to the anode in this case, the oxide layer is not regenerated. The result is that a higher than normal leakage current will flow when a voltage is applied after prolonged storage. As the oxide layer is regenerated in use, however, the leakage current will gradually decrease to its normal level.

Al electrolytic capacitors can be stored voltage-free for at least 1 year after emission of fiscal-bill, and capacitors of the SIKOREL series for as long as 10 years without any loss of reliability. Provided that these storage periods have not been exceeded, the capacitors can be operated at rated voltage directly after being taking out of storage. In this case, reforming as described under 3.7.5 is not required.

When designing application circuits, attention must be paid to the fact that the leakage current may be up to 100 times higher than normal during the first minutes following the application of power.

3.8 Breakdown strength and insulation resistance of insulating sleeves

Most Al electrolytic capacitors made by Icotron are enveloped by an insulating sleeve. The minimum breakdown strenght of the sleeve is 1500 Vac or 2000 Vdc. A test method for verifying the breakdown strength of the sleeves is described in IEC 384-4.

In order to ensure full breakdown strength, care must be taken not to damage the insulating sleeve, especially when ring clips are used for mounting.

The insulation resistance of the sleeve is at least 100 MΩ. IEC 384-4 specifies corresponding test methods.

4 Ripple current considerations

4.1 General

The term ripple current is used for the rms value of the alternating current that flows through the device as a result of any pulsating or ripple voltage. The maximum permissible ripple current value depends on the ambient temperature, the surface area of the capacitor (i.e. heat dissipation area), the dissipation factor *tan* δ (or *ESR*) and on the ac frequency.

As thermal stress has a decisive effect on the capacitor's life expectancy, the dissipation heat generated by the ripple current is an important factor affecting the service life. Diagrams showing the service life as a function of the ambient temperature T_A are given in the individual data sheets (refer to section 5.2 for an explanation on how to use these diagrams).

These thermal considerations imply that, under certain circumstances, it may be necessary to select a capacitor with a higher voltage or capacitance rating than would normally be required by the respective application.

4.2 Frequency dependence of the ripple current

The dissipation factor (which is related to the equivalent series resistance) of Al electrolytic capacitors varies with the frequency of the applied voltage. As a result, the ripple current is also a function of the frequency. In the individual data sheets, the ripple current capability of the capacitors is generally referred to a frequency of 120 Hz, in some cases 100 Hz or 10 kHz. Conversion factors for other operating frequencies are given for each type in the form of a graph.

4.3 Temperature dependence of the ripple current

In some cases the data sheets specify the maximum permissible ripple current for ambient temperatures of 40 °C as well as for the upper category temperature for each capacitor type. For some types with category temperature above 85 °C, the ripple current ratings for 85 °C have also been included for the purpose of comparison.

The data sheets for each capacitor type also include a diagram showing the limit values for continuous operation at other ambient temperatures and ripple currents. This diagram also permits the expected service life to be estimated for given operating conditions.

4.4 Operation at non-clearly defined currents and frequencies

If the load on the capacitor cannot be clearly defined, measures must be taken to ensure that the surface temperature of the case does not exceed the sum of the category temperature and the permissible overtemperature (see table) at any point.

IEC 384-4 specifies the following permissible surface overtemperatures Δ*T* (self-heating, difference between surface temperature of the capacitor and the ambient temperature):

	Upper category temperature °C	Ambient temperature in °C									
		40	50	60	70	80	85	95	105	115	125
		Permissible overtemperature Δ*T* in K									
LL grade	85	10	9	7	5	4	3	-	-	-	-
	125	10	10	10	9	8	7	6	5	4	3
GP grade	85	15	12	10	7	4	3	-	-	-	-

5 Service Life

Service life (also termed useful life or operational life) is defined as the life achieved by the capacitor without exceeding a specified failure rate. Total failure or failure due parametric variation is considered to constitute the end of the service life (see also paragraph 4 of chapter "Quality Assurance").

Depending on the circuit design, device failure due to parametric variation does not necessarily imply equipment failure. This means that the actual life of a capacitor may be longer than the specified service life. Data on service life have been obtained from experience gained in the field and from accelerated tests.

The service life can be prolonged by operating the capacitor at loads below the rating values (e.g. lower operating voltage, current or ambient temperature) and by appropriate cooling measures. In addition to the standard type series, Icotron is able to offer types with service life ratings especially matched to customer specifications.

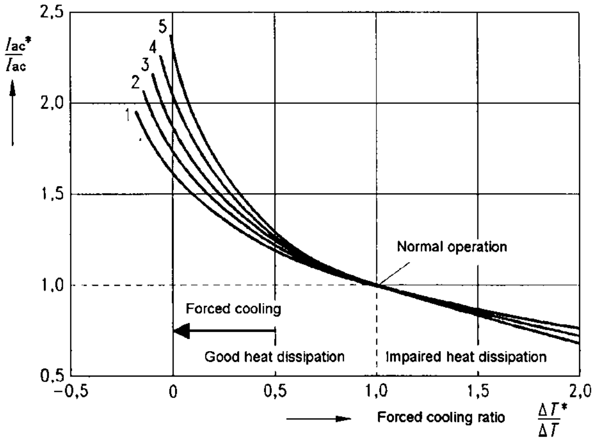
5.1 Cooling

The service life values stated in these data sheets apply to Al electrolytic capacitors with natural cooling, i.e. the heat generated in the winding is dissipated through the casing and by natural convection. It is possible to increase the permissible ripple current and/or prolong the service life by using additional cooling by heat sinks, water or forced ventilation. Conversely, impaired cooling (e.g. due to closely packed capacitor banks, thermally insulating sealing and vacuum) will reduce the service life.

In order to lower the thermal resistance between winding and case, can-type capacitors produced by Icotron have a thermal bridge between the capacitor winding and the base. As a large amount of heat is dissipated through the base of the case, the use of a heat sink connected to the capacitor base is the most efficient cooling method.

Only the thermal resistance between the case and the surrounding air, which is greater than the thermal resistance between the capacitor winding and the case if forced cooling is not used, can be influenced by the mounting location. The thermal resistance is proportional to the temperature difference ΔT. The user can measure this temperature difference ($T_{case} - T_A$) under normal conditions and under forced-air conditions (ΔT^*) and constant ripple current load conditions, and then calculate the relative reduction or increase of the thermal resistance from the forced cooling ratio $\Delta T^*/\Delta T$. In turn, the forced cooling ratio can be used to determine the ripple current factor Iac^*/Iac. The latter is a measure of how much the ripple current load can be increased without reducing the service life if forced cooling is used.

The diagram below (figure 16) shows the effect of the forced cooling ratio, as determined by measurement, on the ripple current factor Iac^*/Iac for various case sizes. In this diagram, the service life of the capacitor with forced cooling (ripple current load: Iac^*) has been equated to the service life rating of the Al electrolytic capacitor under normal operating conditions (ripple current load: Iac).



Dimensions $d \times l$ (mm)

1 75 x 220
2 75 x 145
3 50 x 105
4 35 x 80
5 18 x 31,5

Figure 16

Effect of forced cooling on the ripple current capability

ΔT Temperature difference $\Delta T = T_{case} - T_A$
Iac Permissible ripple current under normal conditions (natural convection cooling)
* Values for forced cooling

The following table gives typical values for the forced cooling ratios that can be achieved by forced convection with the respective air velocities.

Air velocity, approximate m/s	Forced cooling ratio $\Delta T^*/\Delta T$
0,5	0,55
1,0	0,45
1,5	0,39
2,0	0,35

Conversely, the ripple current capability Iac^* of Al electrolytic capacitors with impaired heat dissipation is lower than the rated value Iac.

If a cooling fluid (e.g. water or oil) colder than the ambient temperature is used, the forced cooling ratio may be reduced to zero or may even attain negative values. Due to the limited thermal capacity of these media, the linear laws assumed for the use of pure thermal resistances no longer apply. In such cases the forced cooling ratio is also a function of the power dissipated in the capacitor itself.
If such cooling measures are to be used, the maximum possible thermal load must be calculated. This is not necessary if only heat sinks and forced convection are used.

If the base of the capacitor is kept at a constant temperature by specific cooling measures, the current can be increased by the factors shown in the table below. To determine the corresponding service life, replace the ambient temperature in the service life graphs by the respective capacitor base temperature.

Capacitor length (mm)	Capacitor diameter (mm)			
	35	50	65	75
55	2,5			
80	1,9	2,1	2,3	
105	1,6	1,8	2,0	2,1
145		1,5	1,6	1,7
220				1,3

5.2 Service life calculation

The tables in the individual data sheets list the rated ripple current for the upper category temperature (UCT = + 85 °C, + 105 °C or + 125 °C) and for a frequency of 120 Hz (in some cases 100 Hz or 10 kHz). The service life for known ripple current loads and ambient temperatures is determined on the basis of the service life graphs as follows:

Determine the quotient $\frac{Iac}{Iac_{R,\,UC}}$ of the required ripple current at the given ambient temperature and the rated ripple current at the upper category temperature. The corresponding service life value is given by the curve passing through the respective ambient temperature and the current quotient co-ordinates, or it can be interpolated if none of the service life curves passes directly though these co-ordinates.

The frequency dependence of the ripple current has not been taken into account in the procedure described above. This must be introduced into the calculation in the form of an additional factor. The following table provides guide values for such factors. For more precise values, consult the characteristic curves shown in the individual data sheets.

Frequency f (Hz)	50/60	100/120	400	800	1000	≥ 2000
Conversion factor (guide value)	0,8	1,0	1,2	1,3	1,35	1,4

The following examples illustrate the calculation procedure, using the data of a capacitor of the B43503 series. For this type series, the upper category temperature is + 105 °C. As an example, a capacitor with the following ratings has been selected from the data sheets:

V_R Vdc	C_R µF	Case dimensions $d \times l$ mm	ESR_{typ} 100 Hz 20 °C mΩ	ESR_{max} 100 Hz 20 °C mΩ	Z_{max} 10 kHz 20 °C mΩ	Iac_{max} 100Hz 40 °C A	Iac_{max} 100Hz 85 °C A	Iac_R 100Hz 105 °C A	Ordering code Short code
400	470	35 x 50	250	630	300	5,4	3,6	1,8	-A477-M90

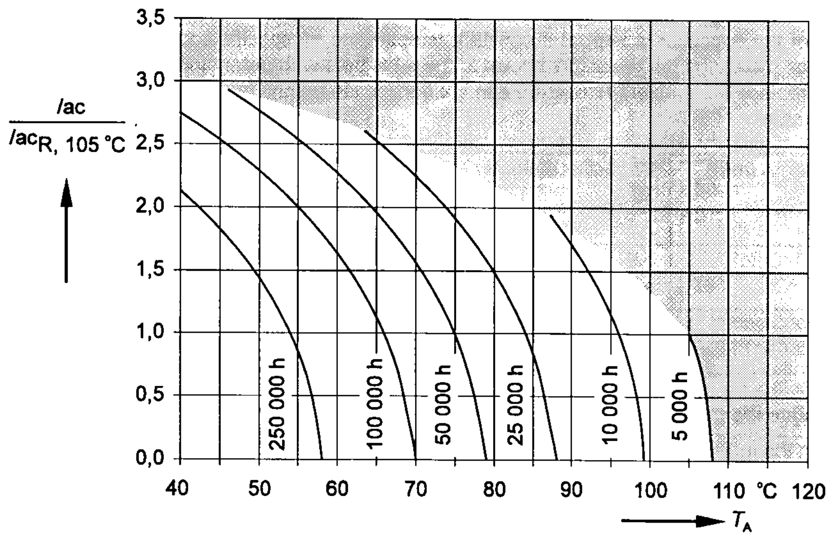


Figure 17

Service life plotted versus ambient temperature T_A under ripple current operating conditions, B43503 series.

Example 1 - Calculating the service life

The following values have been determined for capacitors to be used in a power supply. The corresponding service life is to be calculated.

Ripple current	4,9	A
Frequency	400	Hz
Ambient temperature	50	°C

The equivalent ripple current for 100 Hz is calculated using the frequency-dependence conversion factor (see page 32):

$$\frac{4{,}9\ A}{1{,}2} = 4{,}08\ A$$

The ripple current factor is then calculated using the resulting equivalent 100 Hz ripple current.

$$\frac{Iac}{Iac_{R,\ 105\ °C}} = \frac{4{,}08\ A}{1{,}8\ A} = 2{,}27$$

The service life curve passing through the co-ordinates for the ripple current factor (2,27) and the ambient temperature (50 °C) indicates the service life that can be expected:

100 000 h.

Example 2 - Determining the maximum permissible ambient temperature

The operating conditions listed below have been defined for an industrial application. The maximum permissible ambient temperature is to be calculated:

Operating voltage	340	Vdc
Total ripple current	8,64	A
Frequency	50	Hz
Service life	100 000	h

There are several methods of solving this problem:

First, the equivalent 100 Hz current value is determined (conversion factors given on page 32):

$$\frac{8{,}64}{0{,}8} = 10{,}8\ A$$

The number of capacitors required is then determined for the respective ambient temperature by projecting the values along the 100 000 h curve:

$\frac{Iac}{Iac_{R,\ 105\ °C}}$	Circuit	Ambient temperature
2,75	3 parallel	40 °C
2,0	3 parallel	55 °C
0,5	12 parallel	68 °C

Further value combinations can be determined in the same way.

Example 3 - Checking the ripple current load on an aluminum electrolytic capacitor

In many applications, Al electrolytic capacitors are subjected to ripple currents of varying frequency.

The equivalent total ripple current load shall be calculated for the following given rms values:

Current 1: Iac_{rms} at 400 Hz	2,0	A
Current 2: Iac_{rms} at 4 kHz	3,5	A
Ambient temperature	55	°C
Required service life	125 000	h

The first step is to calculate the equivalent 100 Hz values for the two current values (frequency-dependence conversion factors given on page 32) and the root-mean-square value of the two equivalent values:

$$\text{Current } I_1: \frac{2,0}{1,2} = 1,67 \text{ A at 100 Hz}$$

$$\text{Current } I_2: \frac{3,5}{1,4} = 2,5 \text{ A at 100 Hz}$$

$$I_{\text{total rms}} = \sqrt{I_1^2 + I_2^2}$$

$$I_{\text{total rms}} = \sqrt{(1,67\text{ A})^2 + (2,5\text{ A})^2} = 3,0\text{ A}$$

The ripple current factor can then be calculated:

$$\frac{Iac}{Iac_{R,\ 105\,°C}} = \frac{3,0}{1,8} = 1,67$$

The service life curve that coincides with the respective coordinates, 1,67 on the Y-axis (ripple current factor) and 55 °C on the X-axis (ambient temperature) indicates a **service life of > 125 000 h.** So, the required service life is thus achieved.

6 Climatic stress

Limits must be set for the climatic conditions to which electrolytic capacitors are subjected (in part for reasons of reliability and in part due to the variation of the electrical parameters with temperature). It is therefore important to observe the permissible minimum and maximum temperatures and the humidity conditions stated in coded form as IEC climatic category (see paragraph 6.4). The IEC categories are given for each type in the corresponding data sheet.

6.1 Maximum permissible operating temperature (upper category temperature)

The upper category temperature is the maximum permissible ambient temperature at which a capacitor may be continuously operated. It depends on the capacitor design and is stated in the respective IEC climatic category. If this limit is exceeded the capacitor may fail prematurely.

For some type series, however, operation at temperature above the UCT is permissible for short periods of time. Details are given in the individual data sheets.

Service life and reliability depend to a large extent on the capacitor's temperature. Operation at the lowest possible temperature will increase both service life and reliability and is therefore recommended. For the same reason, it is advisable to select the coolest possible position within the equipment as a location for aluminum electrolytic capacitors.

6.2 Minimum permissible operating temperature (lower category temperature)

The conductivity of the electrolyte diminishes with decreasing temperature, causing an increase in electrolyte resistance. This, in turn, leads to increasing impedances and dissipation factors (or equivalent series resistances). For most applications, these increases are only permissible up to a certain maximum value. Therefore, minimum permissible operating temperatures are specified for Al electrolytic capacitors. These temperature limits are designated "lower category temperature" and are also part of the IEC climatic category.

It should be emphasized that operation below this temperature limit will not damage the capacitor. Especially when a ripple current flows through the device, the heat dissipated by the increased equivalent series resistance will raise the capacitor temperature so far above the ambient temperature that the capacitance will be adequate to maintain equipment operation.

6.3 Storage temperature

Al electrolytic capacitors can be stored voltage-free at temperatures up to the upper category temperature. (see paragraph 3.7.6 "Leakage current behavior after voltage-free storage" .)

However, it must be taken into account that storage at elevated temperatures will reduce leakage current stability, service life and reliability. In order not to impair these qualities unnecessarily, the storage temperature should not exceed + 40 °C and should preferably be below + 25 °C.

The standards for Al electrolytic capacitors specify a lower storage temperature that corresponds to the lower category temperature. Al electrolytic capacitors by Icotron withstand the lowest specified storage temperature, i.e. - 65 °C, without being damaged.

6.4 IEC climatic category

The permissible climatic stress on an Al electrolytic capacitor is given by the respective IEC climatic category. In accordance with IEC 68-1, the climatic category comprises 3 groups of numbers, separated by slashes.

1st group: Lower category temperature (limit temperature) denoting the test temperature for test A (cold) in accordance with IEC 68-2-1

2nd group: Upper category temperature (limit temperature) denoting the test temperature for test B (dry heat) in accordance with IEC 68-2-2

3rd group: Number of days denoting the duration of test Ca (damp heat, steady state) at 93 +2/-3 % relative humidity and 40 °C ambient temperature, in accordance with IEC 68-2-3