 - 10 Tanδ vs. Frequency Characteristics

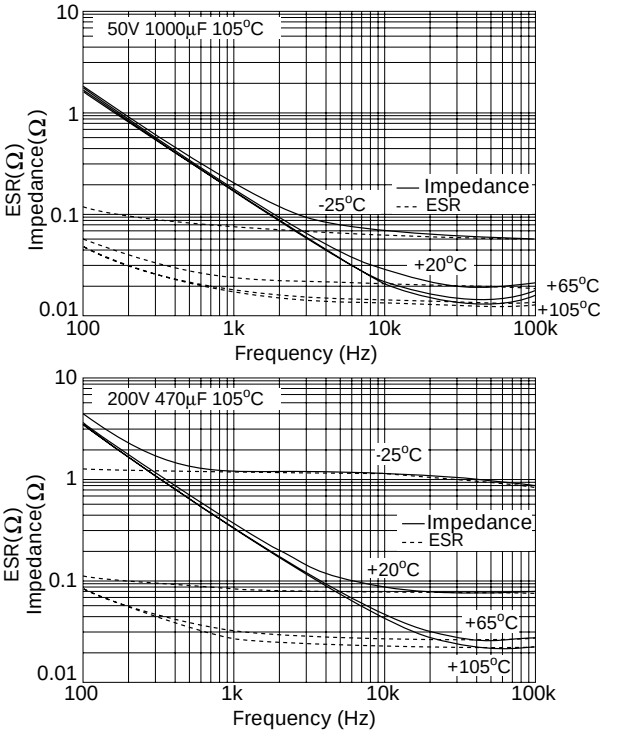


Fig. 1 - 11 Impedance, ESR vs. Frequency Characteristics

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 smaller change of ESR and capacitance with temperature. The quality of performance at low temperatures is particularly 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.

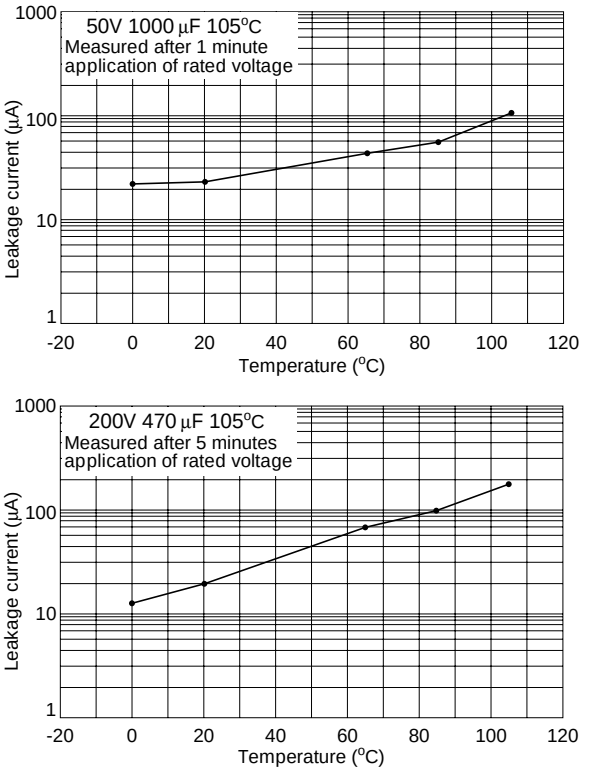


Fig. 1 - 12 Leakage current vs. Temperature Characteristic