ACCELERATED AGEING TESTS OF ALUMINUM ELECTROLYTIC CAPACITORS FOR EVALUATING LIFETIME PREDICTION MODELS

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Abstract: During the course of the presented work accelerated ageing tests at constant temperature for aluminum electrolytic capacitors were carried out. The obtained results from practical tests are compared with projections of the lifetime of the capacitors given by current theoretical prediction methods and the accuracy of these methods is evaluated. Finally, two prediction methods are combined in order to give a higher accuracy lifetime prediction algorithm.

Keywords: *lifetime prediction, aluminum electrolytic capacitors, reliability testing*

I. INTRODUCTION

In the ever expanding market of the electronic industry, equipment manufacturers most commonly have two main goals when designing modules: assure the highest reliability rating possible at the potential lowest end price. This is one reason why reliability factors influence the manufacturer's decision when choosing component suppliers and what makes quality assurance and reliability prediction more and more important in today's electronic industry.

A second reason why reliability prediction and lifetime expectation estimation is of great value is because of the increasing popularity of electronics in safety critical applications. Not only with the development of electronic cars and the airline industry spiking to an all-time high, where the malfunctioning of such devices or electronic modules could lead to great financial losses and even to loss of human lives, but also with humanity relying on electricity and electronic equipment even for the most mundane of tasks, electronics is a lifeline for today's society. As a result it is no more enough to just calculate component failure-in-time (FIT) ratings using consecrated reliability prediction methods [1], it is also necessary to exactly know when the expected failure will occur.

Therefore, there are tendencies to develop equipment lifetime prediction methods and early warning systems that could prevent catastrophic failures as studies have shown that most component failures occur at the influence of electrical and environmental working conditions which have a great impact of component degradation.

II. TEST SETUP

For the accelerated ageing tests, aluminum electrolytic capacitors were used, as they are still quite common in cost-driven applications. Moreover, low cost components were chosen from 3 popular manufacturers, all capacitors being tested having a tolerance rating of ±20%. Different values and capsule dimensions were chosen, in order to determine if this is an influential factor in ageing. The main characteristics of the tested capacitors are presented in Table 1. The lifetime column presents the guaranteed lifetime of the capacitors by the manufacturer in their respective datasheets at maximum working temperature and voltage. In order to provide accurate results, a number of 15 capacitors were subjected to accelerated ageing from each batch. Tested series have been coded S1 through S4 for easier reference in the following.

Before the start of the tests, the capacitance and equivalent series resistance (ESR) values of each capacitor were measured and failure thresholds were calculated using the industry standard definition [4][5]. According to this, a capacitor is considered to have failed when one of the following conditions is true:

1. Its capacitance value has decreased by 20% below its initial value
2. Its ESR value has increased by 100% over its original value
3. The leakage current is greater than its original value

During the tests, leakage current values were ignored because of the lack of testing equipment, so only the first two failure mechanisms were taken into account.

After the initial evaluation capacitors were placed on a PCB with the help of connectors, adjacent to each other. Connectors were used in order to avoid component degradation due to heat from soldering methods, and an adjacent placement was chosen, as this is very commonly the case on PCBs. As it can be seen from the thermal imaging shot of the test setup (Figure 1), there are excess heat buildups where the capacitors touch each other, as in these points airflow is greatly diminished and the cooling characteristics of the aluminum capsules are significantly lowered. This excess heat can also have a great influence on component failure times.

The capacitors were then connected to a constant 9V DC voltage source and were subjected to the thermal profile shown in Figure 2. At the beginning of each cycle component capacitance values and ESR values were determined using an LC-meter and were noted. Measurements were done at 10 Hz and 1V applied

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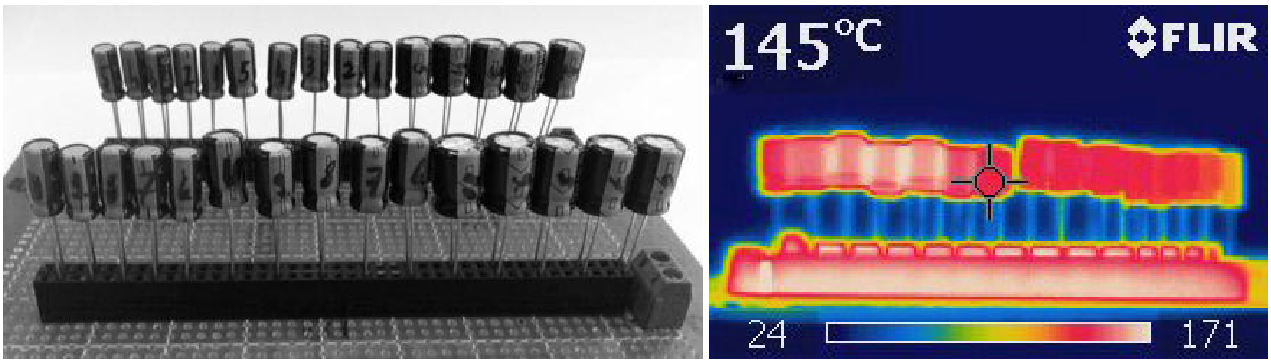


Figure 1. Original and thermal image of test setup.

Table 1. Tested capacitors

Series code	Manufacturer	C (µF)	V_{max} (V)	T_{max} (°C)	Lifetime (hrs)	Package size DxH (mm)	PRV*
S1	Samwha	47	16	85	2000	5x11	No
S2	Aishi	220	16	105	1000	6x12	No
S3	Samxon	470	16	105	2000	8x12	Yes
S4	Aishi	1000	16	105	1000	10x17	Yes

* - Safety pressure release valve (PRV) present

voltage and measurement terminals were connected as close to the capacitor body as possible in order to avoid the influence of the electrode lengths on the measurements [6]. It was also determined if the capacitors pass the failure criteria mentioned earlier. The test was continued until all capacitors from one given batch failed both from the point of view of capacitance as well as their ESR values.

The accelerated ageing temperature (T_H) was chosen to be 155°C and the ambient temperature (T_A) to be 25°C. T_H was so chosen to be low enough not to cause permanent damage in the component structure, but also to allow reasonable test times. Testing at maximum working temperature of the components (105°C) would have meant a lifetime and therefore test durations of approx. 83 days, which is unreasonably long.

At the beginning of the cycle capacitors were placed in a thermal chamber and were gradually heated (t_R = 10 mins) to T_H. Gradual heating was used so to avoid fast thermal cycling stress, as it was proven that fast thermal cycling has an effect on capacitor degradation [7] and this was not the purpose of the study. Capacitors were then kept at the constant stress temperature t_{Hn} time, after which they were left to cool naturally to ambient temperature, at which they were left for time t_{An}. During the tests heating times were always chosen to be equal to times at ambient temperature ($t_{Hn} = t_{An} = 8 \div 12$ hrs), this way the heating profile has a duty cycle of 50% which simulates the way electrical equipment is usually exploited in the field, being used only in one part of the day. Cooling time, t_F, was determined by the natural cooling tendencies of the capsule of the capacitors, as no forced cooling was used, components being left to cool naturally.

At the end of the thermal cycle (at times M_{n-1}, M_n, etc.) if the component was deemed failed, two failure times were calculated, by applying (1) for calculating capacitive and using (2) for determining ESR failure times.

$$t_{CF} = \sum_{i=1}^{n} T_{H_n}, \text{if } C_n < (C_0 + 20\%) \qquad (1)$$

$$t_{ESRF} = \sum_{i=1}^{n} T_{H_n}, \text{if } ESR_n > (ESR_0 + 100\%) \qquad (2)$$

III. LIFETIME ESTIMATIONS

In order to compare practical results with those given by prediction methods used in the industry to establish component reliability, the expected lifetimes of the capacitors were calculated using three different methods.

The first method, designated Method 1, generally accepted in the field and given by (3) states, that with every rise of 10°C in temperature, the lifetime of the capacitor halves. This way, taking the guaranteed lifetime at maximum operating temperature from the datasheet, the lifetime of the capacitor can be estimated at any working condition.

$$L_{exp} = L_0 \cdot 2^{\frac{T_0 - T_{op}}{10}} \qquad (3)$$

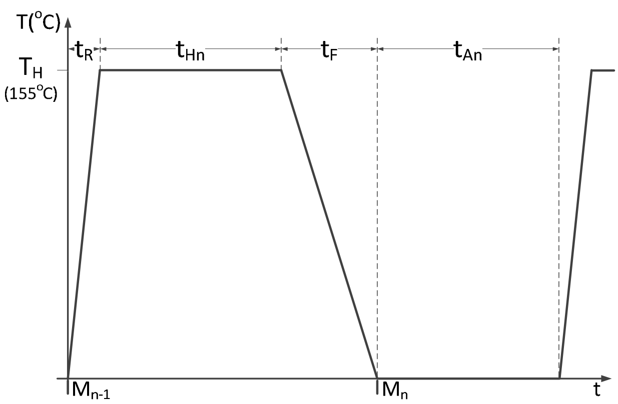


Figure 2. Thermal profile of the accelerated ageing tests.

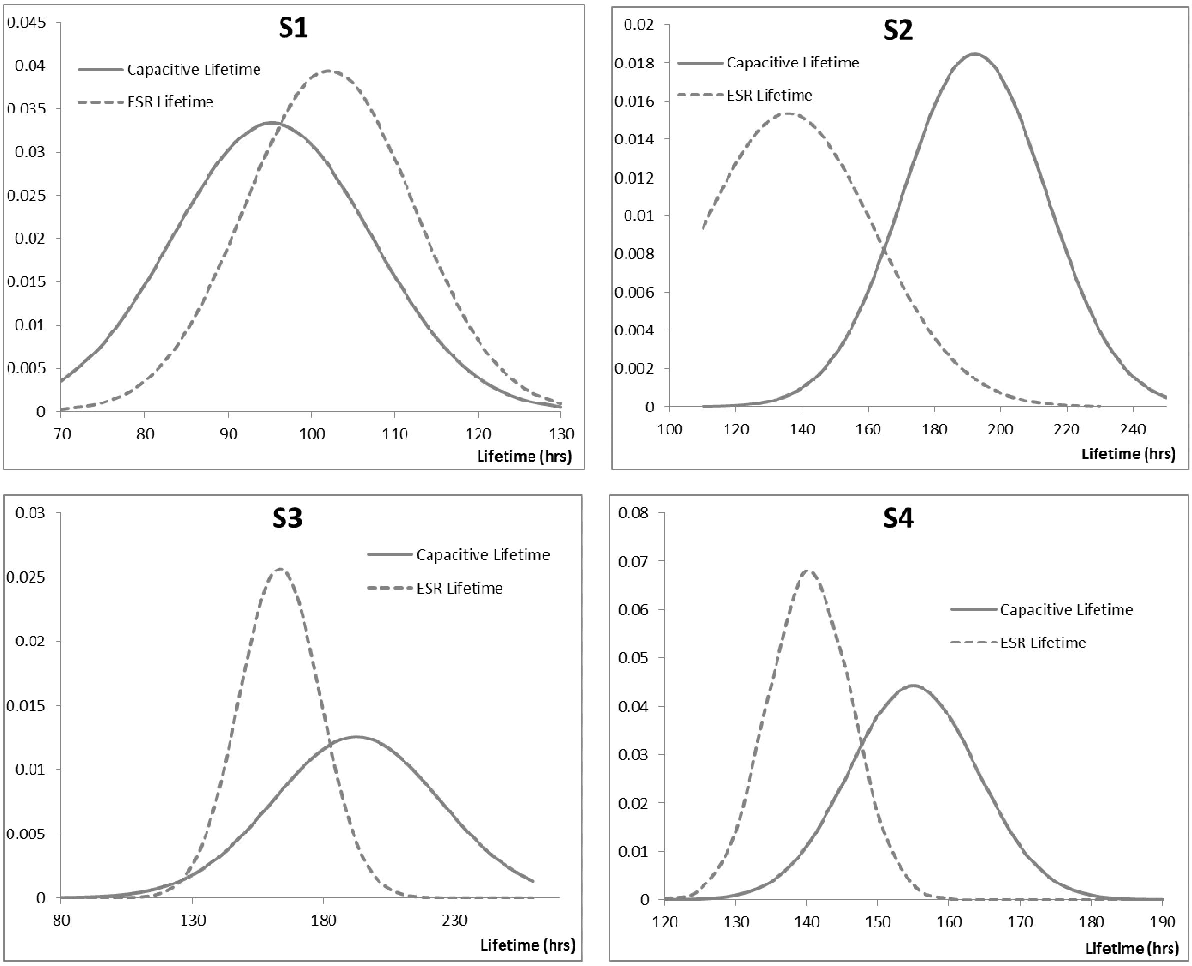


Figure 3. Distribution of measurement results.

In (3) Lexp is the estimated lifetime of the capacitor in hours at operating temperature T_{op}, while L_0 is the guaranteed lifetime at temperature T_0 from the datasheet.

A more advanced prediction algorithm, named Method 2, is presented by A. Debhi, W. Wondrak, et al. in [2]. This prediction method not only takes into account the estimations given by (2) but also states that capacitor lifetime is extended if it is not used at its maximum rated voltage. This results from (4), where V_{op} is the actual operating voltage of the capacitor, V_o is the maximum operating voltage supported by the component and *n* is specific to the capacitor capsule, and has the value of 0 for axial capacitors and 1 for radial ones. This means that this prediction methodology suggests that only radial capacitors are actually affected by working voltages, these also being used in the experiments carried out.

$$L_{exp} = L_0 \cdot \left(\frac{V_o}{V_{op}}\right)^n \cdot 2^{\frac{T_0 - T_{op}}{10}} \quad (4)$$

The last lifetime prediction method, coded Method 3, is based on an adapted version of Arrhenius' law and it assumes that the temperature during stress is known and fixed [3], which is true for the experiments conducted. This method is suggested by H. Gualous, R. Gallay, et al. in [4] and is expressed by (5) where t_i represents the estimated lifetime of the capacitor calculated in hours for temperature T_i expressed in kelvins, k is the Boltzmann constant, and E_A and B_{est} are material specific measures, E_A being the activation energy and is calculated using (6) and B_{est} is a material specific parameter and can be calculated using (7).

$$t_i = B_{est} \cdot \exp\left(\frac{E_A}{k \cdot T_i}\right) \quad (5)$$

$$E_A = \frac{k \cdot \ln\left(\frac{t_1}{t_2}\right)}{\frac{1}{T_1} - \frac{1}{T_2}} \quad (6)$$

$$B_{est} = \frac{t_1}{\exp\left(\frac{E_A}{k \cdot T_1}\right)} \quad (7)$$

Using the above presented methods combined with reliability data found in their datasheets, lifetime expectations were calculated for the batches of capacitors to be tested for testing temperature (T_H) of 155°C. The results of these calculations are presented in Table 2.

As it can be seen from the results, the presented methods give significantly different results for the same capacitor types, which lead to the conclusion that one of the algorithms will be closer to reality than the others.

Also to be noted is that result differences occur because the maximum working temperature for batch S1 capacitors is only 85°C, instead of the 105°C as is the case for all other tested components. Other result differences are due to different manufacturers guaranteeing different lifetimes at same temperatures as presented in Table 1 for S2, S4 versus S3.

Table 2. Capacitor lifetime estimations using the three prediction methods presented

Capacitor series	Calculated expected lifetime (hrs)		
	Method 1	Method 2	Method 3
S1	15.6	27.7	54.6
S2	31.2	55.5	71.3
S3	62.5	111.1	142.7
S4	31.2	55.5	71.3

IV. PRACTICAL RESULTS

After the initial measurement capacitors were subjected to accelerated ageing as described in section three. After each thermal cycle the capacitance and ESR values were measured for each capacitor. This evaluation was done until all capacitors have failed both from the point of view of capacitance drop and ESR rise.

The distribution of the measurement result is presented in Figure 3 for all capacitor series. As it can be seen, the lifetime data of the capacitors follow the Gaussian distribution and are represented as the classical Bell curve, with its peak being the average failure time of the components, as presented in Table 3. Average capacitance and ESR evolutions for all capacitor series are presented in Figure 4, failure points being marked by dots.

Table 3. Average failure times for tested capacitors

Capacitor series	Capacitive failure time (hrs)	ESR failure time (hrs)
S1	95.3	102.2
S2	192.2	142.7
S3	192.6	163.2
S4	155.0	140.4

V. EVALUATION OF CURRENT PREDICTION METHODS AND PROPOSED NEW METHOD

With all failure data available, the performance of each prediction algorithm was evaluated by calculating their accuracy in predicting capacitor lifetimes. By applying (8), relative errors for each algorithm were calculated for both types of failures and are presented in Table 4. It can be clearly observed that Method 3 has the best performances for every single case, but relative error values are still quite high. This could be the result of the fact that Method 3 does not take into account the capacitors' maximum operating voltage and their actual operating voltage.

$$\varepsilon_r = \frac{|t_P - t_F|}{t_F} \cdot 100\ [\%] \tag{8}$$

As a result, for a more accurate approach for predicting capacitor lifetimes, equation (5) should be corrected with a factor that takes into account operating voltages over maximum accepted values. The resulting prediction equation is described in (9).

$$t_i = B_{est} \cdot \exp\left(\frac{E_A}{k \cdot T_i}\right) \cdot \left(\frac{V_o}{V_{op}}\right)^n \tag{9}$$

Table 4. Relative errors of the prediction methods

Cap Set	ε_{rC} (%)			ε_{rESR} (%)		
	Met 1	Met 2	**Met 3**	Met 1	Met 2	**Met 3**
S1	83.6	70.9	**42.7**	84.7	72.9	**46.5**
S2	83.7	71.1	**62.9**	78.1	61.1	**50.0**
S3	67.5	42.3	**25.9**	61.7	31.9	**12.6**
S4	79.8	64.1	**54.0**	77.7	60.4	**49.2**

The estimated lifetimes for the capacitors calculated using equation (9), as well as the relative errors obtained by applying this new prediction method are presented in Table 5. Comparing data from Table 4 and Table 5 it can be seen that this new method results in reducing relative errors by more than half. While the average relative error in case of Method 3 is 46.4% in case of capacitive failure prediction and 39.6% in case of ESR failure prediction these errors are reduced to 21.4% and 20.32% respectively, when applying equation (9), so even with the worst case scenario as taking just ESR failures into account, as these are the first to manifest, the proposed method brings a significant improvement over the classical prediction algorithm.

Table 5. Relative errors of the proposed method

Capacitor Series	Estimated lifetime Proposed method (hrs)	ε_{rC} (%)	ε_{rESR} (%)
S1	97.07	1.85	5.02
S2	126.76	34.05	11.17
S3	253.69	31.72	55.38
S4	126.76	18.22	9.72

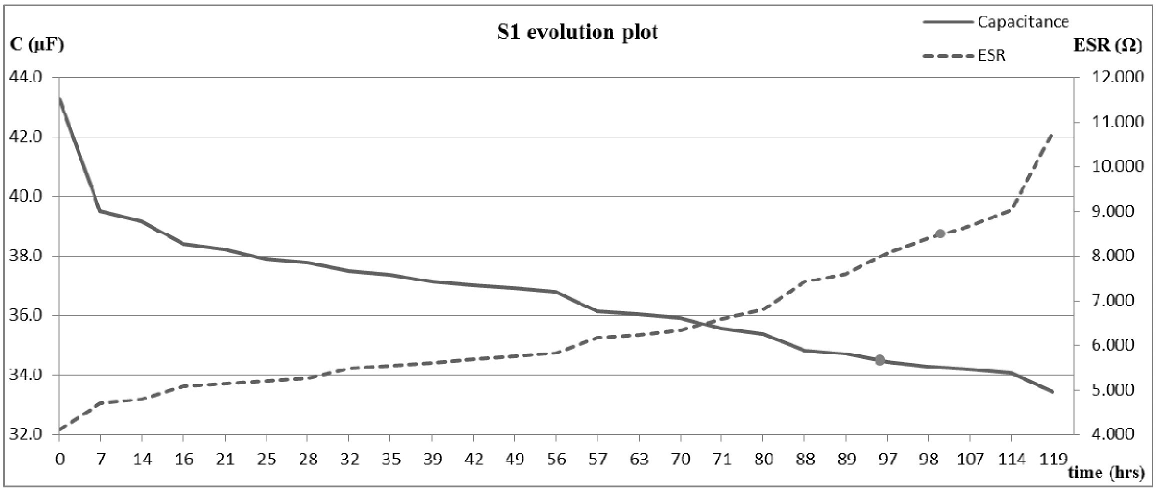
V. DISCUSSION

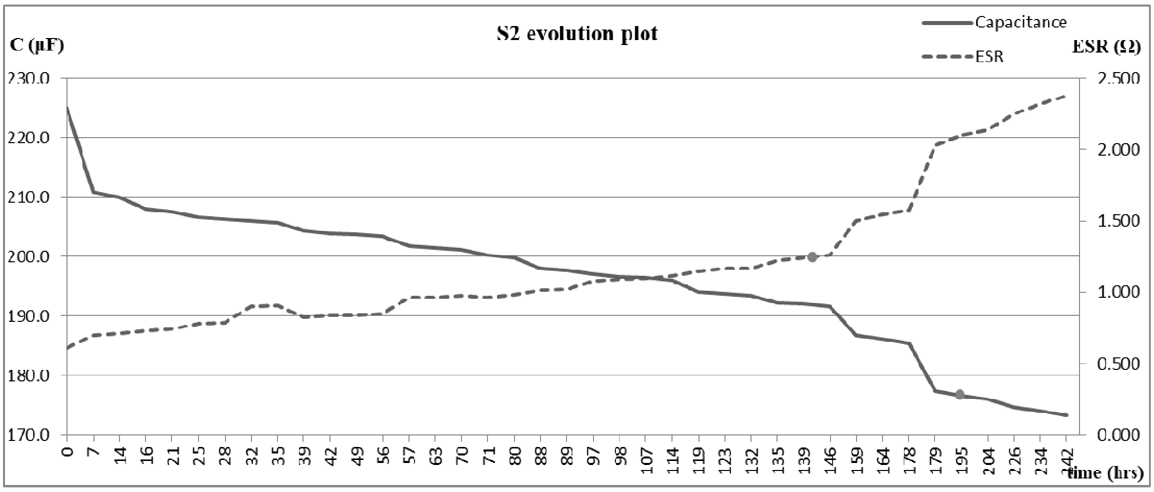
Analyzing the obtained results and the plots of the measurement, some conclusions can be drawn. First off, it is to be noted that since the capacitors have a ±20% tolerance rating their initial capacitance and ESR values differ somewhat, but are all in the accepted range. This means that during the accelerated ageing tests capacitance and ESR values will not coincide for the evaluated capacitors in one specific series, however this is not important, relevant being that over time while subjected to the tests the relative variation of these two parameters are the same at each evaluation point. This criterion is respected during the tests for all capacitor series. Moreover, it is respected even across different series, most notable being series S2 and S3 where capacitance and ESR evolution plots are very similar.

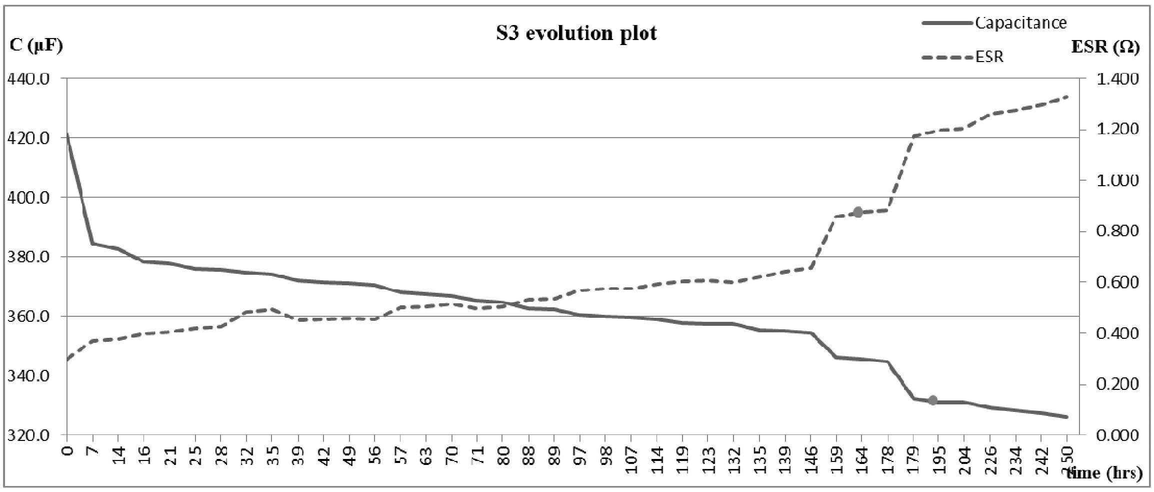
Observing the evolution plots, 3 different regions can be delimitated. Firstly, at the start of the ageing tests there is a sudden drop in capacitance and a rise in ESR values, which in the second stage seem to become more stable and have a linear evolution. From this stage two different tendencies can be separated: smaller capsule capacitors keep this linear evolution until they fail. This is particularly obvious for batch S1. Bigger capsule capacitors, but with the same size, series S2 and S3, have a more sudden rise in ESR values and decrease in capacitance at the end of their lifetime. In addition to this, these capacitors, having packaging sizes very similar, have also similar evolutions. So close in fact, the at 28 hours into the test, they both manifest a so called come-back effect, where for a short period of time the ESR value returns below previously measured values. This effect lasts for both series for 11 hours.

Another tendency of evolution is that found at bigger capsule capacitors, here S4, which after the linear evolution phase suffer a rapid degradation near the end of their lifetimes, capacitance drop and ESR rises being exponential. This is consequent with the findings in [4], which means that capacitors with bigger packaging have the same evolution tendencies as supercapacitors.

Also to be noted that aside from the S1 capacitors, in which capacitive and ESR failures occurred close together, in all other cases ESR failures occurred much earlier on than capacitive failures. This contradicts findings both in [4] and [5], however due however due to the different technologies (electrochemical double layer







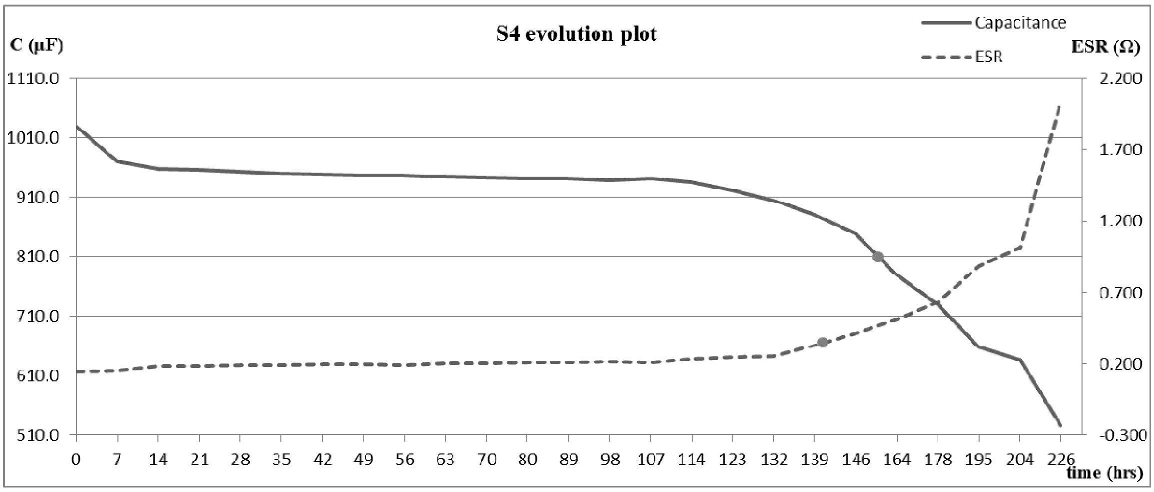


Figure 4. Capacitance and ESR evolution plots during accelerated ageing tests for different capacitors sets.

supercapacitors vs. aluminum electrolytic capacitors) it is very possible that the failure mechanism could differ greatly.

Most stable evolution was noticed also for the S1 capacitors. Analyzing their evolution plots, these had an almost perfectly linear evolution, being the most predictable during measurements, relative capacitance and ESR change being almost always the same at evaluation points

V. CONCLUSIONS

Being widely used and reliability critical components, the lifetime prediction of electrolytic aluminum capacitors was the focus of this article, as it can be affected by high working temperatures in extreme environments [8]. It has been deemed that current prediction algorithms are not accurate enough to precisely estimate lifetime for electrolytic aluminum capacitors. In order to prove this statement, capacitive and ESR failures were analyzed for this class of capacitors.

During the accelerated ageing tests it has been also found that capacitors with smaller packaging tend to be more stable than those with greater capsule diameter, the borderline between these two behaviors being the 6 millimeter mark. This border coincides with that specified by most capacitor manufactures (e.g. 6.3 millimeters for Samxon), which separates different capacitor lifetimes at maximum allowed temperature.

It has been found that smaller capsule capacitors have a linear failure mechanism, both capacitive and ESR failures will occur gradually, over time, while capacitors with bigger packaging will have a more sudden failure rate, reaching an almost exponential evolution as they approach the end of their lifetime. In this manner, these later components, behave just as super- or ultracapacitors, as presented in studies carried out both in [4] and [9].

Plotting of capacitance and ESR evolution lines also proved that the actual capacitances of the components are irrelevant when it comes to ageing and a much more influential factor is the size of the capsule of the components. This fact is supported by two different value capacitors (220 µF and 470 µF) having almost identical evolutions due to very similar casing sizes.

Finally, an improved lifetime prediction algorithm was proposed which combined the advantages that the most precise prediction method had to offer with a correction factor that takes into account capacitor operating voltages versus maximum allowed voltages. Calculations compared to measurement data proved that this prediction method provides higher accuracy than presented methods. Also to be noted that no actual prediction algorithm can achieve 100% accuracy, as none can account for components delivered with manufacturing faults, which cause infant mortality [1].

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