2.7. Capacitor Degradation and Failure Mechanisms: Exploring Different Causes Across Technologies

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ABSTRACT

Capacitors are among the most failure-prone components in many electronic systems. In power supplies and other continuously operating power electronic equipment, capacitor failure is often the primary cause of system malfunction.

Two distinct concepts are frequently referenced sometimes interchangeably in technical literature: capacitor degradation (or wear-out) and total failure.

Capacitor Degradation (Wear-Out): This refers to the progressive deterioration of key characteristics, particularly capacitance and equivalent series resistance (ESR), which may be mission-critical. This process is often non-linear and tends to accelerate over time due to continued operation under worsening conditions.

Total Failure: Often represented through statistical models such as Failure in Time (FIT) rates and Mean Time Between Failures (MTBF), total failure may or may not result from prior degradation and/or operating conditions.

This paper summarizes the various causes of both degradation and total failure, analyzing why specific environmental factors impact certain capacitor types while leaving others largely unaffected.

INTRODUCTION

Metallized Film Capacitors

Film capacitors are often designed as wound capacitors. In general, there is a distinction based on the structure of the electrodes. On the one hand, there are the metal film capacitors, in which a metal film essentially alternates with a film of insulating material, resulting in a three-layer structure when unwound, with the dielectric in the middle. On the other hand, the majority of film capacitors are manufactured with metallized films. [1, pp. 208-209]

In this process, dielectric films are coated with a thin metal film. These dielectric foils can be made of paper or plastic. MKP film capacitors are characterized by a high dielectric strength of around 650 V per µm of base film and a very low dissipation factor of around 0.025 %. [1, p. 216]. A Typical value for the dielectric strength of polypropylene is 400 V per µm.

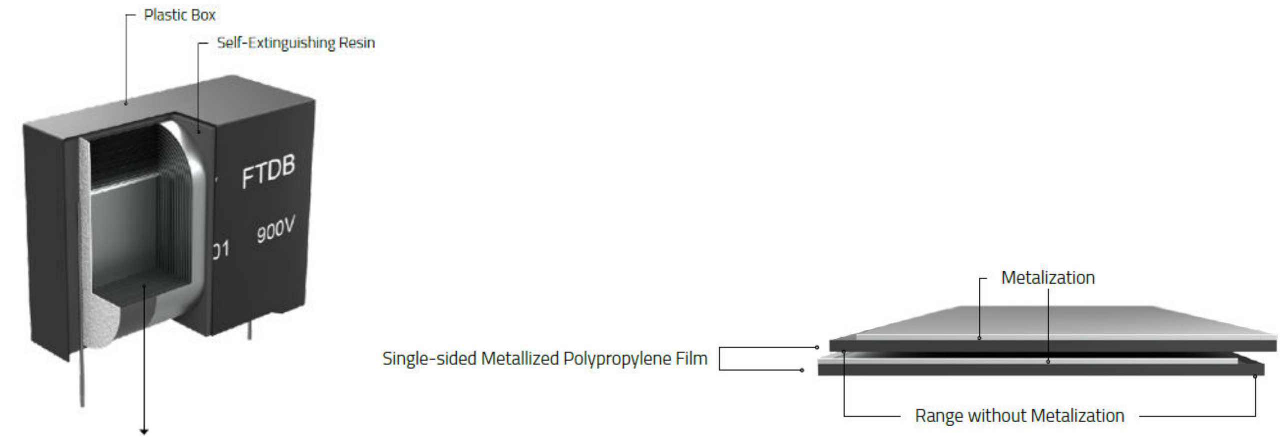

Figure 1: Construction of a MKP DC-Link Film Capacitor

The structure of such a capacitor is illustrated in Figure 1 using the WCAP-FTDB DC-Link film capacitor from Würth Elektronik. The vapor-deposited films are wound tightly with a slight offset (see Figure 1). The plastic box is filled with a synthetic resin coating, e.g. to protect the winding from moisture. The inductance of the winding is short-circuited by the complete end contact, resulting in a capacitor with good self-resonance behavior. [1, p. 211]

Electrolytic Capacitors

Most electrolytic capacitors are based on the dielectric aluminum oxide or tantalum oxide. [2, p. 1963]

The basic structure of a radial electrolytic capacitor is illustrated below. It essentially consists of two layers of aluminum foil with a layer of paper in between. This system is then wound and impregnated with electrolyte. The coil is placed in an aluminum can, which is sealed with a rubber stopper. A baseplate is added for the SMT mounting technology.

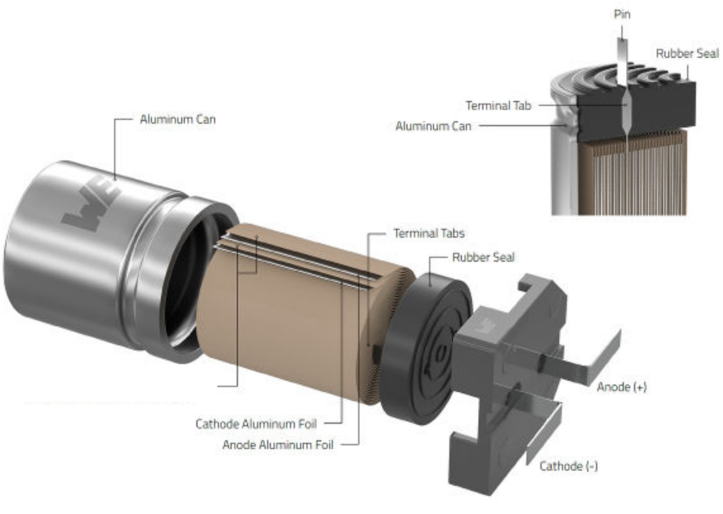

Figure 2: Construction of a hybrid polymer aluminum capacitor

The layers of the aluminum electrolytic capacitor are composed as follows: The dielectric is formed by an Al_2O_3 layer. This can be produced by anodic oxidation on the surface of an aluminum foil. Only part of the aluminum is converted into an oxide layer by anodic oxidation, which is why the other part acts as an anode. [2, p. 1963]

In addition to classic aluminum electrolytic capacitors, aluminum-polymer and aluminum-hybrid-polymer capacitors are also used in many areas.

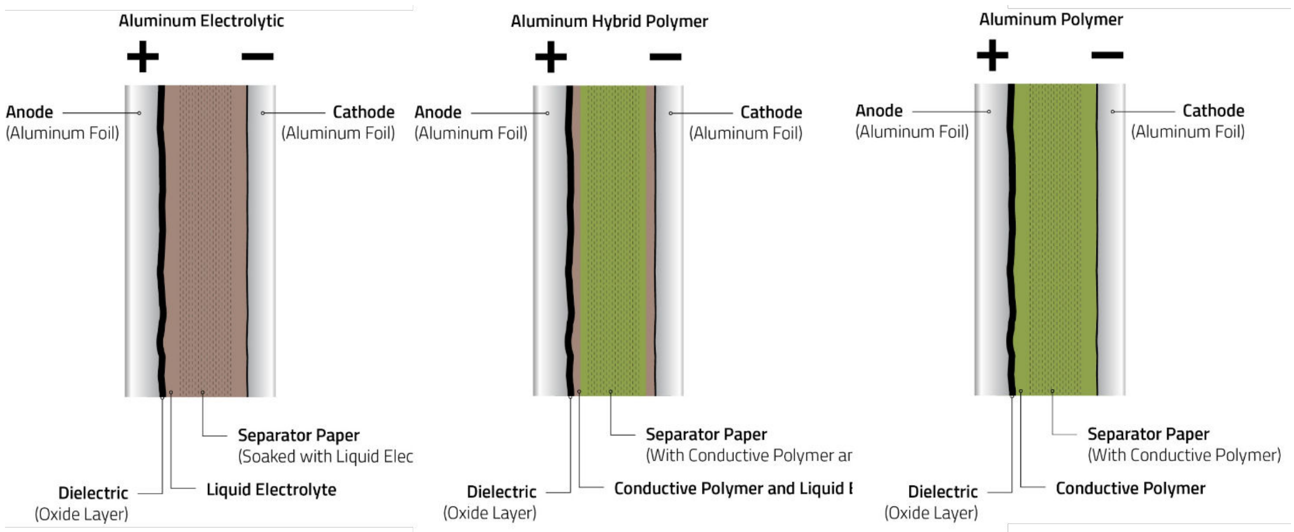

Figure 3: Internal structure of (left) aluminum electrolytic liquid, (mid) aluminum hybrid polymer and (right) aluminum polymer capacitors

Figure 3 illustrate the basic layer structure of the technologies mentioned above.

The main difference here is that a liquid electrolyte is used in classic aluminum electrolytic capacitors (also known as electrolytic capacitors) and a conductive polymer is used in aluminum polymer capacitors.

Capacitors with conductive polymer are specified by various manufacturers with significantly higher permissible ripple currents compared to classic aluminum electrolytic capacitors. This can be attributed to the fact that polymer capacitors and also aluminum hybrid polymer capacitors have a significantly lower ESR (equivalent series resistance) than classic aluminum electrolytic capacitors.

The aluminum hybrid polymer capacitor is manufactured very similarly to the polymer capacitor, but the winding of the hybrid polymer capacitor is additionally impregnated with electrolyte.

Supercapacitors (EDLC)

Electric Double Layer Capacitors (EDLCs) are a common type within the family of components known as Supercapacitors (sometimes referred to as ultracapacitors or gold capacitors by certain manufacturers). Their structure is, in some respects, similar to that of electrolytic capacitors, featuring a winding of pre-treated aluminum foils with separator paper in between.

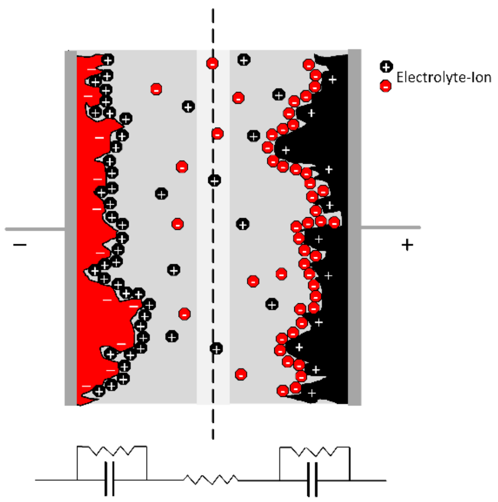

Figure 4: Internal structure of an electric double layer capacitor

The internal structure of an EDLC (see Figure 4) consists of two porous carbon-based electrodes with extremely high surface area. These electrodes are separated by a thin, ion-permeable separator soaked in an electrolyte. When voltage is applied, ions from the electrolyte accumulate at the interface between the electrode surface and the electrolyte, forming electric double layers. This structure allows for rapid charge and discharge without chemical reactions, enabling high power density and long cycle life.

MLCC

Ceramic capacitors form a wide range of capacitors with different properties. Ceramics are generally understood to be an inorganic, polycrystalline body that is created by a firing process at high temperatures. MLCCs (Mulitlayer Ceramic Capacitor) are considered in this work. A schematic structure is shown in Figure 5. These consist of a uniform ceramic block with comb-like sintered electrodes, which are contacted on the front side by fired metallizations [1].

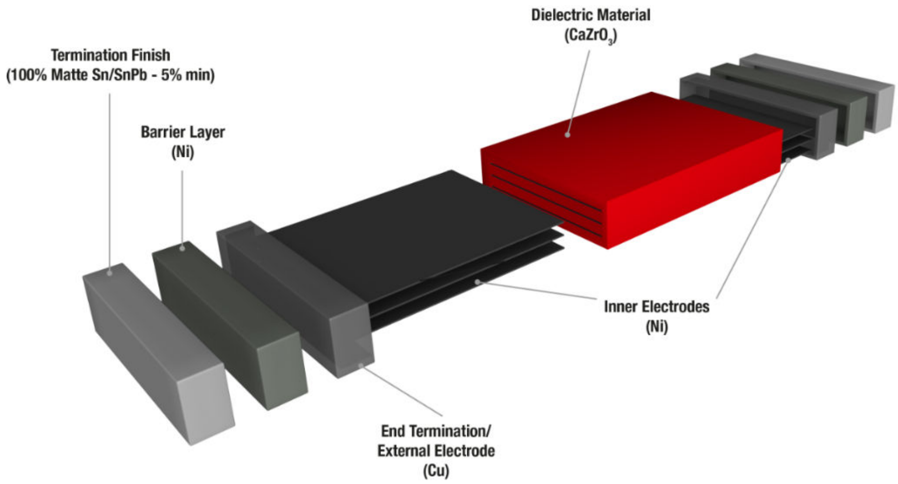

Figure 5: Internal construction of a class I multilayer ceramic capacitor (MLCC)

MLCCs can be broadly categorized into Class 1 and Class 2 types, with Class 3 no longer in use. This classification is primarily based on the type of ceramic material employed in their construction [1]:

Class 1 MLCCs utilize ceramics with a relatively low dielectric constant, typically ranging from approximately $\varepsilon_r = 13$ to 500. These capacitors are known for their high stability and precision. Key characteristics include an almost linear temperature dependence of capacitance, a very low temperature coefficient of approximately ±30 ppm/K, and negligible aging effects. Additionally, Class 1 MLCCs exhibit no significant voltage dependence in their capacitance, have low dielectric losses ($\tan\delta \approx 0.001$), maintain small capacitance tolerances, and offer very high insulation resistance. These properties make them ideal for applications requiring high accuracy and stability.

In contrast, Class 2 MLCCs are based on ferroelectric ceramics and are characterized by a much higher dielectric constant, typically in the range of $\varepsilon_r = 700$ to 15,000. These capacitors are designed for applications where higher volumetric efficiency is needed. However, they exhibit a non-linear dependence of capacitance on both voltage and temperature, and their temperature coefficient can vary by several percentage points per Kelvin. Class 2 MLCCs also experience significant aging effects and have a higher loss factor (approximately $\tan\delta \approx 0.03$). Despite these drawbacks, they still maintain high insulation resistance and can provide extremely high volumetric capacitance, making them suitable for general-purpose and high-capacitance applications.

Failure Rate of Capacitors

Definition

The Mean Time between Failures describes the average time between two failures of a system. Similarly, there is also the Failure in Time (FIT) specification. This describes failures per billion operating hours and is reciprocal to the MTBF specification. [3, p. 4]

$$MTBF = \frac{10^9}{FIT} \tag{1}$$

$$FIT = \frac{10^9}{MTBF} \tag{2}$$

FIT/MTBF Calculation (Telcordia Standard)

There are various ways of assessing the reliability of systems. One of these is to calculate the MTBF according to the Telcordia Technologies Special Report SR-332. [4] These failure rates can be applied to electronic products. In particular, this approach has been significantly influenced by companies in the telecommunications industry. Failure rates are not constant, they follow a bathtub curve as shown in Figure 6:

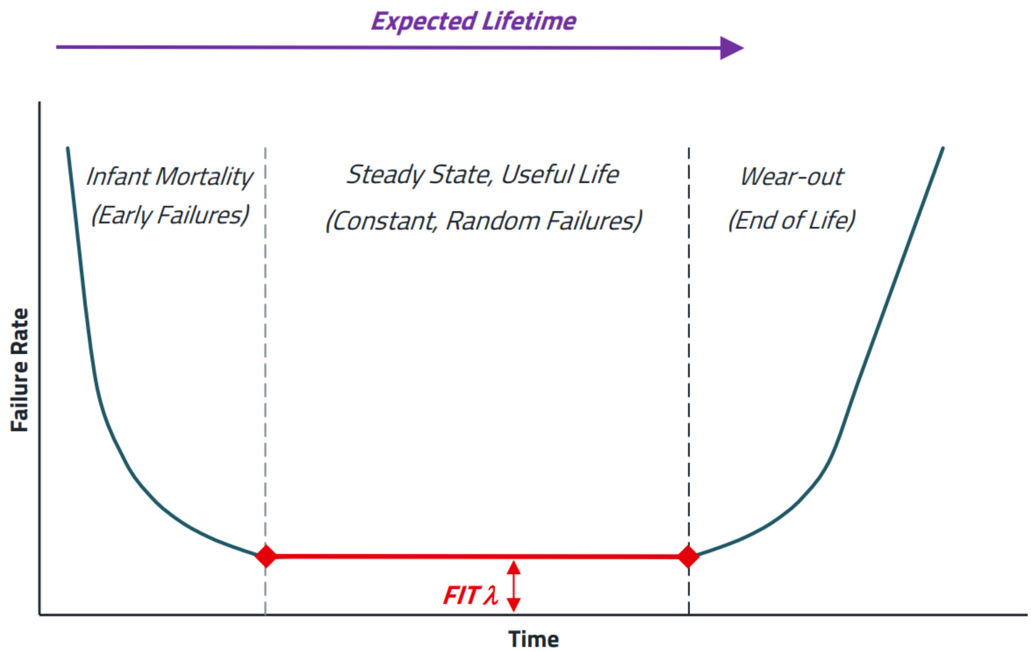

Figure 6: Bathtub curve for failure rates [5]

This also consists of the *early failures*: here the failure rate is very high but decreases quickly. The standard assumes that this period covers the first 10,000 hours. In other words, just over a year. *Steady state* describes a period in which the failure rates are almost constant. The standard assumes a period of around 20 years.

As an example we look at the failure rate for electrolytic capacitors according to the Telcordia standard. Four different curves are specified, which differ according to the different stress levels. The stress level is defined as follows in Eq. (3):

$$stress[\%] = \frac{V_{applied,DC} + V_{peak,AC}}{Vr} \quad (3)$$

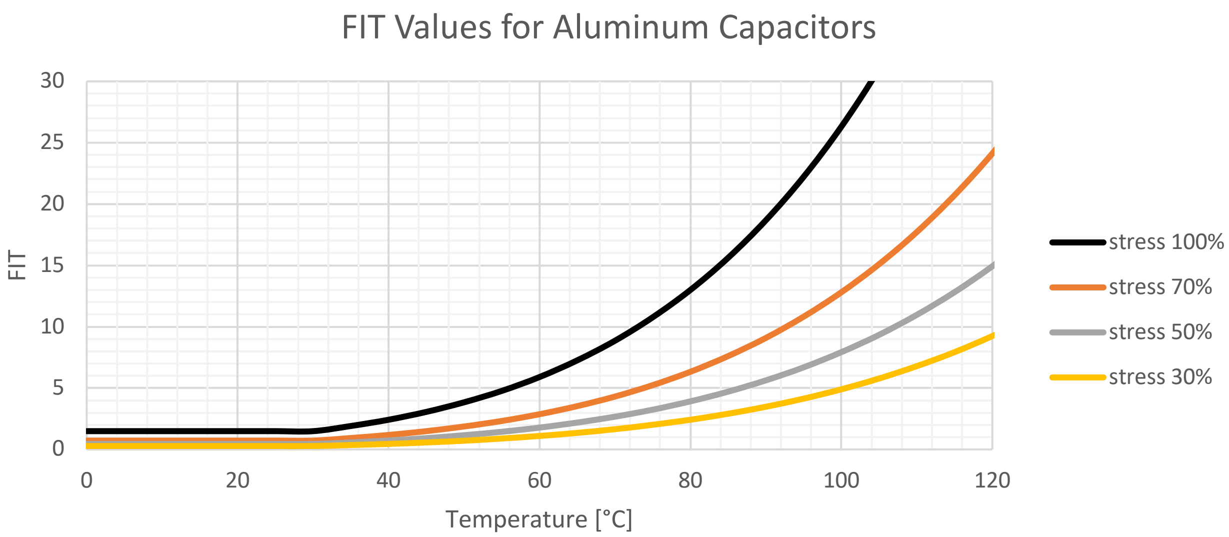

Figure 7: FIT Values for Aluminum Capacitors of Würth Elektronik [5] [4]

Assuming an operating point of 100% nominal voltage and 80 °C, this means that the FIT rate is 13. This value is a median value. The value for MTBF is then calculated by (1) to approx. 8781 years. This makes it clear at first glance that this value differs greatly from the service life of electrolytic capacitors.

The MTBF is a measure of the statistical reliability of a large number of systems or components. It therefore differs from the specification of a lifetime. The lifetime refers to a specific system or component and, using the example of capacitors, describes how long these components can be operated until they exceed or fall below limit values in relation to their capacitance or loss specifications. [5]

With regard to capacitors, or more specifically: electrolytic capacitors, it is explicitly pointed out that these components often switch to the *wear-out* phase within the first 20 years (assumption for the *steady state* phase). The standard states that the failure rates in this case are only valid for the *steady state* period. [4, p. 57]

Other technologies are covered in the Telcordia standard too, but this is not shown in this paper. Please refer to the FIT and MTBF document of the respective manufacture or to the Telcordia standard.

The Telcordia standard also does not define exactly when a capacitor is considered to have failed. In contrast, capacitor manufacturers specify limit values for the capacitors as part of their service life estimation. For this reason, the degradation mechanisms of different capacitors are discussed in more detail in the next chapter.

Degradation and Lifetime Estimation

Aluminum Electrolytic Capacitors

The aging of aluminum electrolytic capacitors and aluminum hybrid polymer capacitors can generally be described using the Arrhenius equation [6]:

$$L_{Al.} = L_0 2^{\frac{T_{max}-(T_x+\Delta T)}{10}} \left(\frac{V_r}{V_{max}}\right)^{V_x} \quad (4)$$

$$L_{Al.} = L_0 K_T K_I K_V \quad (5)$$

Where L_0 is the initially specified service life. This service life is specified in the manufacturer's data sheets. The following table is given as an example.

Test Conditions	Endurance	Shelf Life
Lifetime	2000 h @ 105 °C	1000 h @ 105 °C
Voltage	$U_{R\ applied}$	None
Current	I_R	None
Δ C	≤ ± 30 % of initial measured value	≤ ± 30 % of initial measured value
DF	≤ 300 % of the initial specified value	≤ 300 % of the initial specified value
Leakage Current	≤ the initial specified value	≤ the initial specified value
Comment		Before measurement: Restore capacitor to 20 °C, apply VR for 30 min.

Figure 8: One example of the lifetime information from the datasheet of one Aluminum Electrolytic Capacitor (Würth Elektronik P.N. 865080740005). The permitted degradation during the endurance accelerated test is compiled in this table.

The difference between the maximum specified temperature T_{max} and the sum of the ambient temperature T_x and the self-heating ΔT forms the temperature factor in the above formula. The voltage factor is formed from the nominal voltage V_r and the applied voltage V_{max} and the exponent V_x.

The self-heating due to the ripple current in connection with the ESR of the capacitor is represented by ΔT. The formula can be divided into a pure temperature factor K_T and a ripple current factor K_I. This is shown in formula (5). [6]

Aluminum-polymer capacitors cannot dry out due to the use of a solid material. In this case, ageing is essentially based on a temperature-dependent change in the materials used. The service life is determined by the following equation:

$$L_{Al.-Pol.} = L_0 10^{\frac{T_{max}-T_x}{20}} \quad (6)$$

While this modified Arrhenius model fit the temperature dependency, research [7] include a relative humidity dependency alongside temperature in polymer capacitors, where we may include the more recent hybrid polymer capacitors. In [7] we see how the exposure to elevated temperature and humidity caused an increase in both ESR and leakage current in tested solid polymer capacitors. The increase in ESR is attributed to the loss of conductivity of the PEDOT polymer layer.

In the specific case of H-Chip type polymer aluminum capacitors, also called Multilayer Polymer Capacitors, testing at high temperature and high humidity (like 85°C / 85%) showed consistent acceleration of failure times as well as failure modes [8]. Capacitance drop was followed by an increase of leakage current. Due to the different construction and sealing enclosure, such results should not be assumed to apply for cylindrical “canned” polymer or hybrid polymer aluminum capacitors.

In experiments using hybrid polymer aluminum electrolytic capacitors, a dependency of bias voltage was reported in [9] to be approximately 25% increased lifetime when rated voltage was applied.

Metallized Film Capacitor

Various ageing models of film capacitors are collected in the review paper [10]: These include the Arrhenius model and diverse methods to correct it. Since various factors such as temperature and voltage have a somewhat smaller effect when applied simultaneously than when the factors are multiplied alone, one model known as Eyring law is used to generalize Arrhenius to many factors other than temperature [11]. Furthermore, [12] describe an ageing law based on electrochemical corrosion and investigates degradation due to high ripple currents.

However, analyses aimed at developing a standardized service life formula for film capacitors show that the ageing parameters can vary significantly depending on the manufacturer, even if the specifications are the same. This can be seen in [12]. At the same time, some manufacturers indicate lifetime curves in the format shown in Figure 9.

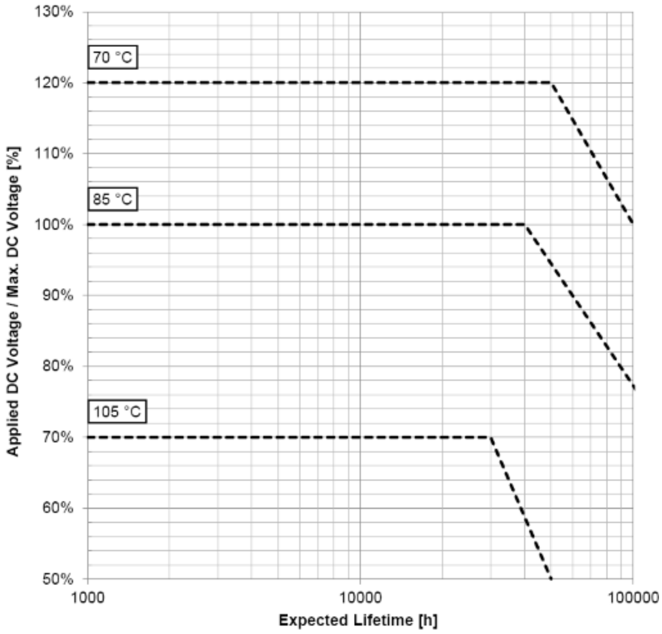

Figure 9: Example for the expected Lifetime / derating graph from the datasheet of WCAP-FTDB

In addition to models that primarily take pulse voltages into account, there are also papers that deal with the influence of AC voltage, temperature and humidity. In [13] this is particularly considered in relation to safety capacitors. These components are designed for particularly good self-healing properties. Therefore, these components are only metallized with a very thin metallization layer of a few nm. Since these components are operated with AC voltage, the critical failure mechanism is electrochemical corrosion under AC load and humid environmental conditions. It is a particularly critical mechanism as some applications require stable capacitance values under harsh environmental conditions. These include, for example, automotive applications or low power applications where the capacitor is part of a capacitive power supply. [13]

MLCC

In the last decades two events have shaped the reliability of consumer-grade MLCCs: The transition to Base-Metal-Electrodes (BME) from more expensive Precious-Metal-Electrodes (PME) and the increasing trend of miniaturization with high capacitance density components [14].

BME MLCCs, while offering higher volumetric efficiency, are more susceptible to insulation resistance degradation due to oxygen vacancy electromigration under electric fields. In contrast, PME MLCCs, processed in oxidizing atmospheres, exhibit more stable long-term reliability. The burn-in process, commonly used for screening, has been shown to negatively impact BME MLCCs by inducing irreversible defect migration. Additionally, BME capacitors are more sensitive to electrode morphology, where discontinuities and roughness can significantly elevate local electric fields and leakage currents. These factors necessitate advanced modeling and quality assessment techniques, such as TSDC (thermally stimulated depolarization current) and physics-based machine learning, to ensure BME MLCC reliability in high-reliability applications. [15]

According to [16], the degradation mechanism in $BaTiO_3$-based BME MLCCs under dc bias is primarily driven by the electromigration of oxygen vacancies toward the cathode, resulting in asymmetric oxygen distributions within grains and across grain boundaries. As a result, the activation energy for conduction is reduced and insulation resistance degrades over time, ultimately compromising device reliability.

On the other hand, the trend for smaller and lighter electronic devices specially in consumer products drive the demand for high density MLCC packaging. This is sometimes referred to as high CV value (Capacitance * Voltage), which is achieved by both decreasing the dielectric thickness and increasing the number of electrodes. Highly accelerated lifetime testing (HALT) with high temperatures and high voltage over specification have determined that the probability of failure is inversely proportional to dielectric thickness [17]. It has been proposed to establish a minimum requirement for dielectric thickness for each given voltage rating to prevent early failure in high reliability applications.

From the external (environmental) factors affecting MLCC reliability, the most significant are those that cause cracking (sometimes also called micro-cracking) in the ceramic structure: During manufacturing component handling and thermal shock during soldering, and after soldering PCB flexing and other mechanical stress during testing or mounting in the application [18].

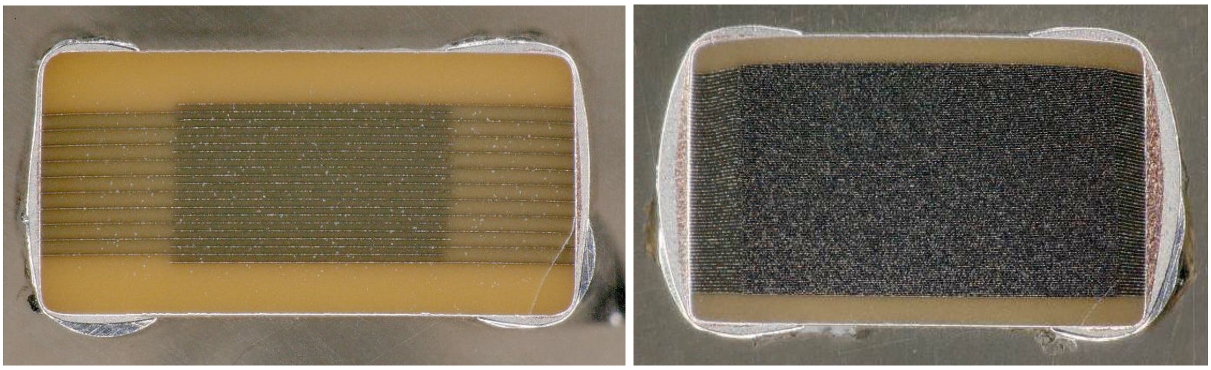

Figure 10: Two cross-section images of MLCCs with cracking (Würth Elektronik eiSos).

Left: high voltage low density 33 nF, 500 V rated, size 1206. Right: High density 1 µF, 25 V rated, size 0805.

Relatively speaking, large cracking planes may create short-circuit conditions or very low insulation resistance, which may case catastrophic failure or be visible with at plain sight. Other cracking situations and micro-cracking may not cause an immediate electrical issue, like in the cross-section images in Figure 10. In such cases, long term issues may arise during operation if the electrodes shift along the cracking plane. Leakage current measurements may not be adequate to detect it, also at high temperature. A report [18] proposed leakage current testing only after exposure to high humidity.

Supercapacitors

Like electrolytic capacitors, the wounded electrodes and paper assembly is soaked in a liquid electrolyte and sealed inside a can to prevent moisture ingress and prevent electrolyte loss. The drying up of the liquid electrolyte is accelerated by the operating temperature and as such the temperature is the main degradation factor.

But in the case of EDLCs, the applied voltage will play an important role: According to [19] the degradation mechanism of voltage in Supercapacitors primarily involves side reactions that occur during float charging. Although EDLCs ideally operate through non-faradaic processes (e.g. like capacitors, without electron transfer happening in the electrode through electrochemical reactions), prolonged exposure to high voltage leads to irreversible faradaic reactions. On the positive electrode, electrochemical oxidation consumes oxygen, carbon from the electrode material, and anions from the electrolyte, forming amorphous films that hinder ion desorption and diffusion. This results in increased internal resistance and a decline in capacitance. Simultaneously, the negative electrode undergoes electroreduction, potentially forming similar obstructive layers.

Recent advancements in the modeling of electric double-layer capacitor (EDLC) degradation have highlighted the limitations of traditional lifetime prediction methods, which often rely on short-term, accelerated aging data. In [20] a comprehensive study combining long-term endurance measurements at both elevated (65°C) and ambient (24°C) temperatures with a novel exponential deterioration model is presented. This model incorporates time-dependent acceleration factors for voltage and temperature, enabling more accurate forecasts of capacitance loss and ESR increase over operational lifetimes. The findings reveal two distinct degradation phases and demonstrate that commonly used acceleration factors, such as a constant base of 2 for temperature scaling, may underestimate lifetime under moderate conditions.

The proposed model not only aligns well with empirical data (achieving mean absolute percentage errors as low as 2%) but also offers a flexible framework for integrating environmental and operational parameters into lifetime predictions. By capturing the dynamic nature of degradation rates, the model supports more informed design decisions, such as component oversizing or voltage derating, to extend service life. These insights are particularly valuable for applications where reliability and sustainability are critical, reinforcing the need for long-term testing and adaptive modeling approaches in EDLC reliability engineering.

Case Studies

Aluminum Electrolytic Capacitors – measuring electrolyte loss

As mentioned in the previous chapter the service life of electrolytic capacitors is mainly affected by temperature and applied voltage. High temperatures affects the drying rate of electrolyte in the capacitor and therefore also affect the capacitance. The manufacturers therefore carry out endurance tests in which the component parameters must not deviate more than specified in the data sheets (see Figure 8).

To answer the question about the effect of electrolyte loss, the endurance test was performed with additional intermediate capacitance measurements as well as precise weight measurements. The test was carried out on 10 samples of the selected THT aluminum electrolytic capacitors of 2200 µF rated capacitance and 10 V of rated voltage.

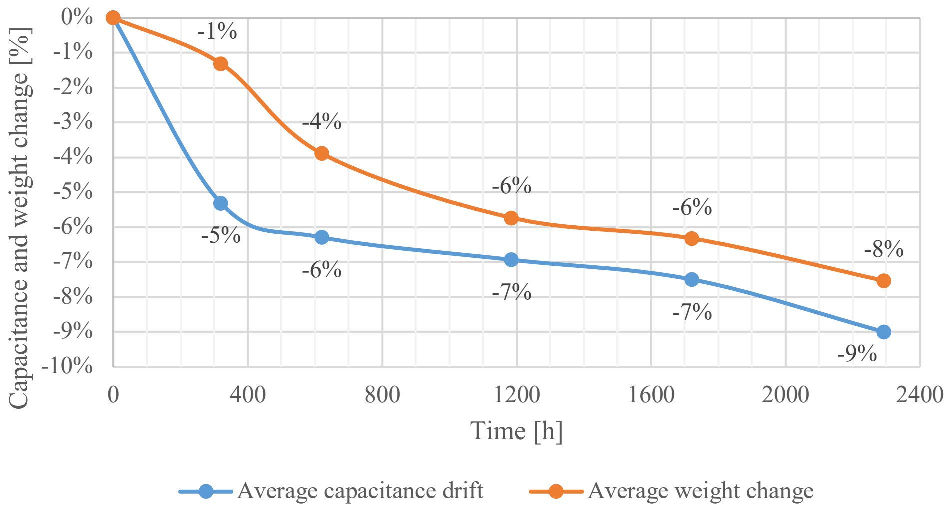

Figure 11: Intermediate measurements of capacitance and weight loss during the high temperature test of a 2200 µF / 10 V THT Capacitor for 2292 hours @ 105 °C and 10 V

In Figure 11 the mean values of the measurements are shown over time. It can be seen that the weight decreases in a certain way parallel to the capacitance.

Furthermore, the specification end-of-life (endurance definition) allow a maximum change in capacitance of 20% within the lifetime of 2000 hours. It is noticeable that the mean capacitance drop is well below this value.

Aluminum Polymer and Aluminum Hybrid Polymer Capacitors

In the above chapter, the aim is to calculate the service life based on temperature and voltage. However, especially with aluminum polymer or aluminum hybrid polymer capacitors, humidity also has an effect on the parameters of the capacitor. In addition to the leakage current, the ESR changes significantly according to [8] while the Capacitance value barely changes. To show this influence a measurement under 85°C and 85 % relative humidity was performed for Aluminum Hybrid Polymer Capacitors. The results are shown in Figure 12.

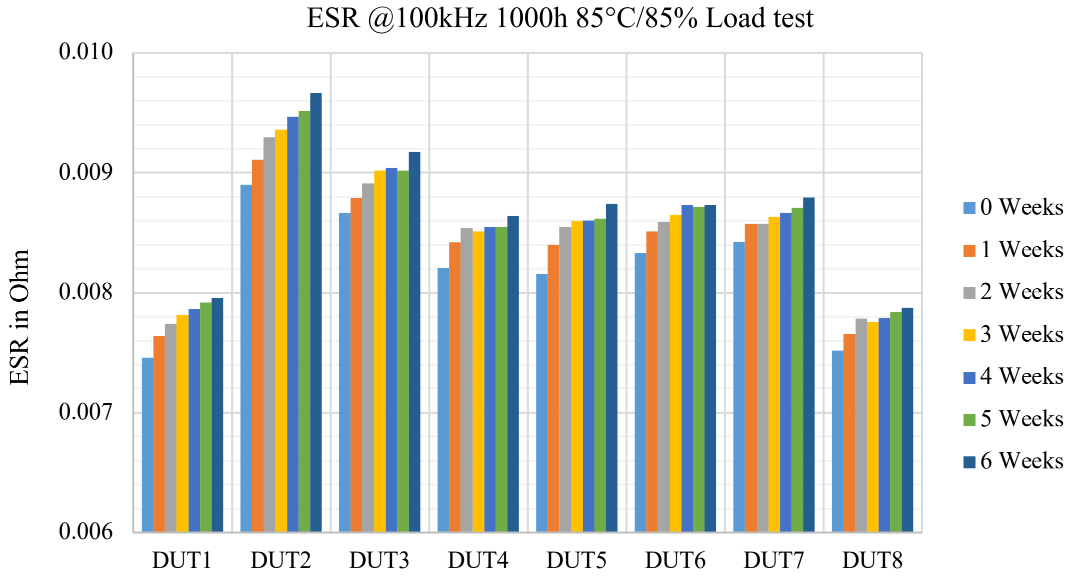

Figure 12: ESR Measurement of a 33 µF / 63 V Aluminum Hybrid Polymer Capacitor @ 85 °C/85% for 1000 hours

It is clear to see that the ESR increases significantly over time. Nevertheless, after the test, the component remains well below the ESR value specified in the data sheet of 40mΩ. No noticeable drop in capacitance was measured in this experiment, which is also shown in [8].

Film capacitors under harsh conditions

As described above, metallized film capacitors, which are used for interference suppression, are particularly susceptible to the combination of humidity, temperature and applied AC voltage unless special precautions are taken.

In Figure 13 is an example of a standard X2 capacitors being tested at 85°C, 85% relative humidity and 230 VAC for 1000 hours. It is important to note, that this component was not designed to endure such operating conditions in the application as this is a highly accelerated test. In the same test setup THB (Temperature, Humidity, Bias) X2 capacitors were tested, too. The result shows that the THB components exhibit significantly better behavior. However, it is also clear that there are major differences between the manufacturers. Dotted lines are standard X2 capacitors. Solid lines are THB X2 capacitors.

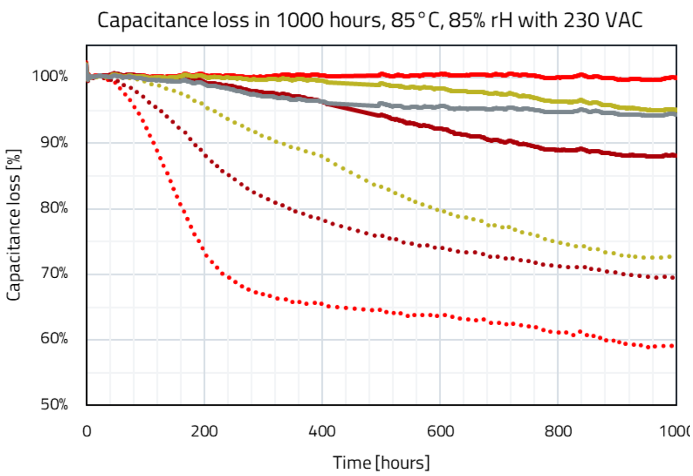

Figure 13: Capacitance drop during the 85/85 Test with X2 boxed metalized PP film capacitors from different manufacturers with and without THB rating

It is clear to see that the capacitance already drops very sharply at the beginning, until it drops only slightly from around 250 h. With regard to the ESR (not shown in Figure 13), it appears to increase sharply from 700 h. However, the ESR already increases after the first 100 h. This is an indication that these environmental conditions lead to strong changes in the component after only a short time.

Multilayer Ceramic Capacitors – long term capacitance loss due to DC-Bias polarization

Although the wear-out mechanisms of multilayer ceramic capacitors (MLCCs) were discussed in the previous chapter, such degradation is generally not expected under normal operating conditions. Another phenomenon often cited is the so-called aging of MLCCs. For Class II MLCCs, this is typically characterized by a capacitance loss of approximately 2–5% per decade of time, beginning 24 hours after a thermal reset above the Curie temperature [21]. While this effect is noteworthy, it does not significantly impact performance in practical applications. Under actual operating conditions (in the presence of DC and AC signals), the capacitance drift induced by these signals tends to dominate.

Among the various polarization-related effects influencing MLCC performance, the voltage-dependent capacitance variation is quantitatively the most significant. A long-term effect associated with this dependency has been observed and characterized [22]. As shown in Figure 14, the rate of stabilization increases with higher DC bias levels, likely due to enhanced polarization of the dielectric material under stronger electric fields.

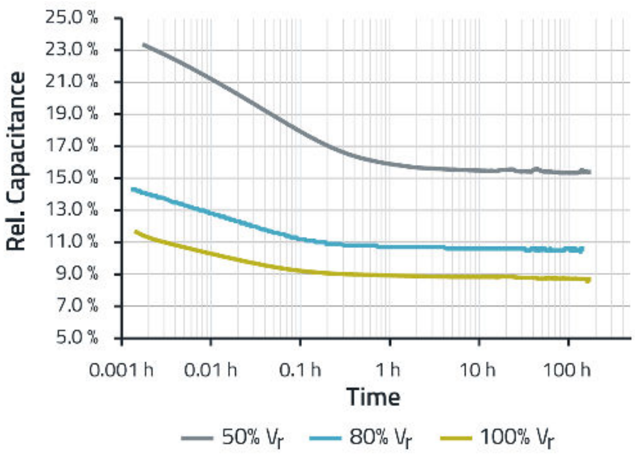

Figure 14: Measured relative capacitance vs time for three different DC voltages in reference to V_{Rated} of ceramic capacitor Würth Elektronik 885012209073 (10 µF, 50 V, 1210 size). [22]

This long-term effect does not belong in the scope of this work, because this effect is reversible by applying a temperature over the Curie temperature, a process by which the polarized structure of the dielectric will reset. While this is not a wear-out mechanism, it is still interesting to consider it as a capacitance drop that may cause issues after just some hundreds of hours of continued operation if the capacitance drops below certain thresholds. Therefore, the long-term DC bias dependency should be considered in reliability assessments.

Supercapacitors – Electric Double Layer Capacitors over very long time

One noticeable issue overall in the literature is the reliance on accelerated test to measure the effect of different factors by performing tests at exaggeratedly harsh conditions for the capacitors. Most commonly, high temperature is used to accelerate wear-out to more practical time frames. Specially in the field of academic research, the limited available time in dissertations like PhDs or Master Thesis, as well as the temporary nature of some professorship/research tenures explain the overwhelming preference for highly accelerated life testing (HALT).

Accelerated testing is reasonable specially for quality assessment checks like the *endurance test* for electrolytic capacitors, although it might skew some results due to incorrect acceleration models and ignore some of the other factors that might affect operating life in the field.

One exception of this trend is the ongoing experiment performed on many Würth Elektronik Supercapacitors as collected by R. Kalbitz's work [20]. A number of samples were connected to the rated voltage of 2.7 V and let at room temperature for over 4 years to reproduce the typical configuration of a backup storage based on Supercapacitors.

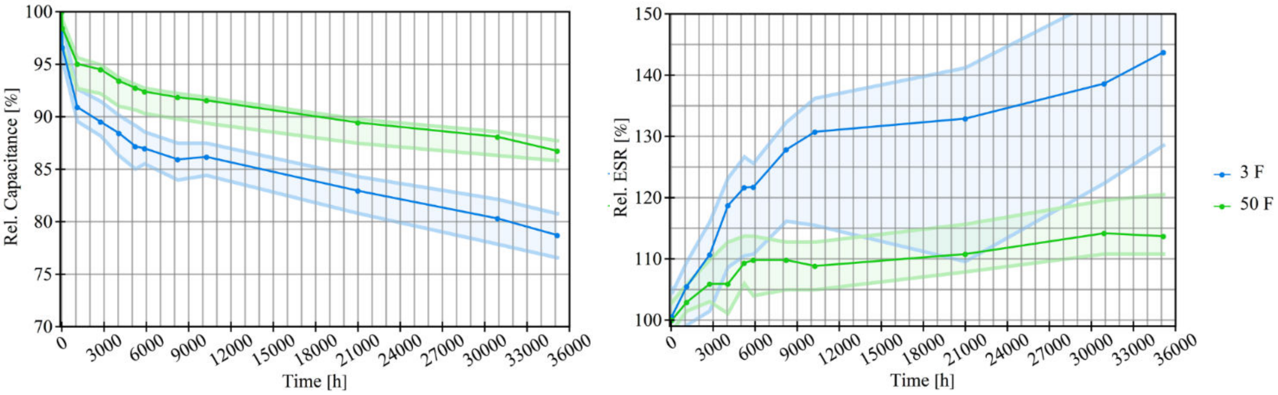

Figure 15: Median relative capacitance (left) and ESR (right) vs. time for different batches of capacitor types tested at room temperature, i.e. 24°C, and permanently applied DC voltage of 2.7 V. The semitransparent area marks the 10th percentile and 90th percentile. [20]

One interesting finding that can be extracted by the measurements over time overview in the Figure 15 is that while the fastest degradation happens in the first 2000 to 3000 hours, the rate of wear-out changes over time. Clearly, the rate of ESR increase gets slower after about 10000 hours which is more than one year. Another result is that the distribution of values is relatively large (specially ESR in 3 F capacitors) although consistent over time, which points out that the differences between parts are due to fabrication differences and not different wear-out severity.

SUMMARY AND CONCLUSIONS

This paper shows the differences between a calculation of the statistical failure rate according to the Telcordia standard and the lifetime calculation. It becomes clear that an individual lifetime estimation is necessary for electrolytic capacitors and metalized film capacitors.

In a specific application, we can consider that a "practical End of Life" happens when the capacitor is not able to fulfill its intended purpose (mostly filtering, decoupling, coupling or energy storage) in the connected electrical system. This failure to operate may be caused by either a degradation of the key parameters (most commonly capacitance and series resistance) or a more sudden change in its properties which may cause the capacitor to act like a short or open circuit.

As we have seen, the causes and mechanisms that produce these failure scenarios depend on the capacitor technology. The variety of dielectric materials as well as manufacturing processes is a consequence of the considerable diversity of applications and requirements where capacitors are used.

Recently, more researchers ([15] , [23]) are creating and proposing methods using physical-based machine learning to create predictions that incorporate more stress factors and reduce the measurement time to create quality assessment of production batches.

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