FAILURE ANALYSIS OF ALUMINUM ELECTROLYTIC CAPACITORS

An examination of the failure mechanisms in aluminum electrolytic capacitors

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This booklet is the summary of the authors' experience performing failure analysis on aluminum electrolytic capacitors over the past fifteen years.

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Failure Analysis of Aluminum Electrolytic Capacitors

Aluminum electrolytic capacitors (AE) are used primarily for their relatively large capacitance values. They are constructed as illustrated in Fig. 1. These capacitors are fabricated using aluminum foil strips, one of which, the anode, is chemically treated to form a layer of aluminum oxide dielectric. Leads are attached to both the anode and cathode and the strips are rolled into a single roll that is inserted into the aluminum case. The leads feed through a rubber "seal", the assembly is filled with electrolyte, and the case is finally crimped onto the rubber plug seal. Shrink wrap plastic is typically used as an outer layer to permit application of part markings and logos (e.g. Fig. 2 - 4).

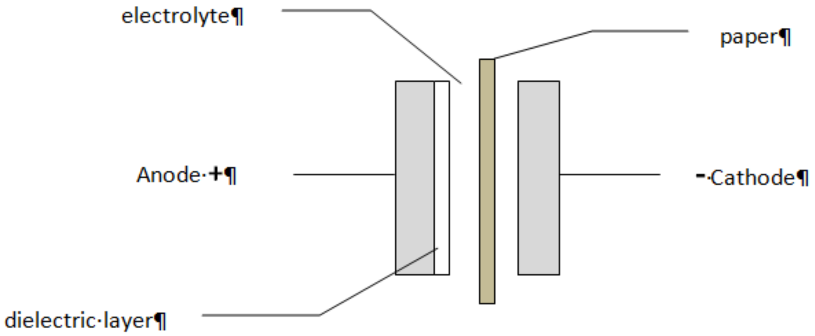

Fig. 1 - Schematic illustration of aluminum electrolytic capacitor construction.

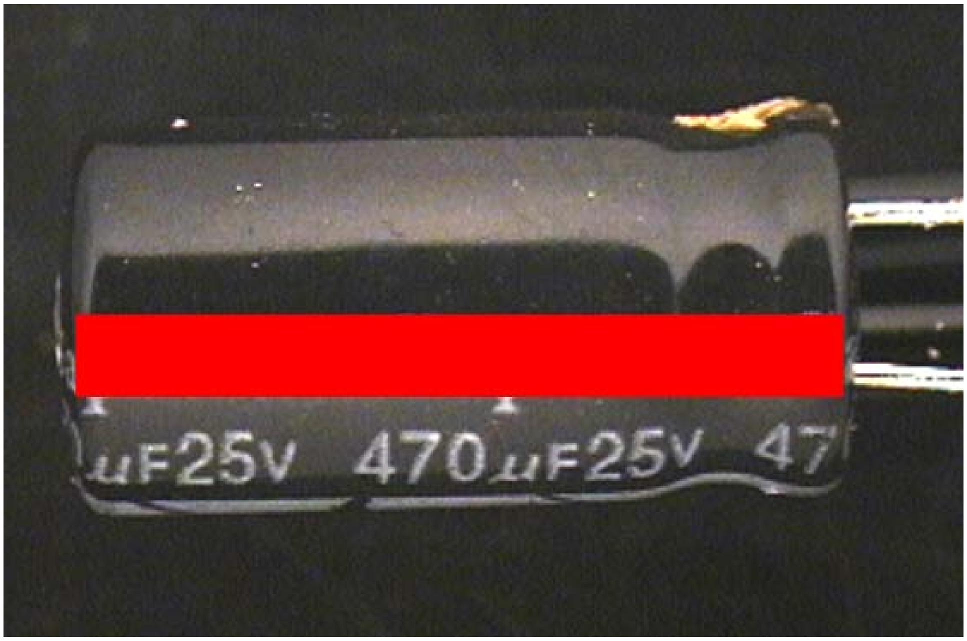
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Fig. 2 – Aluminum electrolytic capacitor, 470 uF, 25V. The manufacture's logo is blanked for anonymity.

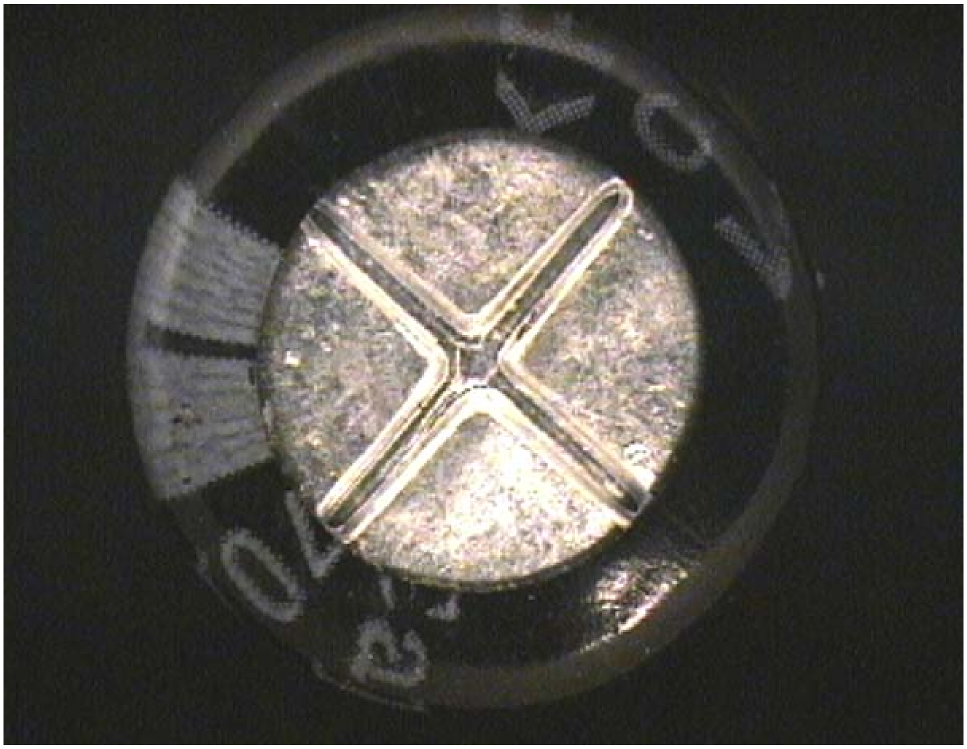


Fig. 3 – Vent at the top end of an aluminum electrolytic capacitor.

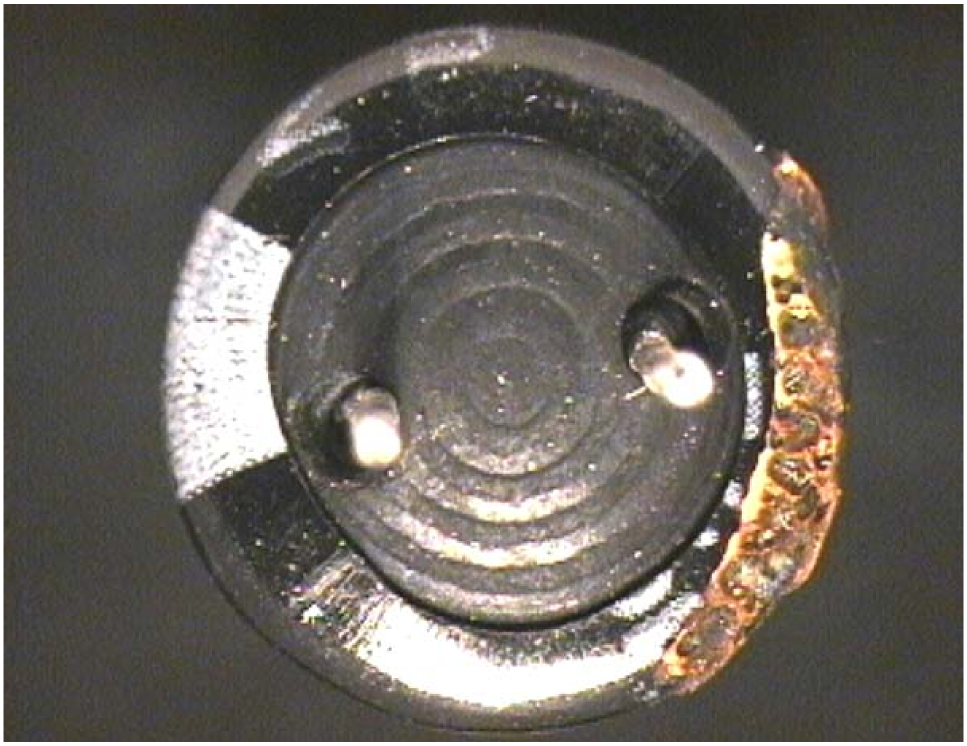


Fig. 4 – Leads exiting the seal at the bottom end of an aluminum electrolytic capacitor.

FAILURE MECHANISMS

WEAR-OUT

Aluminum electrolytic capacitors have a finite lifetime during which capacitance (C) and the volume of electrolyte decrease, while the dissipation factor (DF) and equivalent series resistance (ESR) increase. It is important for the failure analyst to try to determine if the capacitor failure is the result of a normal wear-out process, the failures are related to some type of inherent weakness in the capacitors (e.g. bad electrolyte, poor construction, etc), or the capacitors were subjected to damage as a result of assembly into the printed wiring board (e.g. excessive temperature, lead stress, solvent ingress, etc).

The lifetime is typically considered the time until the capacitance reaches half of its initial value. Alternatively, the lifetime may be considered the time until the dissipation factor reaches double its initial value. Aluminum electrolytic capacitors are rated for a certain load life at rated voltage and temperature. For example, a typical capacitor might be rated for 1000 hrs at 16V and 105°C. The life of aluminum electrolytic capacitors decreases with increasing operating (or core) temperature. Generally the operating temperature is significantly less than the rated maximum temperature such that the expected life is significantly longer that the rated load life. The time-to-failure as a function of temperature can be estimated using Eq. 1.

$$t_f = A \cdot \exp\left(\frac{E_a}{kT}\right) \quad \text{Eq. 1}$$

where,

t_f = time to failure (hours)

A = 2.96E-10 (hours) for 1000 hour-105°C capacitors

E_a = the activation energy = 0.94 eV

k = Boltzman's constant = 8.62E-05 eV/°K

T = operating or core temperature (°K)

The constant, A, can be calculated for a variety of different capacitor grades. Examples of these values are listed in Table 1. Larger values of the constant "A" represent longer lifetimes for the respective capacitors.

Table 1 – Calculated life constant, A, for equation 1 for various commercially available aluminum electrolytic capacitors.

T(C)	t (hrs)	A (hrs)
105	1000	2.96E-10
125	1000	1.26E-09
105	2000	5.92E-10

The amount of electrolyte in the capacitor decreases, the capacitance decreases, and the dissipation factor increases as the capacitor nears the end of life condition as shown in Fig. 5. One of the key observations related to wear-out is the absence of electrolyte, i.e. the capacitor is "dried out". This is considered the cause of the corresponding loss of capacitance during wear-out. The loss of mass due to electrolyte loss during normal wear out can be modeled using Eq. 2.

$$M = M_{init} - \mathrm{A} * (\exp(\mathrm{Bt}) - 1) \quad \text{Eq. 2}$$

where,

M = mass of the capacitor (grams)

M_{init} = initial of the capacitor (grams)

A & B = constants

t = operating age (years)

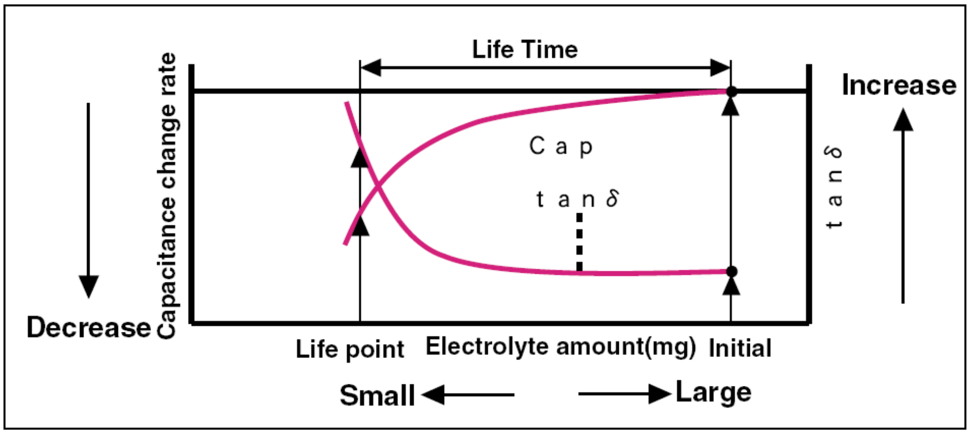


Fig. 5 – Wear-out characteristic of aluminum electrolytic capacitors [5].

Eq. 2 was used to fit experimental data for a group of capacitors that had failed (i.e. $C \leq 0.5*C_0$) and a group from the same lot of capacitors that had not yet failed (i.e. $C > 0.5*C_0$) as shown in Fig. 6. Regression analysis gave parameter values of A = 0.032 grams, B = 1.29

yr^{-1}, and M_{init} = 2.52 grams. There is a significant amount of scatter in the data, but the trend is fairly clear. The capacitors as a group exhibit a loss of mass with operating time that is understood as the loss of electrolyte. This data suggested that the capacitors that had not yet failed were likely to fail after additional operation and were not likely different than the "bad capacitor".

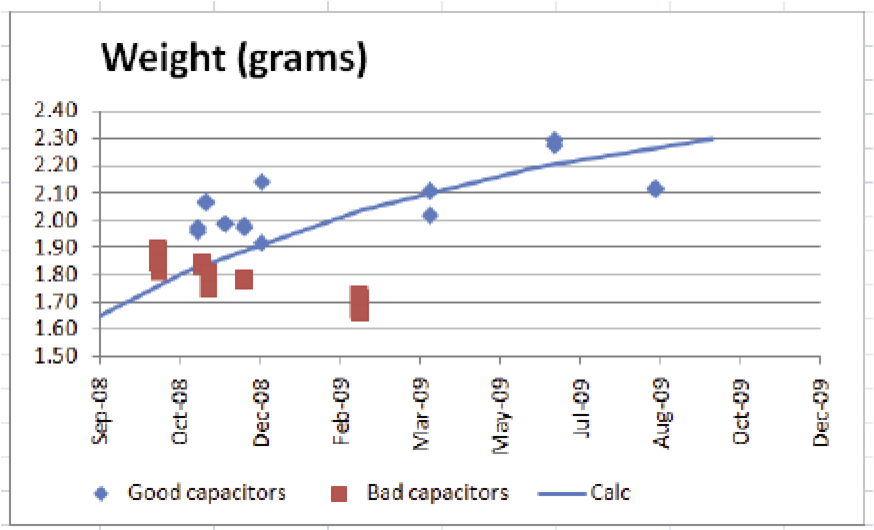


Fig. 6 - Capacitor mass versus PCBA lot date code (note - operating time increases right-to-left).

The loss of capacitance during normal wear-out can be modeled with the following equation, which is essentially the same as Eq. 2,

$$C = C_{init} - A * (\exp(Bt) - 1) \qquad \text{Eq. 3}$$

where,

C = capacitance (F)

C_{init} = initial capacitance (F)

A & B = constants

t = operating age in years

Capacitance measurements can be made on a suspect lot of capacitors as a function of operating time and the data regression fit to Eq. 3. This then allows for calculation of the "actual life" of the capacitors, i.e. time to $C = 0.5*C_0$, which can be compared to expected life. If the actual life is significantly lower than the expected life, then one can begin to try to identify the cause of the premature failures.

OPERATING TEMPERATURE

The operating temperature is a significant factor limiting the operating life of AE capacitors (see Eq. 1 above). The first consideration is generally given to the maximum ripple current in the application, which causes joule heating of the capacitor. Manufacturers specify the maximum ripple current for their capacitors often along with derating factors for ambient temperature, frequency, and air velocity [11]. It is important to define these parameters in order to establish that any suspected premature failures are not due to inaccurate accounting of the effects of ripple current on the operating temperature of the capacitors. Parler [11] suggests that large core temperature rises from high ripple current shorten life more than one might expect because increasing ESR accelerates the temperature rise.

The effect of excessive operating temperature on the physical condition of AE capacitors is generally similar to normal end-of-life characteristics, including loss of electrolyte, loss of capacitance, and increased dissipation factor (& ESR). The diagnosis of excessive operating temperature therefore generally requires independent verification by way of thermocouple measurements on the capacitors in the actual application.

FOIL PURITY

Hillman and Helmold [1] identify the purity of the aluminum foil as one factor that can contribute to excess hydrogen gas formation in aluminum electrolytic capacitors. The purity threshold is stated to be 98% by weight aluminum. Below this threshold, impurities such as iron, copper, and zinc can form a galvanic couple with the aluminum and generate electrons that react with hydrogen ion according to Eq. 4.

$$2H^+ + 2e^- \rightarrow H_2\ (g) \qquad \text{Eq. 4}$$

The gas can build up internal pressure inside the capacitor case forcing electrolyte out of the case usually past the seals or by rupturing the vent resulting in decreased capacitance and ultimately failure of the capacitor.

This failure mechanism may appear to be very similar to normal wear-out failure. The confirmation required is determination of the foil purity. If the foil purity is determined to be less than ~ 98% aluminum, then this mechanism should be considered a contributing factor in the failure.

SOLVENT INGRESS

Aluminum electrolytic capacitors sometimes fail open-circuited due to corrosion of the leads or lead attachments to the foil. Halogenated solvents corrode capacitors through the following chemical reactions [14],

Decomposition of solvent …

$$RX + H_2O > ROH + H^+ + X^-$$

where

RX is the halogenated solvent

X^- is the halogen ion (typically Cl^- or Br^-)

Corrosion reactions …

$$Al + 3X^{-} > AlX_3 + 3e^{-}$$

$$AlX_3 + 3H_2O > Al(OH)_3 + 3H_2 + 3X^{-}$$

The presence of halogen ions causes aluminum to continuously dissolve producing hydrogen gas, increasing the capacitor's leakage current, and resulting in venting or an open circuit failure.

If a capacitor is installed on a printed circuit board with the spacing of its lead wires forcibly spread or narrowed, cleaning solvents can penetrate the capacitor and cause corrosion. Therefore, it is important to ensure that the hole-spacing on the board matches the lead spacing of the capacitor before installation. Furthermore, halide flux contamination in the cleaning solvent may penetrate a capacitor and cause corrosion.

REVERSE POLARITY

Reversing polarity for an aluminum electrolytic capacitor results in a reaction to form alumina dielectric on the cathode foil, which rapidly generates hydrogen gas [8]. The reaction is,

$$2Al(s) + 3H_2O(l) >>> Al_2O_3(s) + 3H_2(g)$$

The gas generally causes venting of the capacitor along with electrolyte leakage and functional failure. Polarity of suspect AE capacitors should always be documented prior to removal from the assembly as part of the failure investigation.

FAILURE ANALYSIS

Failure analysis of AE capacitors should generally include all or most of the following analysis steps,

- gather relevant information
- measure the mass of the capacitor
- electrical measurements
- external examination
- internal examination
- SEM/EDS analysis
- FTIR analysis of electrolyte
- microsection analysis of foil

This list is by no means exhaustive, but it provides a good basis for determination of root cause in most cases. Each of these are discussed in the following sections.

RELEVANT INFORMATION

Prior to conducting failure analysis of suspect AE capacitors the analyst should review the device specification and attempt to define the actual tine-to-failure, the expected time-to-failure, the actual loading conditions (e.g. ripple current, voltage levels, etc.) in the application, ambient temperature, and any other available relevant information. This can help to remove possible factors from the list of causes and help focus attention on the remaining factors during the analysis effort.

MASS OF THE CAPACITOR

The mass of the suspect AE capacitors should be measured and compared to identical devices that are in "new" condition. This information provides a measure of the level of electrolyte loss, if any. If possible, it can also be advantageous to measure the mass of identical devices that have not yet failed in order to determine the apparent wear-out characteristic as was described in the "Failure Mechanisms - Wear-out" section above.

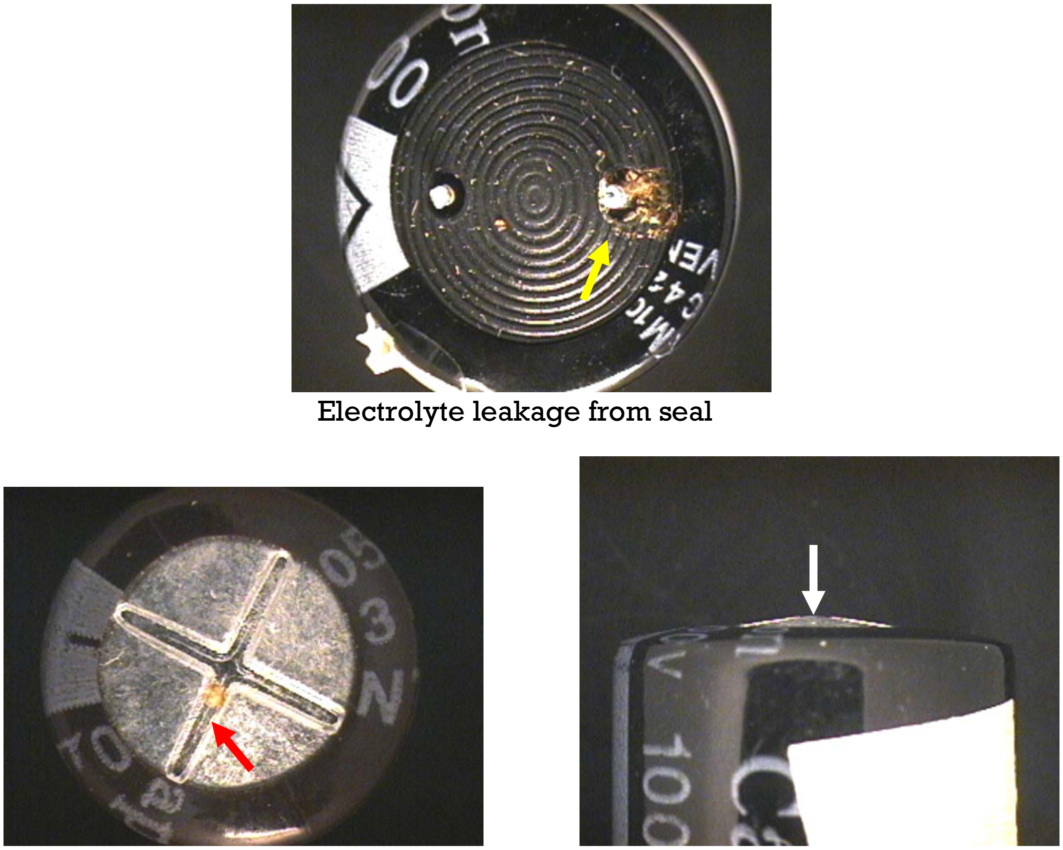
ELECTRICAL MEASUREMENTS

Electrical measurements should include capacitance, dissipation factor, and electrical leakage current at rated voltage. These measurements should also be made on devices that are in "new" condition and devices that have not yet failed for comparison with the subject failure.

It is often important to "condition" the devices at rated voltage prior to making capacitance and dissipation factor measurements. Ref. [3] states that "aluminum electrolytic capacitors stored for more than 5 to 10 years may have increased levels of DC leakage current." This implies that the devices are inherently unstable if stored without a bias voltage to maintain the integrity of the dielectric. The conditioning treatment at rated voltage is intended to heal some of the damage due to degradation during storage.

EXTERNAL EXAMINATION

External examination documents the external condition of the capacitor including the condition of the vent, the rubber seals, and the case. Vent rupture, electrolyte around the seals, and bulging of the case are all indicators of possible wearout failure. Bulging is reportedly caused by the generation of hydrogen gas within the case [1]. The generation of hydrogen gas at damage sites in the dielectric layer begins to exceed the capacity of depolarizers in the electrolyte that are intended to inhibit the gas formation [5].



Electrolyte leakage from seal

Electrolyte leakage at vent

Bulging capacitor

Fig. 7 – External examination of an aluminum electrolytic capacitor.

INTERNAL EXAMINATION

Internal examination can be performed after carefully opening the aluminum can. One way to accomplish this is to carefully bisect the can using a clean, sharp X-acto blade (Fig. 8). The first observation to note is whether or not the capacitor roll appears wet or dry. The roll shown in Fig. 8 is still wet with electrolyte. If wet, samples of electrolyte can be collected for FTIR and SEM/EDS analysis.

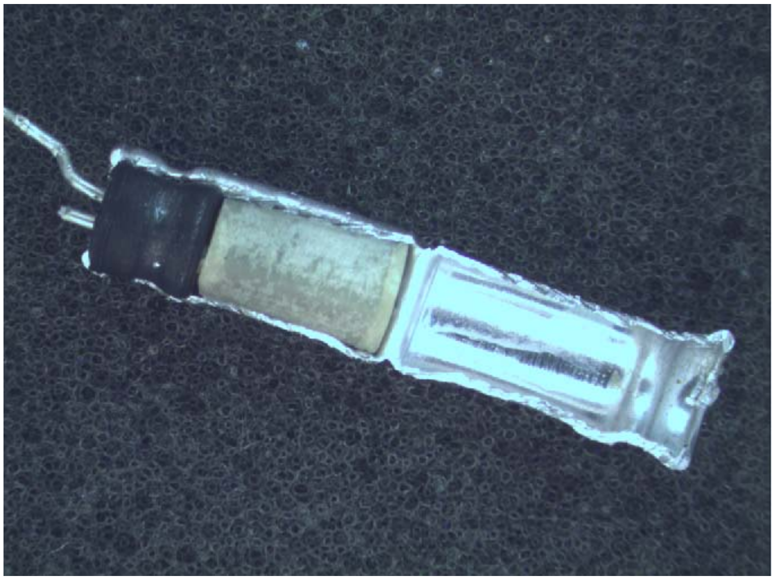


Fig. 8 - Bisected AE capacitor. Note that the anode lead was clipped in order to maintain identification during subsequent dissection.

The roll can be removed from the can and the seal can be slipped off of the leads (might require prior straightening of the leads). The inside surface of the seal should be examined in the SEM in order to document any contamination that may have ingressed at the lead/seal interface.

The capacitor should be unrolled for examination of the anode and cathode foil for any damage areas and examination of the termination of the leads to the foil (e.g. Fig. 9).

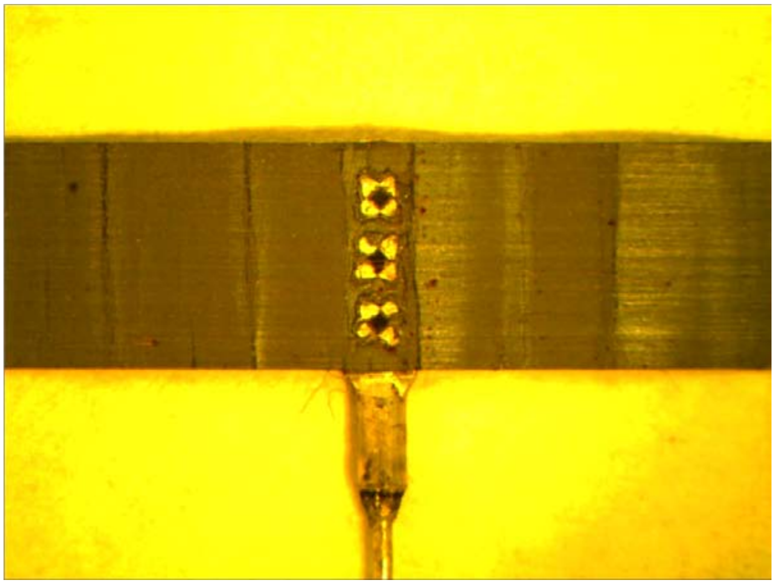


Fig. 9 - Swaged termination to capacitor foil.

At this stage, samples can be obtained for SEM/EDS analysis of the anode and cathode foil, the paper separator layer, and the terminations.

SEM/EDS ANALYSIS OF ELECTROLYTE

SEM/EDS analysis is useful for analyzing the condition of the foil surfaces, the presence or absence of corrosion at the terminations, and the elemental spectra of various internal components.

SEM/EDS analysis of various residues on internal surfaces of aluminum electrolytic capacitors have shown the following list of elements. Some of these are likely constituents of the electrolyte. Some may be contaminants.

Phosphorous –from phosphoric acid, a primary electrolyte constituent.

Aluminum –an important indicator if dielectric thinning, which causes an increase in capacitance, is the operative failure mode [2].

Oxygen –expected as Al_2O_3, H_2O, glycol, and in the cellulose paper.

Carbon - an expected constituent in glycol and in the cellulose paper.

Calcium –found in capacitor aluminum foil as impurity in [2]; possible getter constituent.

Silver – possible impurity in aluminum foil.

Zinc - can form galvanic couples with aluminum [2]; possible getter constituent.

Chlorine –usually considered a contaminant [4].

Silicon – from silicone seals.

Sulfur – possible getter constituent.

Fig. 10 shows the SEM EDS spectrum and associated BSE SEM images for an electrolyte sample dried onto copper SEM mounting tape. The copper tape provides a background signal of copper, which is not an expected constituent of the electrolyte. Use of a typical aluminum SEM sample stub would preclude examination for dissolved aluminum in the electrolyte sample.

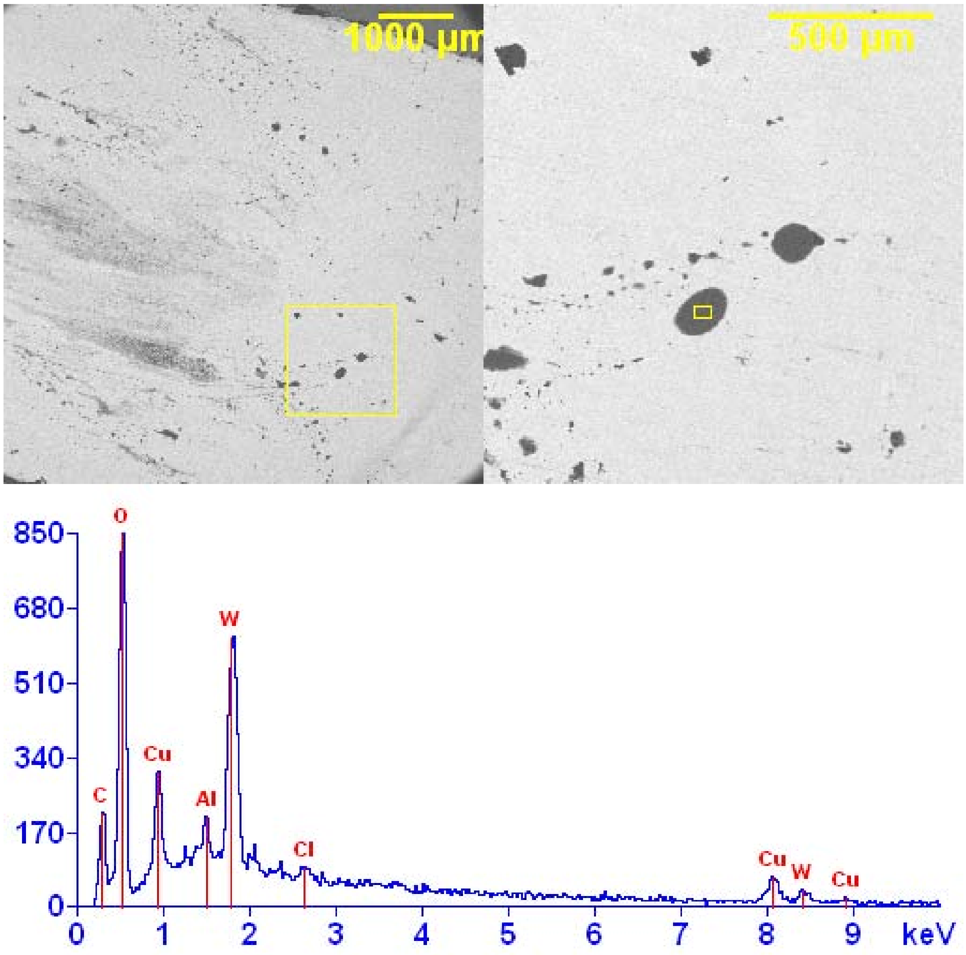


Fig. 10 - EDS spectrum of electrolyte on copper substrate. The aluminum in the spectrum is an indication of possible internal corrosion caused by the electrolyte.

FTIR ANALYSIS OF ELECTROLYTE

The primary constituent of the electrolyte is typically antifreeze. Fourier Transform Infrared (FTIR) Spectrometry can be useful for characterization of electrolyte constituents. Fig. 11 shows the FTIR spectrum of capacitor electrolyte compared with a reference spectrum for orange-antifreeze. The antifreeze is primarily a medium for convective heat transfer. It also extends the operating temperature range of the capacitor since it raises the boiling point of the electrolyte and reduces its freezing point.

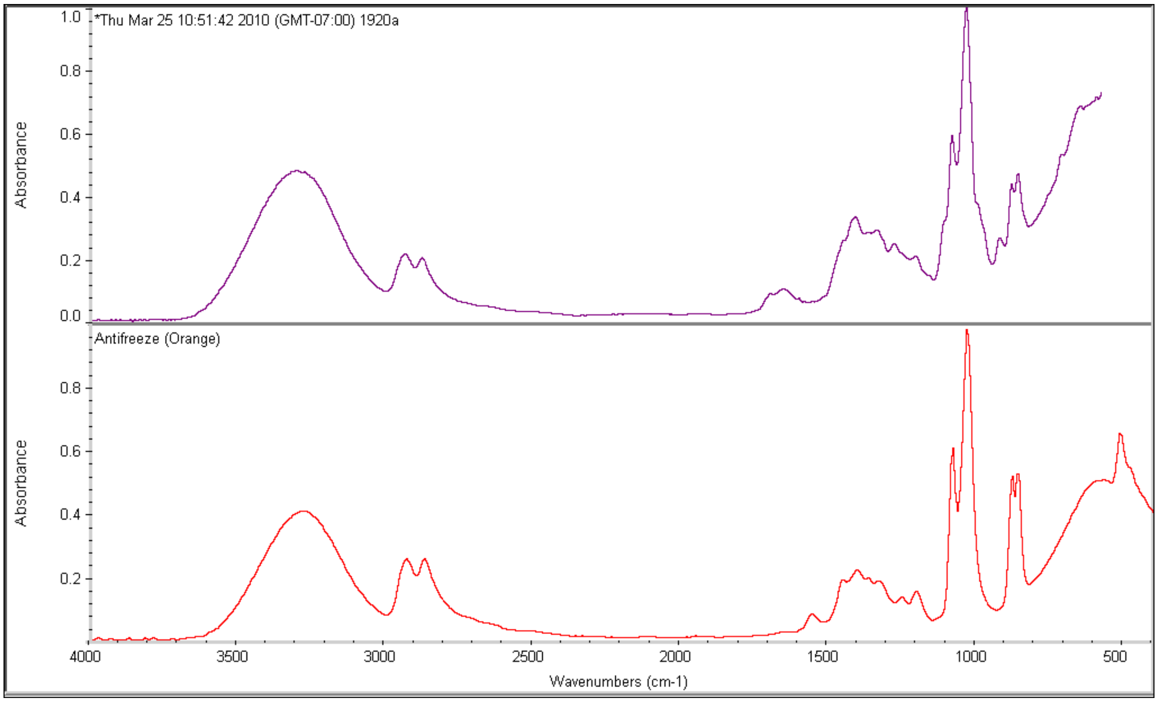


Fig. 11 – FTIR spectrum of capacitor electrolyte compared with a reference spectrum for orange-antifreeze (capacitor label 450V, 270 uF, 715606 (M), HC, CE, 105°C).

Ref. [3] states that "Water in the electrolyte plays a big role. It increases conductivity thereby reducing the capacitor's resistance, but it reduces the boiling point so it interferes with high temperature performance, and it reduces shelf life. A few percent of water is necessary because the electrolyte maintains the integrity of the aluminum oxide dielectric."

The authors of this booklet have investigated the use of FTIR spectra to quantify the water in electrolyte. This investigation included creation and analysis of standards of ethylene glycol based antifreeze with known additions of water (see Fig. 12). Subsequently, the FTIR spectra of actual electrolyte were analyzed (e.g. Fig. 13). The concentration of water for the example in Fig. 13 was estimated as 1.2% by volume, which is less than the "few percent of water" that [3] suggested is required for acceptable electrolyte conductivity. This seems to make sense since the capacitor had failed and was at or near its end of life condition.

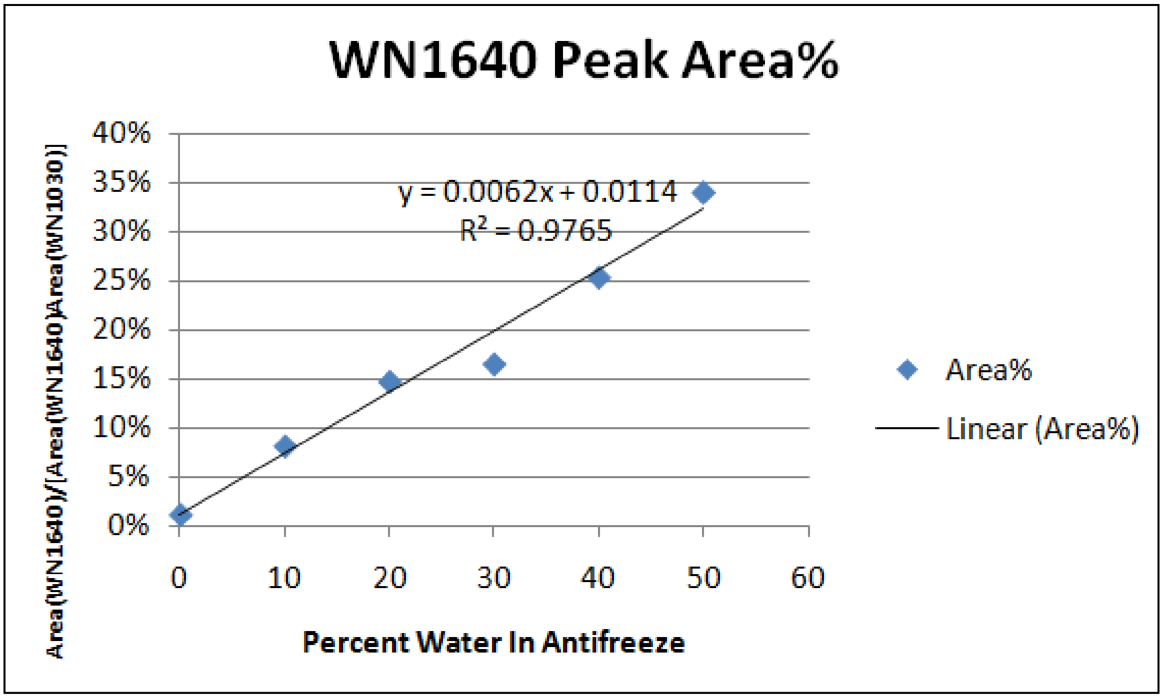


Fig. 12 - Calibration curve for water in electrolyte based on the area fraction of the WN1640 peak relative to the WN1030 peak for various standard solutions.

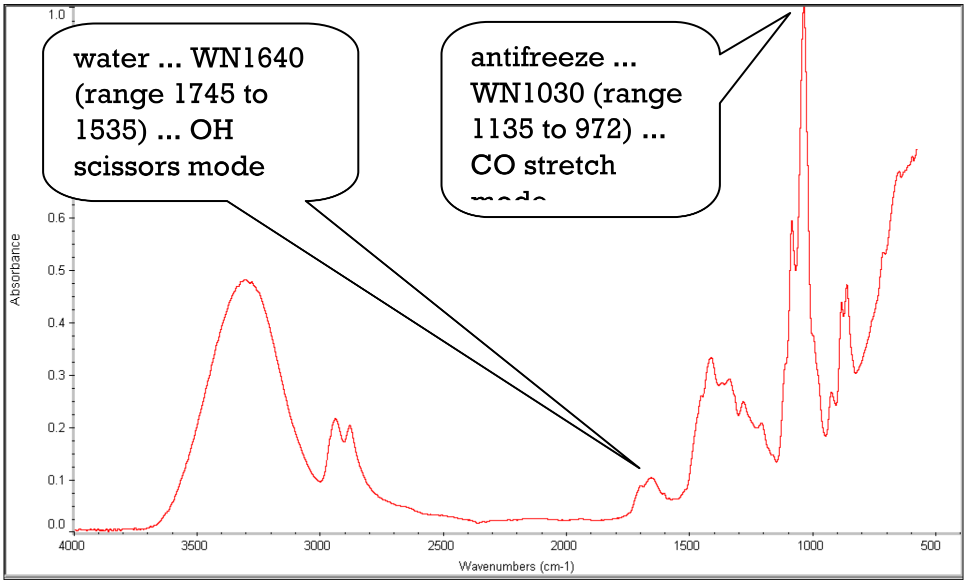
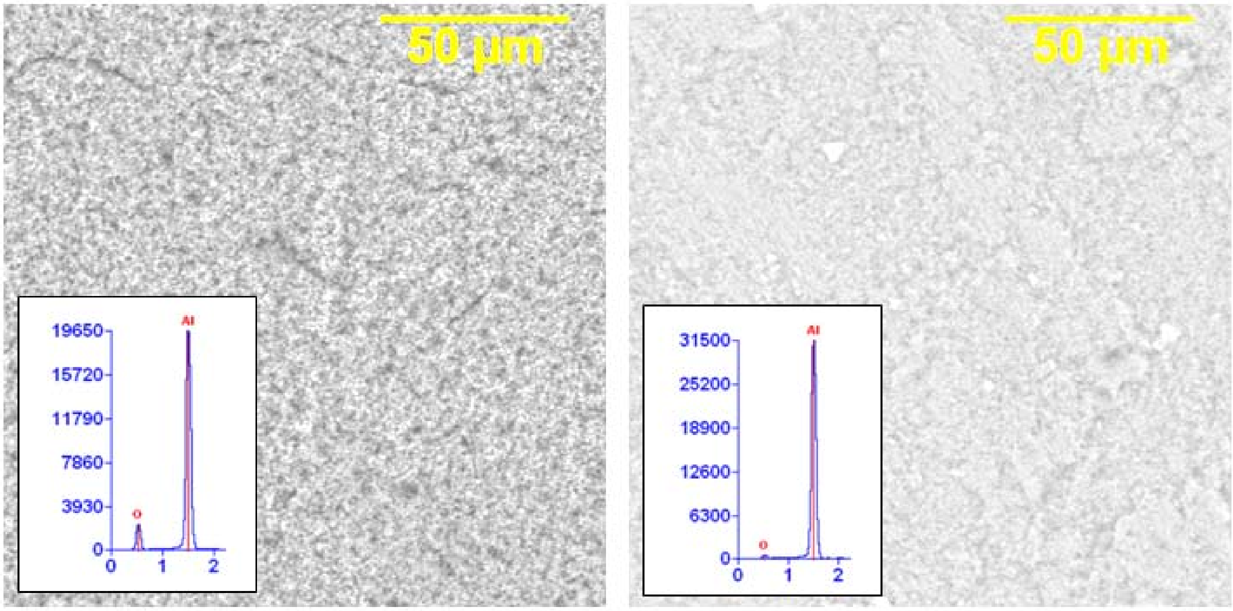


Fig. 13 - FTIR spectrum of capacitor electrolyte.

SEM/EDS ANALYSIS OF FOIL SURFACE

SEM/EDS analysis of the foil surface can reveal corrosion damage and other anomalies related to the failure of the capacitor. Fig. 14 shows BSE SEM images of the anode and cathode foil surfaces respectively for a "known good" capacitor. The insets in these images are the elemental spectra from the same surfaces showing thick oxide dielectric on the anode as a larger oxygen peak.



Anode foil - known good capacitor

Cathode foil - known good capacitor

Fig. 14 - BSE SEM images of the anode and cathode foil surfaces respectively for a "known good" capacitor. Insets are the elemental spectra from the same surfaces showing thick oxide dielectric on the anode.

Fig. 15 shows a BSE SEM image of a cathode foil surface from a failed capacitor. The surface shows areas of oxidation indicating that the cathode was corroded. This type of damage can occur due to reverse biasing or perhaps from long periods of storage under no electrical bias.

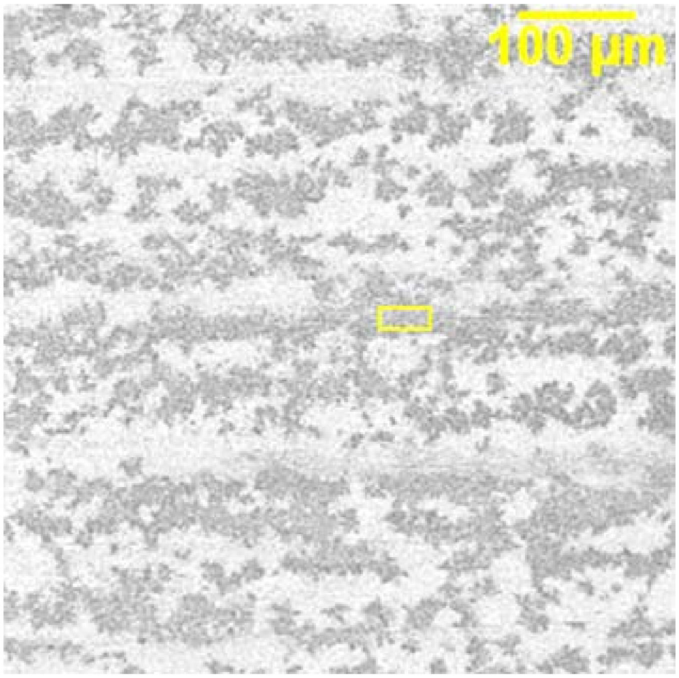


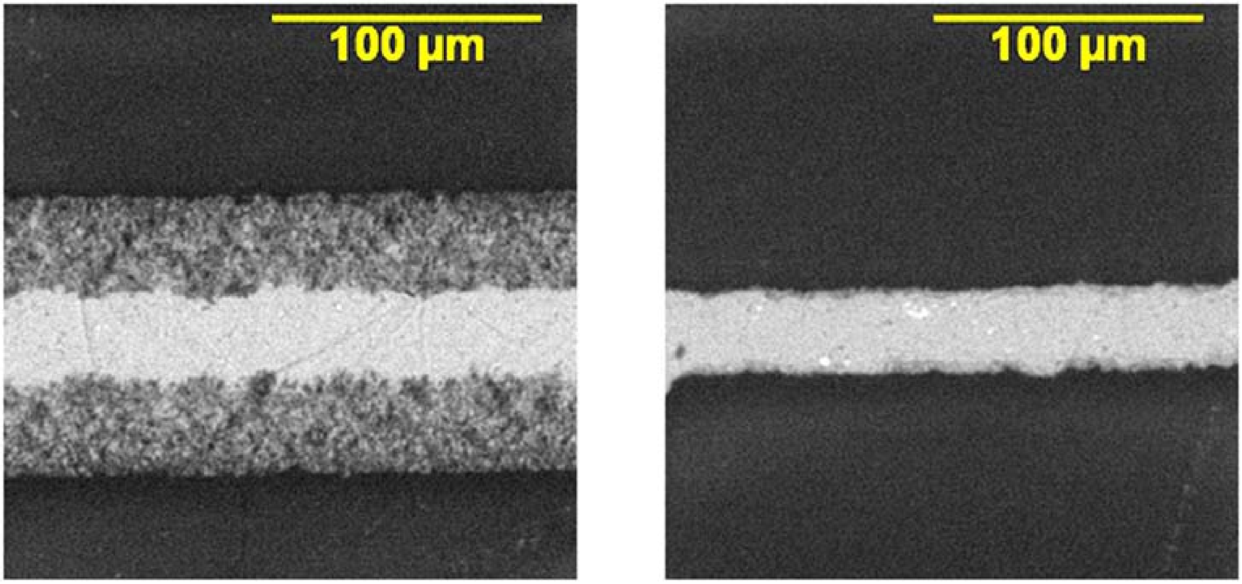
Fig. 15 - BSE SEM image showing oxidation (corrosion) of the cathode foil surface (darker contrast material - e.g. yellow box).

MICROSECTION ANALYSIS OF FOIL

Microsection analysis provides microstructural detail including the depth of the "deep etching" of the anode foil, foil thickness, level of corrosion damage, and other important factors affecting performance of aluminum electrolytic capacitors.

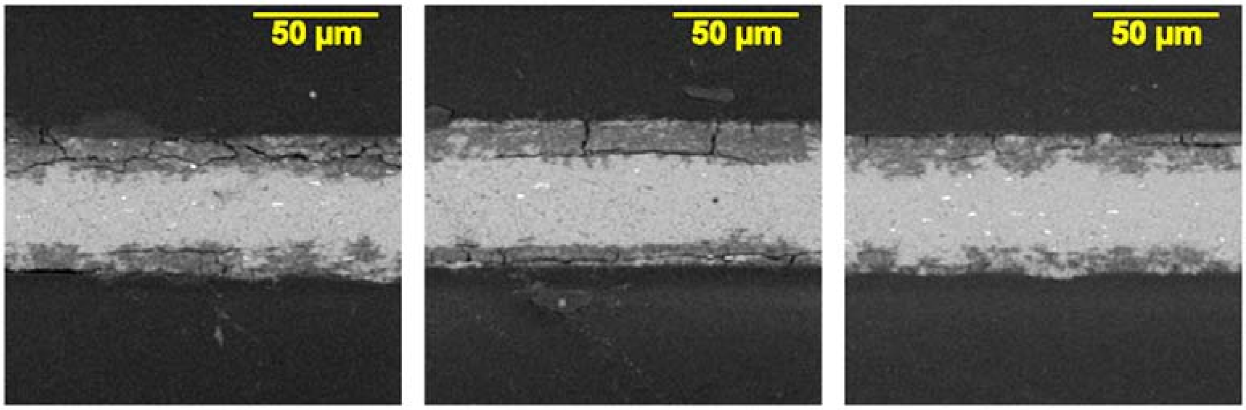
Fig. 16 shows anode foil and cathode foil microsections from a "known good" capacitor. The anode shows a thick layer of "deep etching" on both sides of the foil. The cathode foil shows a very thin layer of oxide that is likely a combination of "native oxide" and corrosion.

Fig. 17 shows microsections of the cathode foils from some suspect capacitors that had reportedly failed with high dissipation factor. It appears as though the DF correlated with the degree of corrosion damage of the cathode foil. This makes sense since the corrosion product, Al_2O_3, is an electrical insulator and would be expected to drive up the dissipation factor and equivalent series resistance.



Anode foil Cathode foil

Fig. 16 - BSE SEM images of anode and cathode foil from a "known good" capacitor.



DF = 0.243 DF = 0.233 DF = 0.174

Fig. 17 - BSE SEM images of cathode foil from a suspect capacitors. The maximum dissipation factor (DF) should be 0.19. It appears that the DF correlates to the degree of corrosion damage of the cathode foil.

CONCLUSIONS

Failure analysis of aluminum electrolytic capacitors can be a daunting task due to the complexities of the failure mechanisms related to these devices. This booklet provides a framework for evaluation of failed devices that in many cases lead to a determination of root cause and appropriate corrective action.

Perhaps one of the most overlooked considerations is the degradation that can occur in aluminum electrolytic capacitors during long term storage. Since in many case the devices are on circuits stored in warehouses for various times and under various conditions prior to delivery to the end user, a significant fraction of reported failures may be related to degradation that limits subsequent life in the application.

REFERENCES

[1] Craig Hillman and Norman Helmold, “Identification of Missing or Insufficient Electrolyte Constituents in Failed Aluminum Electrolytic Capacitors”, CARTS 2004: 24th Annual Capacitor and Resistor Technology Symposium, 29 March – 1 April.

[2] Reliability of Aluminum Electrolytic Capacitors, http://www.industrial.panasonic.com/www-data/pdf/ABA0000/ABA0000TE4.pdf .

[3] Application Guide, Aluminum Electrolytic Capacitors, Cornell Dubilier, http://www.cde.com/catalogs/AEappGUIDE.pdf .

[4] Sam G. Parler, Jr., “Selecting and Applying Aluminum Electrolytic Capacitors for Inverter Applications”, Cornell Dubilier.

[5] Technical Guide of Aluminum Electrolytic Capacitors, Matsushita Electronic Components Co. LTD, March 2, 2000.

[6] “Low-ESR Aluminum Electrolytic Failures Linked to Taiwanese Raw Material Problems”, Passive Component Industry Magazine, September/October 2002.

[7] Edward R. Eaton et al, “A Chemical Base for Engine Coolant / Antifreeze with Improved Thermal Stability Properties”, SAE Technical Paper Series, 2001-01-1182.

[8] Otto Klug, Ph.D. and Andrew Bellavia, "High Voltage Aluminum Electrolytic Capacitors: Where Is The Limit?", © 2001.

[9] Michael L. Gasperi, "A Method for Predicting the Expected Life of Bus Capacitors", IEEE Industry Applications Sociaty, Annual Meeting New Orleans, Louisiana, October 5-9,1997.

[10] P . Venet, F. Perisse, M. H . El-Husseini, & G. Rojat, "Realization of a smart electrolytic capacitor circuit", IEEE Industry Applications Magazine, Jan-Feb 2002, www.ieee.org/ias.

[11] Sam G. Parler, Jr., P.E., "Deriving Life Multipliers for Electrolytic Capacitors", IEEE Power Electronics Society Newsletter, vol. 16, no. 1, Feb. 2004, pp. 11-12.

[12] Sam G. Parler, Jr., "Thermal Modeling of Aluminum Electrolytic Capacitors". Presented at the IEEE Industry Applications Society Conference, October 1999.

[13] Brian Smith, Infrared Spectral Interpretation - A Systematic Approach, CRC Press, 1999, ISBN 0-8493-2463-7.

[14] Technical notes, United Chemi_Con, "Cleaning", http://www.chemi-con.com/index.php?option=com_content&view=article&id=30&Itemid=41, active link as of Feb. 7, 2012.