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White Paper

Uprating of Electrolytic Capacitors

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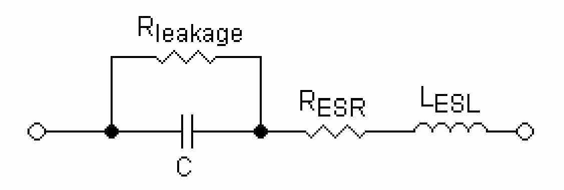
Uprating of Electrolytic Capacitors

Aluminum electrolytic capacitors are comprised of two aluminum foils, a cathode and an anode, rolled together with an electrolyte-soaked paper spacer in between. An oxide film is grown on the anode to create the dielectric. Aluminum electrolytic capacitors are primarily used to filter low-frequency electrical signals, primarily in power designs.

The critical functional parameters for aluminum electrolytic capacitors are defined as capacitance (C), leakage current (LC), equivalent series resistance (ESR), impedance (Z), and dissipation factor (DF). These five parameters are interrelated through the following schematic.



Physically, leakage current (LC) tends to be primarily driven by the behavior of the dielectric. ESR is primarily driven by the behavior of the electrolyte. Physically, impedance (Z) is a summation of all the resistances throughout the capacitor, including resistances due to packaging. Electrically, Z is the summation of ESR and either the capacitive reactance (XC), at low frequency, or the inductance (LESL), at high frequency (see Figure 1). Dissipation factor is the ratio of ESR over XC. Therefore, a low ESR tends to give a low impedance and a low dissipation factor.

1.1 Functional Parameters (Specified in Datasheet)

The functional parameters that can be provided in manufacturers' datasheets are listed below

Parameter	Example
Temp.	-55 to 105C
C	±20% @ 20C
LC	0.01CV / 3 µA
ESR	N/A
Z	3X at -40C
DF	0.08 at 20C

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1.1.1 Capacitance vs. Temperature

It can be seen that the manufacturer's guarantee of ±20% stability of the capacitance is only relevant at room temperature. While a source of potential concern when operating aluminum electrolytic capacitors over an extended temperature range, previous research has demonstrated that the capacitance of this capacitor is extremely stable as a function of temperature (see Figure 2 and Figure 4). So long as the electrolyte is not near the liquidus or solidus temperatures, the capacitance would not be expected to vary by more than ±20% from room temperature.

As seen in Figure 5, DfR has found that there is often a significant margin between rated temperature and the boiling point of the electrolyte. As a general rule of thumb, capacitors rated at 85C tend have liquidus temperatures close to 125 - 135C and capacitors rated to 105C tend to have liquidus temperatures closer to 180 - 205C.

1.1.2 Leakage Current vs. Temperature

As stated above, leakage current is primarily driven by the behavior of the aluminum oxide dielectric. As set temperature was not specified, the datasheet value for leakage current can be interpreted that the manufacturer guarantees this maximum leakage current over the specified temperature range. As a general statement, leakage current tends to be stable at low temperatures and will increase by orders of magnitude at higher temperatures (see Figure 6).

However, since the manufacturer has guaranteed leakage current behavior of the temperature range of interest, these behaviors should not be a concern in the use of this part over -40 to 85C. There is a risk that a designer will focus on the absolute value of 3 µA and will fail to realize that at the higher ambient temperatures the leakage current could reach 100 µA and still be within specification.

1.1.3 ESR vs. Temperature

Manufacturers of aluminum electrolytic capacitors do not provide an ESR value in their datasheet nor do they specify the maximum variation in ESR over the specified temperature range. This is somewhat discerning as it is well known that ESR can be very sensitive to temperatures. At high temperatures, ESR can decrease by approximately one-third to one-half. Since a reduced ESR leads to improved performance, a lower ESR is rarely a concern for electrical designers. On the cold side, ESR can increase by orders of magnitude as the electrolyte approaches the solidus temperature (see Figure 7 and Figure 8).

However, the behavior of impedance and dissipation factor, which are directly influenced by ESR, are greater drivers for circuit design and circuit performance. Therefore, the primary focus in regards to the influence of temperature will be on the behaviors of these two ESR-derived parameters.

1.1.4 Impedance vs. Temperature

The impedance behavior at cold temperatures is clearly stated in the manufacturer's data sheet. As the expected use environment is not expected to be lower than -40C, this parameter is clearly defined. More specifically, as shown in Figure 9, the primary sensitivity to temperature is the high frequency behavior. Impedance at the standard frequencies of 50/60 Hz and 120 Hz is relatively constant over the range of temperatures.

1.1.5 Dissipation Factor vs. Temperature

Dissipation factor behaves in a very similar manner to impedance as a function of temperature. DF at low frequencies varies little with temperature. However, at higher frequencies, dissipation factor can increase by orders of magnitude when exposed to cold temperatures. This may be the parameter of most concern as the maximum DF at cold temperatures is not specified in the manufacturer's data sheet. As can be seen in Figure 10, the relative rise in DF at cold temperatures can vary from manufacturer to manufacturer.

1.2 Functional Parameters (Not Specified in Datasheet)

All functional parameters are specified within the manufacturer's datasheet

1.3 Electrical Overstress[1] (Robustness)

Aluminum electrolytic capacitors can experience electrical overstress type failure mechanisms through the application of excessive voltage or excessive ripple current.

1.3.1 Voltage Rating

The capacitor manufacturers do not provide any indication on the variation on breakdown strength as a function of temperature. However, two activities by the manufacturer tend to limit any concern about change in the voltage rating. First, the manufacturer applies an overvoltage to form the dielectric. This overvoltage can be anywhere from 135 to 200% of the rated voltage. Second, the industry standard life tests require testing at rated voltage and maximum rated temperature. Therefore, the design of the capacitor has been demonstrated to be robust to dielectric breakdown to the extremes of the manufacturer's ratings.

1.3.2 Ripple Current Rating

The maximum ripple current specified by the manufacturer is sensitive to temperature. The manufacturer allows for this by providing a ripple current rating at the maximum rated temperature (105C). At lower temperature, the capacitor is able to handle a larger amount of ripple current as the primarily influence of ripple is the increase in the core temperature of the electrolytic capacitor. Even at low temperatures, where the increase in ESR would result in an increase the equivalent temperature rise, the behavior is somewhat fail safe as the temperature rise would trigger a decrease in ESR.

1.4 Wearout Behavior

The wearout behavior of electrolytic capacitors, evaporation of the electrolyte, is well known. The industry standard wearout model assumes a doubling of life for every 10C rise in temperature. The capacitor manufacturers therefore provide a guaranteed lifetime (1000 hours) at a given temperature (105C) and expect the user to extrapolate to field conditions using the industry standard formula.

For an outdoor environment, a realistic worst-case ambient condition within the United States is defined by diurnal cycling experienced by Phoenix, AZ. This temperature cycle has been simplified by DfR Solutions and is provided in Table 1. Based on this environment and the assumption of a 10ºC temperature rise during the day due to indirect heating from sun exposure, lifetime for electrolytic capacitors can be calculated using the industry-standard formula of doubling of life for every 10ºC drop in ambient temperatures. The results for a 105ºC / 1000 hours rated electrolytic capacitor exposed to this environment are displayed in Table 2. The influence of an additional 10ºC rise in temperature due to power dissipation of adjacent components is displayed in Table 3.

[1] Mechanical overstress mechanisms are relatively independent of temperature

Other formulas have been developed to predict the increase in ESR over time as a function of temperature. One such formula is provided below and displayed in Figure 11

$$\frac{1}{ESR(t)} = \frac{1}{ESR(0)}\left[1 - kt\exp\left(-\frac{4\,700}{T}\right)\right]$$

where the constant k is calculated by the least squares method to fit the experimental points (k = 58). Cornell Dublier also has a model for predicting ESR degradation over time. As a general rule, the electrical designer should always assume that the ESR will increase by 100% by the end of the desired design life. Adding this change to the potential changes at low temperatures, the designer should assume that the ESR could increase by 10 to 15X over initial room temperature readings given the time in the field and the variation in temperature.

1.5 Conclusion

The primary risk in using these electrolytic capacitors beyond their specifications have been identified as the following

- Dissipation factor at low temperature is poorly defined by manufacturer’s data sheets. Some characterization may be appropriate.
- Under severe conditions consisting of a Phoenix environment with sufficient temperature rise on the board, electrolytic capacitors could degrade within 10 years.

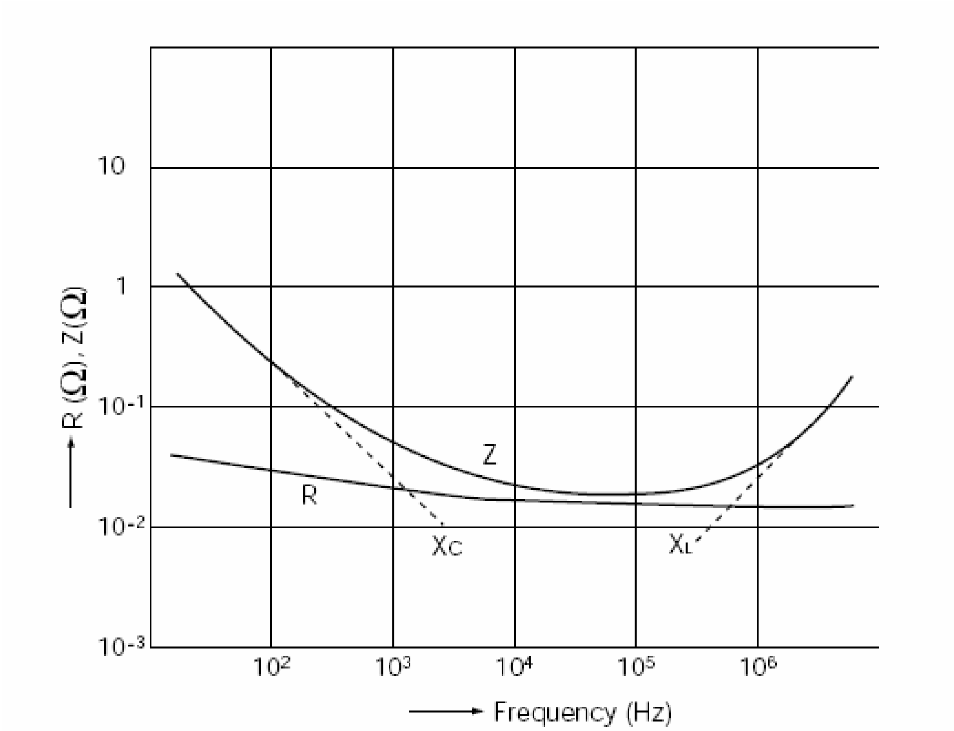

Figure 1: Change in ESR, impedance, and inductance as a function of frequency

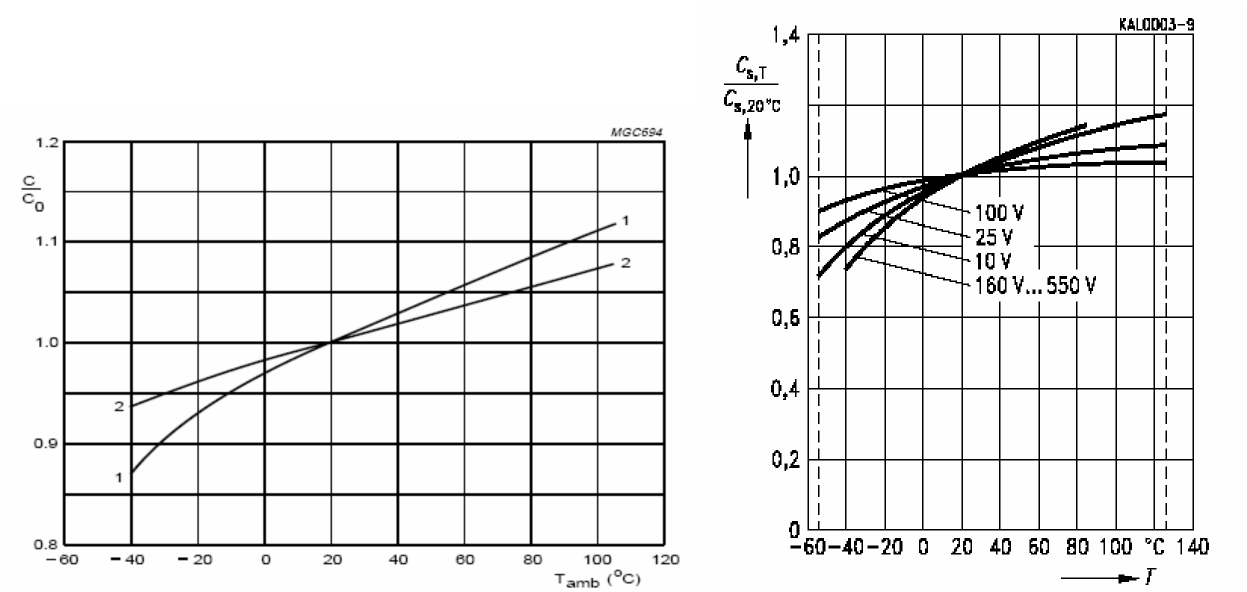

Figure 2: Change in capacitance as a function of temperature (Left: BC Components; Right: Epcos)

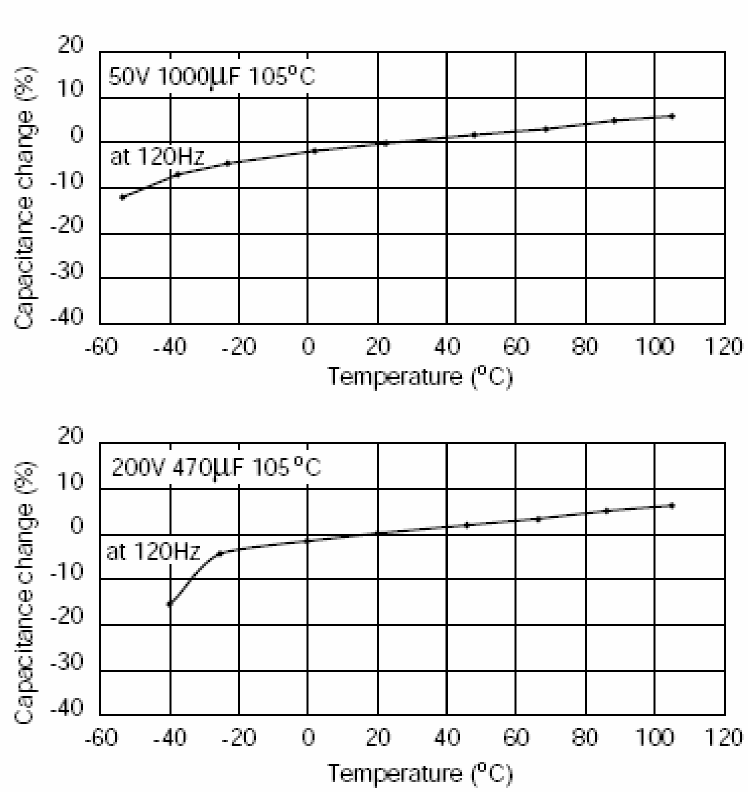

Figure 3: Change in capacitance as a function of temperature (Nichicon)

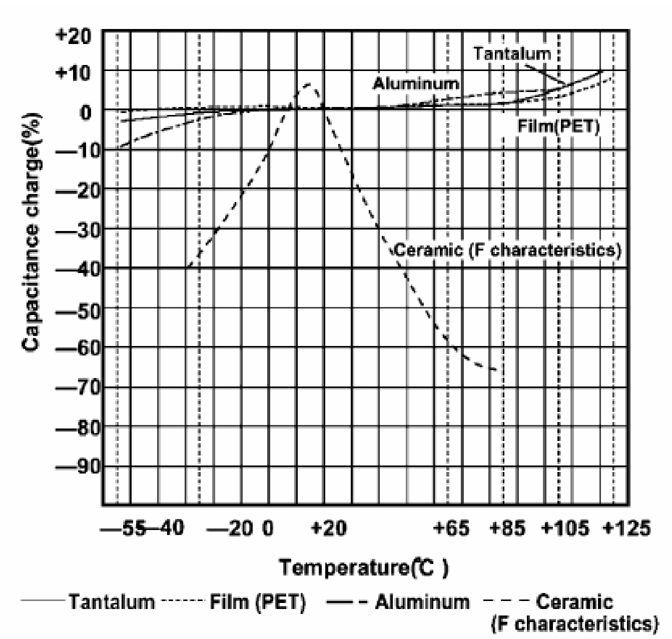

Figure 4: Capacitance variation with temperature for different types of capacitors
(A. Dehbi et al. / Microelectronics Reliability 42 (2002) 835–840).

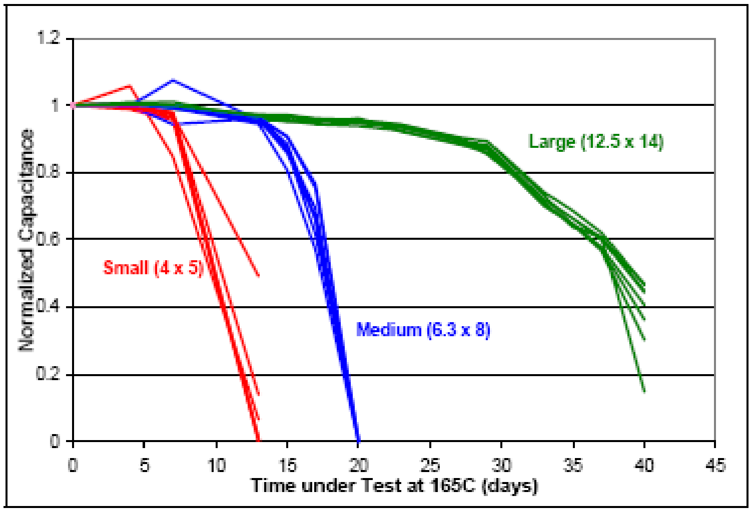

Figure 5: Capacitance degradation over time at temperatures above rated

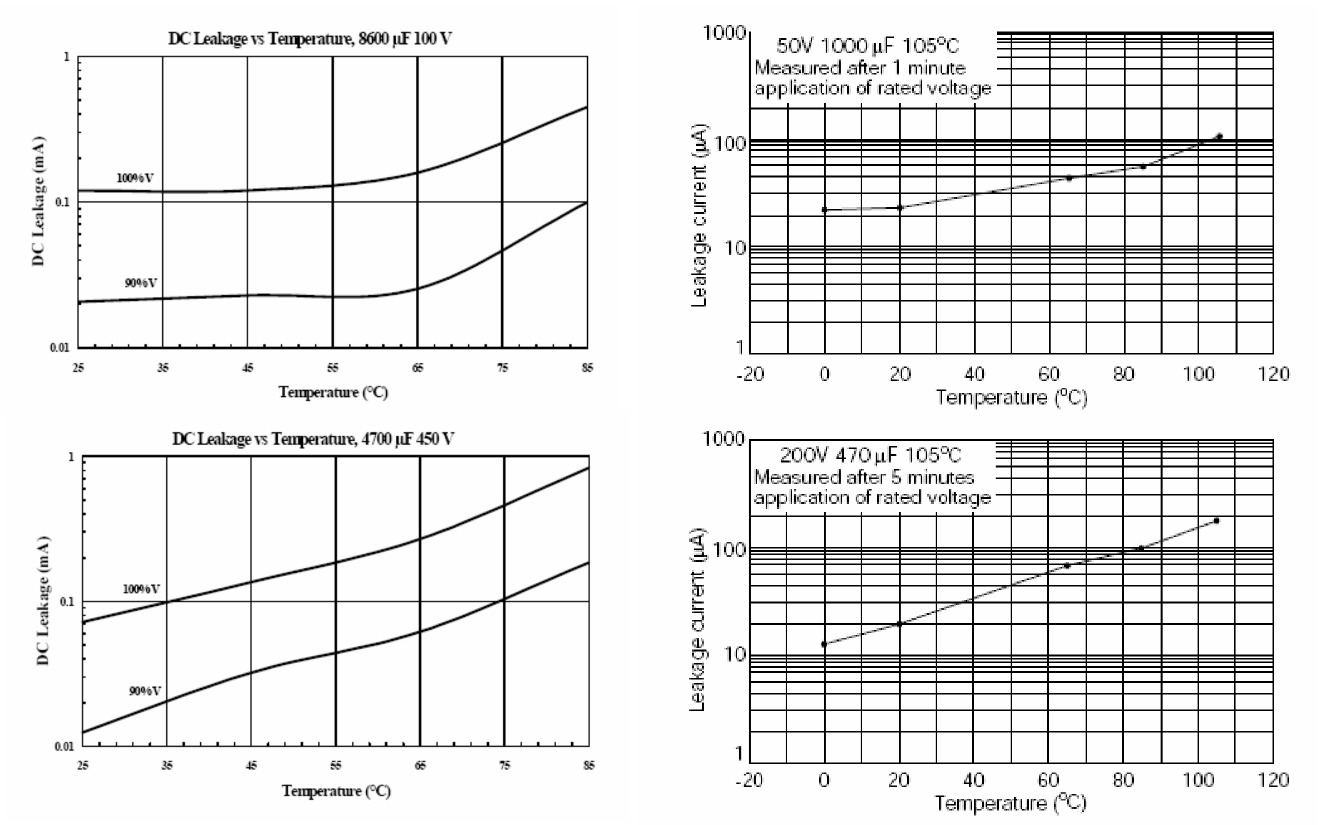

Figure 6: Change in leakage current as a function of temperature (Left: EPCOS; Right: Nichicon)

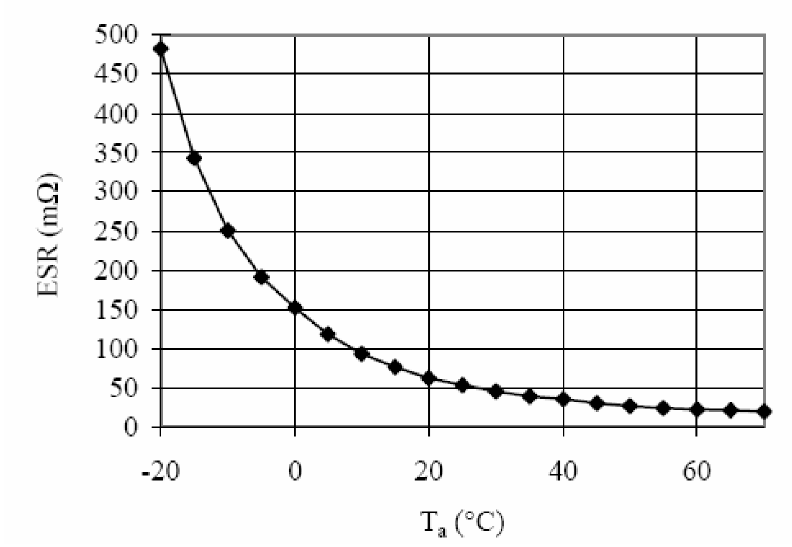

Figure 7: Change in ESR as a function of temperature (Eur. Phys. J. AP 5, 71{83 (1999), Influence of aging on electrolytic capacitors function in static converters: Fault prediction method, P. Veneta, A. Lahyani, G. Grellet, and A. Ah-Jaco}

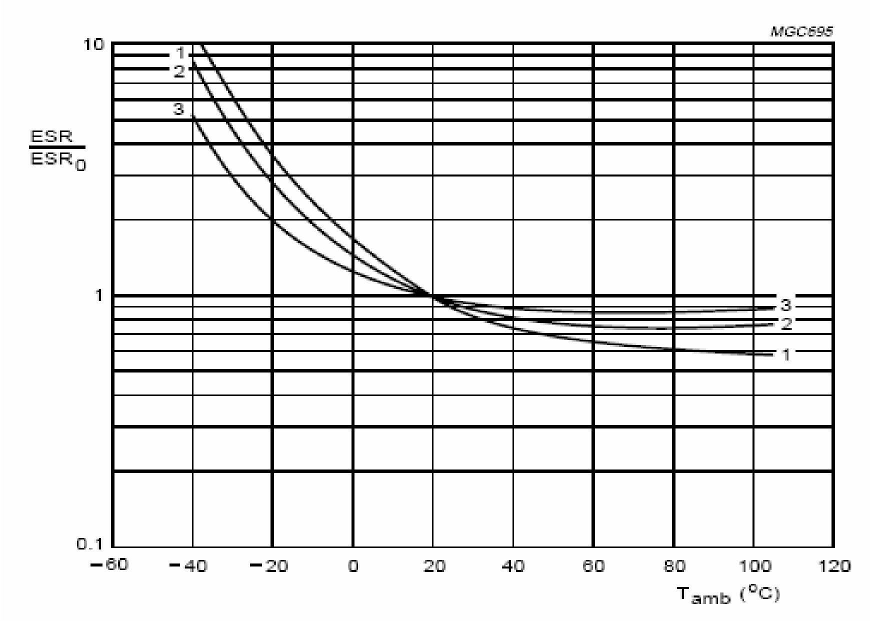

Figure 8: Change in ESR as a function of temperature (BC Components)

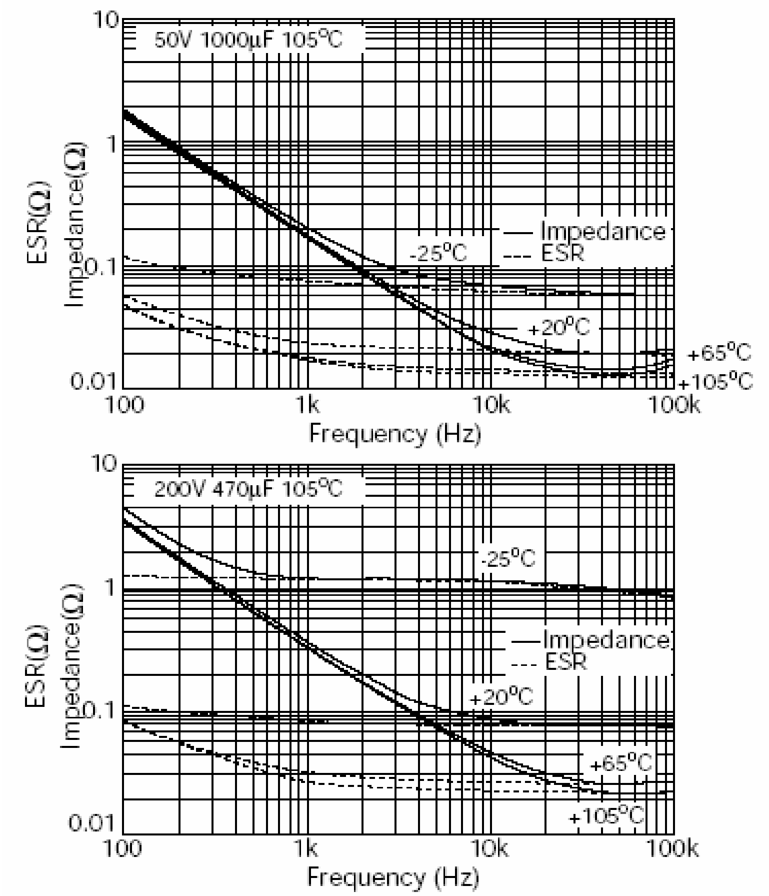

Figure 9: Change in ESR and impedance as a function of temperature (Nichicon)

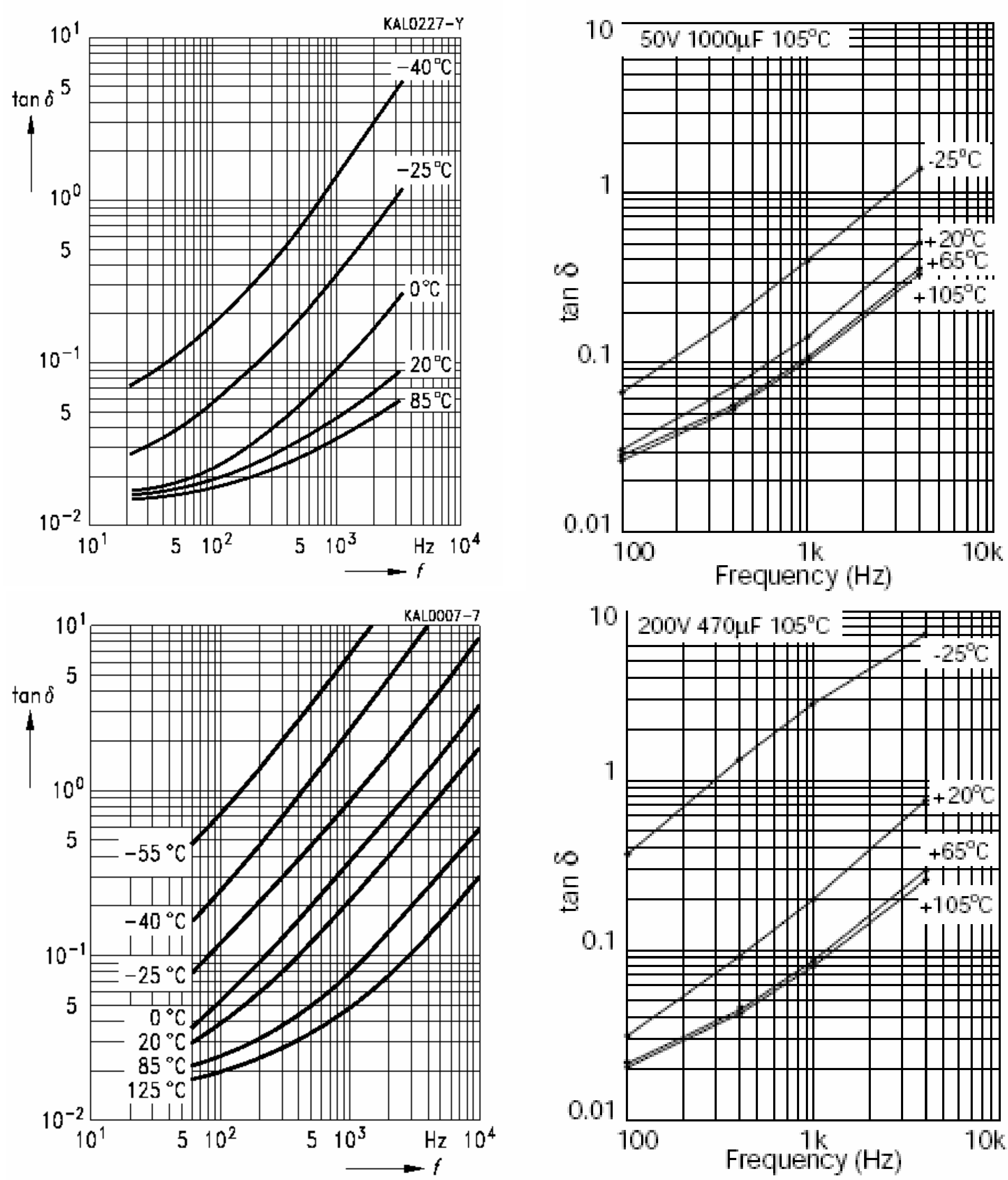

Figure 10: Change in dissipation factor as a function of temperature (left: Epcos; right: Nichicon)

Table 1: Long-term diurnal cycle experienced by Phoenix, AZ (based on data from the Climatic Data Center)

Month	Cycles/Year	Ramp	Dwell	Max. Temp (°C)	Min. Temp. (°C)
Jan.+Feb.+Dec.	90	6 hrs	6 hrs	20	5
March+November	60	6 hrs	6 hrs	25	10
April+October	60	6 hrs	6 hrs	30	15
May+September	60	6 hrs	6 hrs	35	20
June+July+August	90	6 hrs	6 hrs	40	25

Table 2: Damage evolution and lifetime prediction for a 105ºC / 1000 hour electrolytic capacitor exposed to Phoenix, AZ conditions.

Temperature (°C)	Lifetime (hours)	Fraction per Year	Relative Evaporation per Hour	Total No. of Hrs over 10 years	Relative Evaporation
50	45255	0.125	2.21E-05	10950	2.42E-01
45	64000	0.08335	1.56E-05	7301	1.14E-01
40	90510	0.08335	1.10E-05	7301	8.07E-02
35	128000	0.08335	7.81E-06	7301	5.70E-02
30	181019	0.125	5.52E-06	10950	6.05E-02
25	256000	0.125	3.91E-06	10950	4.28E-02
20	362039	0.08335	2.76E-06	7301	2.02E-02
15	512000	0.08335	1.95E-06	7301	1.43E-02
10	724077	0.08335	1.38E-06	7301	1.01E-02
5	1024000	0.125	9.77E-07	10950	1.07E-02
				Total Damage	6.52E-01
				Lifetime	15.3 years

Table 3: Damage evolution and lifetime prediction for a 105C / 1000 hour electrolytic capacitor exposed to Phoenix, AZ conditions + 10ºC rise due to power dissipation.

Temperature (°C)	Lifetime (hours)	Fraction per Year	Relative Evaporation per Hour	Total No. of Hrs over 10 years	Relative Evaporation
60	22627	0.125	4.42E-05	10950	4.84E-01
55	32000	0.08335	3.13E-05	7301	2.28E-01
50	45255	0.08335	2.21E-05	7301	1.61E-01
45	64000	0.08335	1.56E-05	7301	1.14E-01
40	90510	0.125	1.10E-05	10950	1.21E-01
35	128000	0.125	7.81E-06	10950	8.55E-02
30	181019	0.08335	5.52E-06	7301	4.03E-02
25	256000	0.08335	3.91E-06	7301	2.85E-02
20	362039	0.08335	2.76E-06	7301	2.02E-02
15	512000	0.125	1.95E-06	10950	2.14E-02
				Total Damage	1.30E+00
				Lifetime	7.7 years

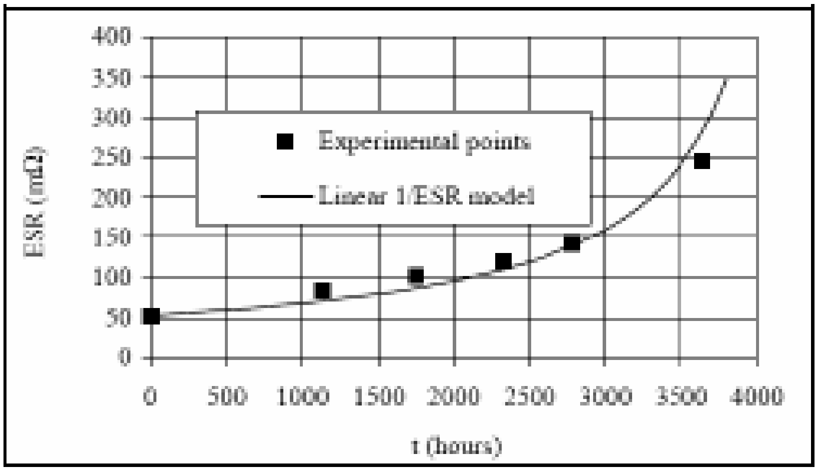

Figure 11: Change in ESR due to evaporation of electrolyte at 105C (Eur. Phys. J. AP 5, 71{83 (1999), Influence of aging on electrolytic capacitors function in static converters: Fault prediction method, P. Veneta, A. Lahyani, G. Grellet, and A. Ah-Jaco}

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