# Physics of failure based analysis of Aluminum Electrolytic Capacitor

Satya Ranjan Sahoo[1*], S.K. Behera[1], Sachin Kumar[2], P.V. Varde[2], G Ravi Kumar[3]

sahoosatyaranjan18@gmail.com

[1] Department of Electronics and Instrumentation Engineering, NIT Rourkela, Odisha 769008

[2] Research Reactor Services Division, Bhabha Atomic Research Centre, Mumbai 400085

[3] Scientific Information and Resource Division, Bhabha Atomic Research Centre, Mumbai 400085

***Abstract***

**Electrolytic capacitors are one of the important devices in various power electronics systems, such as motor drives, uninterruptible power supply, electric vehicles and dc power supply. Electrolytic capacitors are also the integral part of many other electronic devices. One of the primary function of electrolytic capacitors is the smoothing of voltage ripple and storing electrical energy. However, the electrolytic capacitor has the shortest lifespan of components in power electronics. Past experiences show that electrolytic capacitor tends to degrade and fail faster under high electrical or thermal stress conditions during operations. The primary failure mechanism of an electrolytic capacitor is the evaporation of the electrolyte due to electrical or thermal overstress. This leads to the drift in the values of two important parameters-capacitance and equivalent series resistance (ESR) of the electrolytic capacitor. An attempt has been made to age the electrolytic capacitor and validate the results. The overall goal is to derive the accurate degradation model of the electrolytic capacitor.**

***Keywords: Equivalent series resistance, thermal overstress, capacitance***

## I. INTRODUCTION

In the application of large aluminum electrolytic capacitors, the circuit designer faces the problem of obtaining the maximum possible ripple current in the smallest possible package with an acceptable capacitance and useful life. This lifetime is feasible in environment where the optimum temperature surrounding the capacitor is largely dependent on the surrounding temperature, dissipation of power by the capacitor and surrounding components. If the ripple current is pushed too high to reduce the number of capacitors needed, then the rise of temperature due to the equivalent series resistance (ESR) is excessive [1].

If the capacitors are miniaturized, the smaller package size becomes a less efficient heat dissipater, and the ESR is also increased. In either case, the higher temperatures generated internally to the capacitor lead to a shortening of the expected life. There are many approaches in solving this enigma. The usual approach is to specify a capacitor with a higher rated temperature such as 105°C. This approach is unavoidable when the core temperature cannot be reduced below 95°C. Another approach is to lower the ambient air temperature. Specification of very low ESR reduces the heat load on the capacitor, but the limits of low ESR technology are being pushed in many instances already. Circuit designers can also request capacitors with low internal thermal resistance to minimize the rise of the core temperature above the ambient temperature. In cases where efficient heat sinks are economical, the external thermal resistance of the capacitors can be improved. If space is available, the use of larger capacitor packages or Integral Heat Sinks can lower the external thermal resistance, but these approaches run contrary to miniaturization. Unfortunately, many designs have already taken advantage of heat dissipating measures. Alternatively, we can specify longer lifetimes for standard 85°C rated capacitors. Aluminum electrolytic capacitors have been widely used in the electronic industry. Failure mechanism of aluminum electrolytic capacitors due to thermal overstress has been studied.

## II. ALUMINUM ELECTROLYTIC CAPACITOR

As shown in Fig. 1 [2], an aluminum electrolytic capacitor consists of a cathode aluminum foil, electrolytic paper, electrolyte, and an aluminum oxide layer on the anode foil surface, which acts as the dielectric. When in contact with the electrolyte, the oxide layer possesses an excellent forward direction insulation property (Bengt, 1995). To get higher capacitance values for the same surface area of the anode and cathode foils, the foil is etched by a chemical process. Together with magnified effective surface area attained by etching the foil, high capacitance value is obtained in a small volume (Fife, 2006). 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. Here, analysis of non-solid aluminum electrolytic capacitors, in which the electrolytic paper is impregnated with a liquid electrolyte, has been done. After the paltes are etched, they are anodized by coating them with a thin aluminum oxide layer on the surface of the foil. This layer of aluminum oxide acts as the dielectric (insulator) and serves to block the flow of direct current between the two capacitor plates. Figure 2 and Figure 3 shows DB series type Keltron Electrolytic Capacitor that was used for the study.

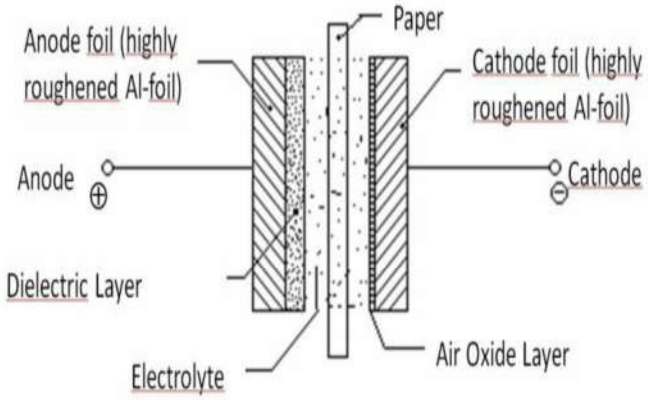


Fig. 1. Internal structure of Aluminum electrolytic capacitor [1].

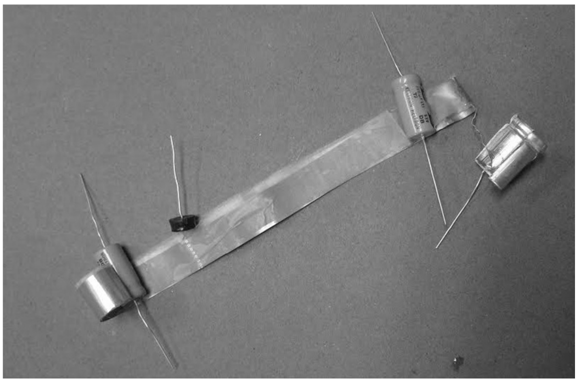

Fig. 2. Cathode of DB series Keltron Aluminum Electrolytic Capacitor.
Source: Photo taken at Life Cycle Reliability Engineering Laboratory, RRSD, BARC Mumbai.

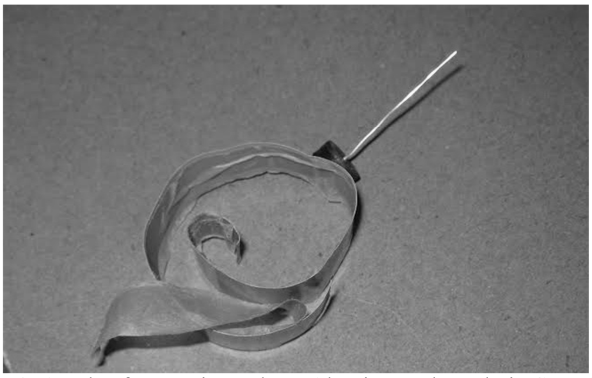

Fig. 3. Anode of DB series Keltron Aluminum Electrolytic Capacitor
Source: Photo taken at Life Cycle Reliability Engineering Laboratory, RRSD, BARC Mumbai.

## III. EQUIVALENT CIRCUIT OF ALUMINUM ELECTROLYTIC CAPACITOR

A simplified electrical lumped parameter model of impedance, M1, defined for an electrolytic capacitor is shown in Figure 4. The ESR dissipates some of the stored energy in the capacitor. An ideal capacitor would offer no resistance to the flow of current at its leads.

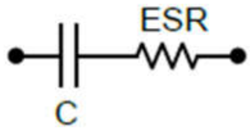


Fig. 4. Lumped parameter model (M1)

It has been observed that under thermal overstress storage conditions (Bengt, 1995; J. Celaya et al., 2011a), the capacitance (C) and ESR value depends of the electrolyte resistance RE. A more detailed lumped parameter model derived for an electrolytic capacitor under thermal overstress condition, M2 can be modified fromM1, as shown in Figure 5. R1 is the combined series and parallel resistances in the model. RE is the electrolyte resistance. The combined resistance of R1 and RE is the ESR of the capacitor. C is the total capacitance of the capacitor.

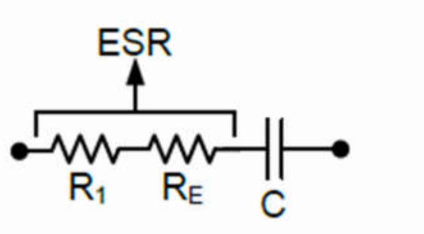


Fig. 5. Lumped parameter model (M2)

## IV. FAILURE ANALYSIS OF ALUMINUM ELECTROLYTIC CAPACITOR

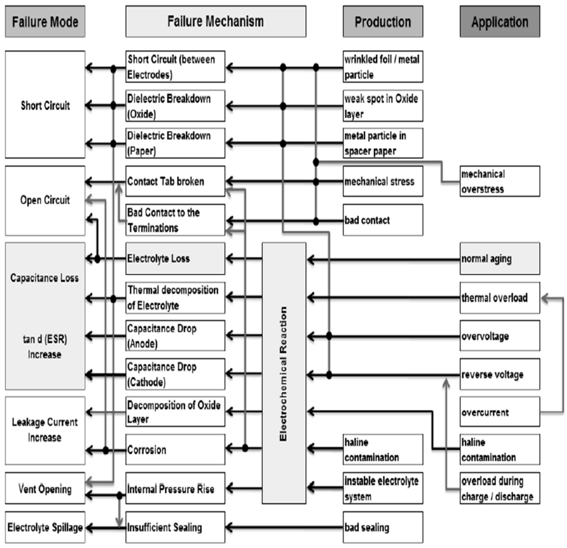


Fig. 6. Failure modes and mechanisms of aluminum electrolytic capacitor

The following two conditions must be considered in defining "failure".

a) Catastrophic Failure:
When a capacitor has completely lost his functions due to a short or open circuit.

b) Degradation Failure:
The gradual degradation of a capacitor. In the case of a degradation failure, the criteria for failure differs according to the use of a capacitor. Capacitor requirements vary depending upon the type of the finished products. Therefore, the specified value in the specification is used as the judging criteria.

Figure 6 and Figure 7 shows different types of failure modes and mechanisms of aluminum electrolytic capacitor [6].

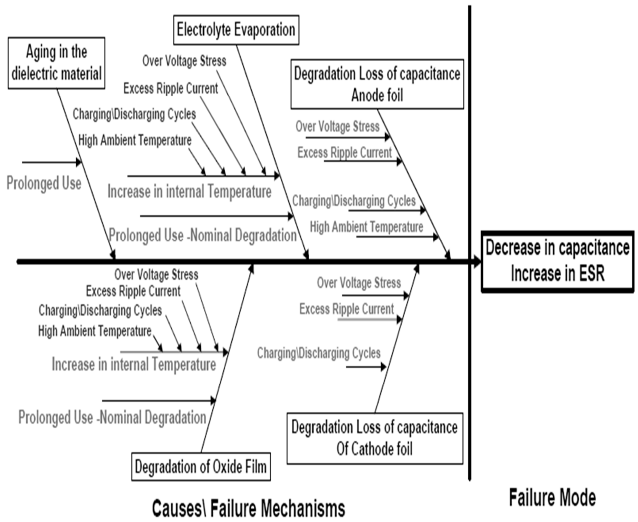


Fig. 7. Fishbone structure of failure mechanism of aluminum electrolytic capacitor

## V. Structural Model of Capacitor

For deriving the physics based models of an electrolytic capacitor it is also necessary to know about the structural and manufacturing details, since health estimations are done based on the type of electrolyte, volume of electrolyte, oxide layer thickness etc. The models defined use this information for making effective degradation/failure predictions [6]. A detail structural study of the electrolytic capacitor under test is discussed in this section. During modelling it is not possible to know the exact amount of electrolyte present in a capacitor. But using information from the structural details as shown in Figure 8, we can approximately calculate the amount of electrolyte present. A very highly porous separator paper is used which soaks all the electrolyte. The paper separator is sandwiched between anode and cathode, each having a thickness dS, dA and dC respectively (dS ~ dA ~ dC). Based on the type and configuration, the electrolyte volume will vary which can be updated in the model parameters. The equation for calculating the approximate electrolyte volume is derived from calculating the total capacitor capsule volume, Vc given by:

$$Vc = \pi * r_c^2 * h_c, \quad (1)$$

Where:
rc = radius of capacitor capsule
hc = height of capacitor capsule
The approximate electrolyte volume, Ve based on all the other known structural details of the capacitor can expressed as:

$$V_e = \pi * r_c^2 * h_c - A_s(d_A + d_C) \quad (2)$$

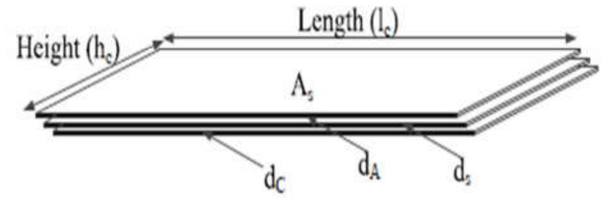


Fig. 8. Open structure of capacitor

## VI. Degradation Model of Capacitor

Exposure to high temperatures, Tapplied > Trated results in accelerated aging of capacitors (Kulkarni, Celaya, et al., 2011; J. Celaya et al., 2011a; 60068-1, 1988). Higher ambient storage temperature accelerates the rate of electrolyte evaporation leading to degradation of the capacitance (Kulkarni, Celaya, et al., 2011; Bengt, 1995). The depletion in electrolyte volume, Ve, (Kulkarni, Biswas, et al., 2011; Rusdi et al., 2005) is given by:

$$V_e(t) = V_0 - (A_s j_{e0} w_e) * t, \quad (3)$$

Where:
$V_0$ = initial electrolyte volume
$J_{eo}$ = evaporation rate
$w_e$ = volume of ethyl glycol molecule
t = time in hours.

The total lumped capacitance from first principles of electromagnetism is given by:

$$C = (2\epsilon_R \epsilon_0 A_s)/d_C \quad (4)$$

Where:
$\varepsilon_R$= relative dielectric constant
$\varepsilon_O$ = permittivity of free space

Thus from Eq. (3) and Eq. (4) we can derive the first principles capacitance degradation model, M3 given by:

$$\mathcal{M}_3 : C(t) = \left(\frac{2\epsilon_R \epsilon_0}{d_C}\right)\left(\frac{V_0 - V_e(t)}{j_{eo}\, t\, w_e}\right) \quad (5)$$

As discussed earlier, increase in the core temperature evaporates the electrolyte thus decreasing the electrolyte volume leading to degradation in capacitance. The resultant decrease in the capacitance can be computed using model, M3 wherein the decrease in electrolyte volume, (Ve) leads to decrease in capacitance, (C).

The flow of current during the charge and discharge cycle of the capacitor causes the internal temperature to rise. The excess heat results in a rise in the internal temperature of the electrolyte.

## VII. Thermal Overstress Experiment

On increasing the temperature of the surrounding, the temperature of core region of capacitor increases leading to the evaporation of the electrolyte.

In the experimental set-up, high temperature storage conditions for capacitor were simulated, where a single capacitor was placed in a controlled chamber and the temperature was raised above their rated specification. Keltron DB series Aluminum electrolytic capacitors were taken from the same lot rated for 63V and maximum storage temperature rating of $85^0$C. Experiments were conducted with 220 uF capacitors with TOS temperature at $115^0$C. The chamber temperature was gradually increased in steps of $25^0$C till the pre-determined temperature limit was reached. The capacitors were allowed to settle at a set temperature for 15 min and then the next step increase was applied. This process was continued till the required temperature limit was attained. To decrease possibility of shocks due to sudden decrease in the temperature, the above procedure was followed. At the end of specific time interval, the temperature was lowered in steps of $25^0$C till the required room temperature was reached. Before being characterized, the capacitors were kept at room temperature for 15 min.

The ESR, Capacitance and ESL value were measured through the Wayne Kerr make Impedance Analyzer.

## VIII. Experimental Setup

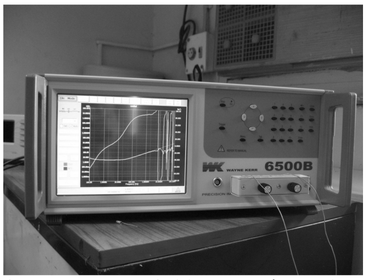


Fig. 9. Wayne Kerr 6500B Impedance Analyzer
Source: Photo taken at Life Cycle Reliability Engineering Laboratory, RRSD, BARC Mumbai.

Fig. 10. Accelerated life, Temperature and Humidity Chamber
Source: Photo taken at Life Cycle Reliability Engineering Laboratory, RRSD, BARC Mumbai.

## IX. Observations and Results

The DB series Keltron Aluminum electrolytic capacitor was initially heated from room temperature.

Table 1

| Temperature (°C) | Capacitance value (uF) | ESR value (mΩ) | ESR(hot)/ESR |
|---|---|---|---|
| 25 | 230.19 | 97.751 | 1 |
| 50 | 235.92 | 68.083 | 0.696 |
| 65 | 236.92 | 61.42 | 0.628 |
| 90 | 242.23 | 45.642 | 0.467 |
| 100 | 245.48 | 43.561 | 0.445 |
| 115 | 251.43 | 37.336 | 0.381 |

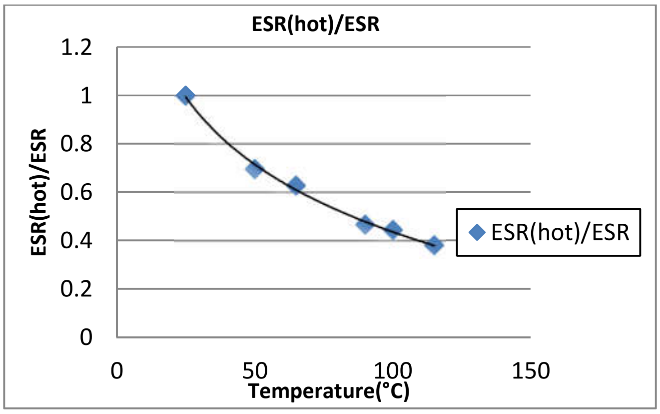


Fig. 11. Plot of ESR with temperature

From figure 11, it is observed that the ESR (effective series resistance) decreases with the increase in temperature. It is because, with the increase in the temperature the conductivity of the electrolyte increase, which leads to the decrease in the ESR.

Conducting wires were connected in the cathode and anode of the aluminum electrolytic capacitor. The capacitor was kept inside the Accelerated life, Temperature and Humidity Chamber as shown in Figure 10, and the temperature was settled at $115^0$C. The wires were taken out from the Accelerated life, Temperature and Humidity Chamber and were connected to the Wyane Kerr Impedance analyzer as shown in Figure 9. The capacitance was measured through Wyane Kerr Impedance analyzer. Following observations was taken:

Table 2

| Temperature (in $^0$C) | Time (in hours) | Capacitance value (in µF) |
|---|---|---|
| 115 | 0 | 254.65 |
| 115 | 20 | 253.60 |
| 115 | 40 | 253.18 |
| 115 | 60 | 253.05 |
| 115 | 80 | 252.87 |
| 115 | 120 | 252.32 |

From Table 2, it is observed that the capacitance value decreases due to thermal overstress.

## X. Conclusion

If the aluminum electrolytic capacitor is subject to thermal overstress for a longer period of time, the capacitance will decrease, whereas the ESR will increase. This is because; when the capacitor is subjected to thermal overstress the electrolyte of the capacitor starts to evaporate. Hence the conductivity decreases which leads to the decrease in capacitance and increase in the ESR value. The behavior of the aluminum electrolytic capacitor with thermal overstress was validated from the above experiment. A life model of Aluminum electrolytic capacitors has been developed that is based on the primary wear-out mechanism of electrolyte vaporization and loss through the end seal. The model incorporates relationships for ESR change with electrolyte loss, ESR change with temperature, and heat transfer value with geometric dimensions.

## XI. References

[1] J. L. Stevens, J. S. Shaffer, and J. T. Vandenham, "The service life of large aluminum electrolytic capacitors: effects of construction and application," in *Conf. Rec. IEEE-IAS Annu. Meeting*, vol. 3, 2001, pp.2493–2499.

[2] Dr. Arne Albertsen, "Electrolytic Capacitor Lifetime Estimation", in JIANGHAI EUROPE GmbH, 2010.

[3] Bengt, A. (1995). Electrolytic capacitors theory and applications. RIFA Electrolytic Capacitors.

[4] Celaya, J., Kulkarni, C., Biswas, G., & Goebel, K. (2011a). A model-based prognostics methodology for electrolytic capacitors based on electrical overstress accelerated aging. Proceedings of Annual Conference of the PHM Society, September 25-29, Montreal, Canada.

[5] Fife, J. (2006, August). Wet electrolytic capacitors (Patent No: 7,099 No. 1). Myrtle Beach, SC: AVX Corporation.

[6] Kulkarni, C. S., Celaya, J. R., Goebel, K., Biswas, G. (2012, September). Bayesian Framework Approach for Prognostic Studies in Electrolytic Capacitor under Thermal Overstress Conditions.

[7] Kulkarni, C., Biswas, G., Celaya, J., & Goebel, K. (2011). A case study for capacitor prognostics under accelerated degradation. IEEE 2011 Workshop on Accelerated Stress Testing & Reliability (ASTR), September 28-30, San Francisco, CA.

[8] Rusdi, M., Moroi, Y., Nakahara, H., & Shibata, O. (2005). Evaporation from water ethylene glycol liquid mixture. Langmuir - American Chemical Society, 21 (16), 7308 - 7310.