

# Rubber Sealing Materials for High Voltage and High Temperature Aluminium Electrolytic Capacitors

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## ABSTRACT

Rubber sealing materials play an important role in aluminium electrolytic capacitors, especially at high voltages and high temperatures. These materials must have outstanding temperature resistance; optimum hardness and mechanical strength for long lasting sealing results; excellent electrical insulating properties; and chemical compatibility with organic solvents and the electrolytes. Ethylene Propylene Diene Monomer (EPDM) rubber is the most commonly used sealing material in aluminium electrolytic capacitors. A series of EPDM-based rubber sealing materials have been examined and characterised by several elastomeric test methods, such as compression set test, as well as chemical compatibility and diffusion tests. The application of EPDM rubber materials in high voltage and high temperature screw terminal aluminium electrolytic capacitors has been investigated via capacitor endurance tests at 400 V and 125°C for 3000 hours. The EPDM rubber sealing materials have shown significant difference in the diffusion rate within  $\gamma$ -butyrolactone (BLO) based and ethylene glycol (EG) based electrolytes. The different EPDM rubbers have a noticeable effect on the capacitor's performance (e.g. ESR). In addition, the rubber selection and ageing mechanism at high temperatures have been discussed.

## 1. INTRODUCTION

With the increase in the industrial demand for aluminium electrolytic capacitors, especially for large screw terminal electrolytic capacitors working at high voltages and high temperatures, long life and high reliability are required. In these applications, the electrolyte used in the capacitors is crucial to ensure excellent capacitor performance. However, elastic sealing materials, i.e. rubber seal rings or rubber gaskets, are also one of the key factors that influence the capacitor performance, particularly the capacitor life. This is because poor rubber sealing materials in the capacitors will cause the diffusion of the electrolyte when operating at high temperatures, e.g. 125°C. This in turn results in high equivalent series resistance (ESR) due to capacitor dry-out. At present, the major elastic sealing materials used in the electronic industry are natural rubber (cis-polyisoprene, NR); ethylene propylene rubber (ethylene propylene copolymer, or a terpolymer with a diene); butyl rubber (isobutylene-isoprene copolymer), styrene butadiene rubber (SBR) and silicone rubber (methyl vinyl silicone); etc. However, Ethylene-Propylene-Diene Monomer (EPDM) elastomers are becoming the fastest growing materials in the market,<sup>1</sup> and this is because the EPDM rubber materials are chemically and thermally more stable than conventional elastomers such as NR and SBR rubbers.<sup>2</sup> Also, EPDM rubbers have excellent resistance to ozone and oxidation, good ability to accommodate large quantity of filler and oil, low temperature flexibility and colour stability. EPDM rubbers are used in a wide range of applications, especially in electrical insulators, as sealing materials and in a variety of automotive applications.<sup>1-3</sup>

EPDM rubber is a type of general-purpose synthetic rubber, which is synthesised through the polymerisation of ethylene and propylene in a variety of ratios, with the presence of different amounts and types of dienes and of a

Ziegler–Natta catalyst.<sup>4</sup> The quantitative ratio of the monomers confers specific properties to the final EPDM rubber. In aluminium electrolytic capacitor applications, the rubber sealing rings must have outstanding temperature resistance; optimum hardness and mechanical strength for long lasting sealing results; excellent electrical insulating properties; and chemical compatibility with organic solvents and the electrolytes. However, there is very little information about elastic sealing materials used for screw terminal aluminium electrolytic capacitors, especially about EPDM rubber characteristics in capacitors working at high voltages and high temperatures. Several EPDM rubber materials with different grades were initially considered. Due to availability and cost of some of them, only two types of EPDM rubber (RS1 and RS2) were selected in this study, and used for 400 V and 125°C screw-terminal aluminium electrolytic capacitors. The main specifications of these EPDM rubbers are presented in Table 1.

**Table 1.** Main specifications of two types of EPDM rubber materials investigated

EPDM Rubber Sample	Polymer (EPDM) (%)	Specific Gravity (g/cm <sup>3</sup> )	Hardness (Shore A)	Elongation (min %)	Tear Strength (KN/m)	Temp. Range (°C)
RS1	25-45	1.10±0.05	60±5	300	18	-55 - 130
RS2	25-45	1.05±0.05	60±5	300	23	-55 - 150

This paper focuses on the investigation of the thermo-mechanical stability of EPDM rubber materials, as well as their chemical compatibilities with different electrolytes and their effects on the capacitor performance.

## 2. EXPERIMENTAL

### 2.1. Elastomeric Sealing Material Test Methods

#### 2.1.1 Compression Set Test

Compression set test measures the ability of a rubber material to return to its original thickness after prolonged compressive stresses at a given temperature and compression deflection. The lower the percentage value (i.e. compression set), the better the material resists permanent deformation under a given deflection and temperature range. The compression set (%) represents the percentage of the rubber deflection that did not recover. The compression set test method used in this work is based on the ASTM D395 B standard. The constant deflection was achieved by using metallic washers (of thickness  $T_w$ ) as spacers in the test device, compressing the whole rubber down to 75% of its original thickness ( $T_o$ ) at 125°C for 22 hours. The rubber was released immediately after taking the test device out of the oven, and then the rubber was cooled down to room temperature to allow it to recover for 30 minutes. After cooling down, the final thickness ( $T_b$ ) of the seal ring was measured using a Mitutoyo micrometer. The formula used to calculate the compression set is:

$$\text{Compression Set (\%)} = [(T_o - T_b) / (T_o - T_w)] \times 100 \quad (1)$$

### 2.1.2 Chemical Compatibility Test

The chemical compatibility test is to evaluate the ability of different EPDM rubbers to withstand liquid electrolytes containing  $\gamma$ -butyrolactone (BLO) and ethylene glycol (EG) as solvents, as well as acids, bases and other chemicals. This test is also used to investigate the effects of the rubber materials in the electrolyte parameters. The test is performed by immersing several rubber seal rings in an aluminium can with 300 ml of electrolyte solution, which is sealed and placed in an oven at 125°C for 30 days. The thickness and weight of the rubber seal rings, as well as the electrolyte parameters were measured prior to and after this test.

### 2.1.3 Diffusion Test

An aluminium electrolytic capacitor comprises a capacitor roll/winding which is impregnated with a suitable electrolyte; and an aluminium can with an open end, which is sealed by a flat cover/deck by using an elastic sealing ring. The seal ring will become a diffusion path for the electrolyte during capacitor operation.

The diffusion test method is designed to examine how much electrolyte diffuses through the elastic sealing rings by monitoring the weight loss of the test samples (either aluminium cans with electrolyte or actual capacitor samples) at a specific operating temperature after a certain period of time. The test samples were placed in an oven at 125°C for a given period of time, and the weight changes (percentage) were calculated after this test.

## 2.2. Sample Capacitor Preparation and Test

The electrolyte used for sample capacitors was based on BLO solvent, containing solutes (conductive salts and neutralisation products from inorganic or organic acids and bases) and some additives. The procedures to prepare the electrolyte (namely WEY400A) and to test its parameters (*e.g.* water content, conductivity, pH and dielectric breakdown voltage) are described elsewhere<sup>5, 6</sup>. In this work, this electrolyte was used for the 400 V and 125°C screw-terminal capacitors.

Two types of EPDM rubber sealing ring (*i.e.* RS1 and RS2) were selected and used as sealing materials in the sample capacitors. The detailed procedures for the capacitor preparation and measurements can be found in our previous works<sup>5-9</sup>. Table 2 summarises the basic capacitor design information.

**Table 2.** Sample capacitor basic design information for endurance tests

EPDM Rubber Sample	Quantity	Size (mm)	Working Voltage	C ( $\mu$ F)	Temp. Range (°C)	Test Temp. (°C)	Applied V <sub>DC</sub> (Volts)	Applied V <sub>DC</sub> + I <sub>LC</sub> (50Hz)	Test Duration (Hrs)
RS1	16	Ø50 × 75	400	270	-55 to 125	125	400	373 V + 1.7 A	3000
	16	Ø75 × 147	400	1800	-55 to 125	125	400	385 V + 5.9 A	3000
RS2	16	Ø50 × 75	400	270	-55 to 125	125	400	373 V + 1.7 A	3000
	16	Ø75 × 147	400	1800	-55 to 125	125	400	385 V + 5.9 A	3000

The capacitor endurance tests were carried out for 3000 hours at 125°C at the upper working voltage with and without ripple current: *DC tests* at 400 V and *DC and Ripple tests* at 373 V and 1.7 A ripple current for Ø50mm capacitors; and 385 V and 5.9 A ripple current for Ø75mm capacitors. Throughout the endurance tests, the Capacitance (C), Equivalent-Series-Resistance (ESR), Impedance (Z) and Leakage Current (LC) of the capacitors were monitored and measured (at 20°C) every 1000 hours.

### 3. RESULTS AND DISCUSSIONS

#### 3.1. Elastomeric Sealing Material Characterisation

##### 3.1.1. Compression Set Test

Compression set tests were carried out at 125°C and 22 hours for two different EPDM rubber materials and in three different sample forms, i.e. rubber sealing rings; rubber slabs and rubber buttons. The test results are shown in Table 3.

**Table 3.** Compression set test for two types of EPDM rubber materials

Rubber Sample/ Compression Set (%)	Rubber Sample Shape & Dimension		
	Sealing Ring (Ø50×3.0 mm)	Rubber Slab (25×25×2.5mm)	Rubber Button (Ø29×12.9mm)
RS1	73.6	20.2	13.8
RS2	10.2	11.3	10.0

The compression set test was conducted under constant deflection in dry conditions, and thus the permanent deformation caused to the rubber materials remains after the release of the compressive stress. In Table 3, the compression set values are expressed as the percentage of the rubber's permanent deflection. Therefore, materials with lower percentages of compression set will exhibit better elastic properties (enhanced resistance to deformation), by comparison with materials with high compression set values. Table 3 shows that RS2 rubber has a great potential for high temperature applications when compared to RS1, because the three types of RS2 samples resulted in the lowest compression set values. Therefore, RS2 rubber material should have an improved sealing performance than RS1 at high temperatures.

##### 3.1.2. Chemical Compatibility Test

###### a) Electrolyte parameter change after thermal stability tests with and without the presence of EPDM rubbers

The chemical compatibility of the EPDM rubber seal rings was evaluated using a series of electrolytes, which are based on two major solvents: BLO and/or EG. The typical parameters of these testing electrolytes are listed in Table 4.

**Table 4.** Parameters of the electrolytes used for Chemical Compatibility Tests with EPDM rubber materials

Electrolyte	Conductivity k (mS/cm, at 25°C)	Breadown Voltage Vs (Volts at 90°C)	pH (at 25°C)	Water Content H <sub>2</sub> O (% , at 25°C)	Working Voltage (V)	Major Solvent
WEY100	2.2 - 2.7	> 120	6.0 - 7.0	4.0 - 5.0	100	BLO
WEY400A	0.85 - 1.0	> 450	5.5 - 6.0	0.5 - 1.0	400	BLO
WEY400B	1.8 - 2.1	> 450	5.2 - 5.8	2.0 - 3.0	400	EG
WEY450	1.25 - 1.45	> 460	5.5 - 6.0	2.0 - 3.0	450	EG
WEY500	0.42 - 0.46	> 515	5.7 - 6.3	0.5 - 2.0	500	EG / BLO

*Note: BLO and EG are present in a 1:1 ratio in electrolyte WEY500*

Five types of electrolyte were used for chemical compatibility tests at 125°C for 30 days. These electrolytes were selected to investigate the rubbers in three different solvent systems; BLO; EG; and EG/BLO. To evaluate the chemical compatibility of the EPDM rubber samples, the parameters of the electrolytes were measured before and after the test. The variations (%) of the electrolyte parameters compared to the blank samples are presented in Table 5.

**Table 5.** Parameter changes for five electrolytes tested with RS1 and RS2 rubber samples at 125°C for 30 days

Electrolyte Parameters	WEY100			WEY400A			WEY400B			WEY450			WEY500		
	Blank	RS1	RS2	Blank	RS1	RS2	Blank	RS1	RS2	Blank	RS1	RS2	Blank	RS1	RS2
H <sub>2</sub> O (%)	-2.47	-0.12	-5.02	108.89	95.56	122.22	26.70	28.57	27.02	25.11	28.32	27.06	20.73	27.24	20.83
K (%)	-11.02	-8.46	-9.06	-11.49	-10.34	-10.34	-25.95	-24.14	-26.73	-37.65	-36.33	-37.77	-11.38	-13.41	-10.98
pH (%)	-12.73	-13.16	-10.83	74.83	75.00	74.17	3.78	3.91	3.75	0.51	1.27	-0.59	2.61	2.48	0.88
Vs (%)	3.47	2.00	4.80	2.08	2.08	3.13	3.33	3.33	3.33	3.51	3.16	3.68	-13.51	-13.96	-13.90

*Note: the blank samples are electrolyte samples without immersed rubber seal rings.*

The results in Table 5 show insignificant differences in the electrolyte parametric changes between the blank samples (without rubber seal rings immersed) and the samples with RS1 and RS2 rubber seal rings immersed in electrolyte. This means that the electrolyte parameters are not considerably altered when RS1 and RS2 are in solution and therefore these two EPDM materials should be compatible with all types of electrolyte.

*b) Weight and radial thickness changes of the rubber seal rings after Thermal Stability tests in electrolytes*

Chemical compatibility tests are not only to test the stability of the electrolytes after storage at high temperatures with different rubber materials, but also to examine the tolerance of the EPDM rubber materials to organic solvents and other chemical components in the electrolyte. Table 6 illustrates the changes in weight and radial thickness of the rubber seal rings after testing with WEY100, WEY400A, WEY450 and WEY500 electrolytes at 125°C for 30 days.

**Table 6.** Changes in weight and radial thickness of the rubber sealing rings (RS1 and RS2) after thermal stability tests at 125°C for 30 days

Electrolyte / Rubber Sample	WEY100		WEY400A		WEY450		WEY500	
	Weight Change (%)	Radial Thickness Change (%)	Weight Change (%)	Radial Thickness Change (%)	Weight Change (%)	Radial Thickness Change (%)	Weight Change (%)	Radial Thickness Change (%)
RS1	-8.83	-1.15	-7.59	-5.21	13.29	5.87	-0.24	0.49
RS2	3.36	2.43	9.67	6.19	7.69	3.55	4.42	2.16

RS1 and RS2 seem to have different performance in terms of weight change. RS1 rubber lost weight in BLO-based electrolytes (WEY100 and WEY400A) and RS2 gained weight after thermal stability tests in the same electrolytes (Table 6). At the same time, using the latter electrolytes, RS1 rubber shrank a little bit after the test and RS2 swelled. This may result in substantial differences in real capacitor tests. Using the other two electrolytes (WEY450

and WEY500, both of them containing EG solvent), both RS1 and RS2 swelled. The main difference between RS1 and RS2 was the weight change, showing higher changes for RS1 in WEY450 electrolyte and lower changes for the same rubber in WEY500.

### 3.1.3. Diffusion Test

The EPDM rubber seal rings (RS1 and RS2) were used to seal aluminium cans containing four different electrolyte solutions (WEY100, WEY400A, WEY400B and WEY500), and the sealed cans were placed in an oven at 125°C for a given period of time. The weight changes of the cans were monitored at different times (from 7 days up to 30 days). In this work, aluminium cans with the dimension of Ø50×75mm were used for diffusion tests. The diffusion of the electrolytes through the two EPDM rubbers was measured over time (Figure 1).

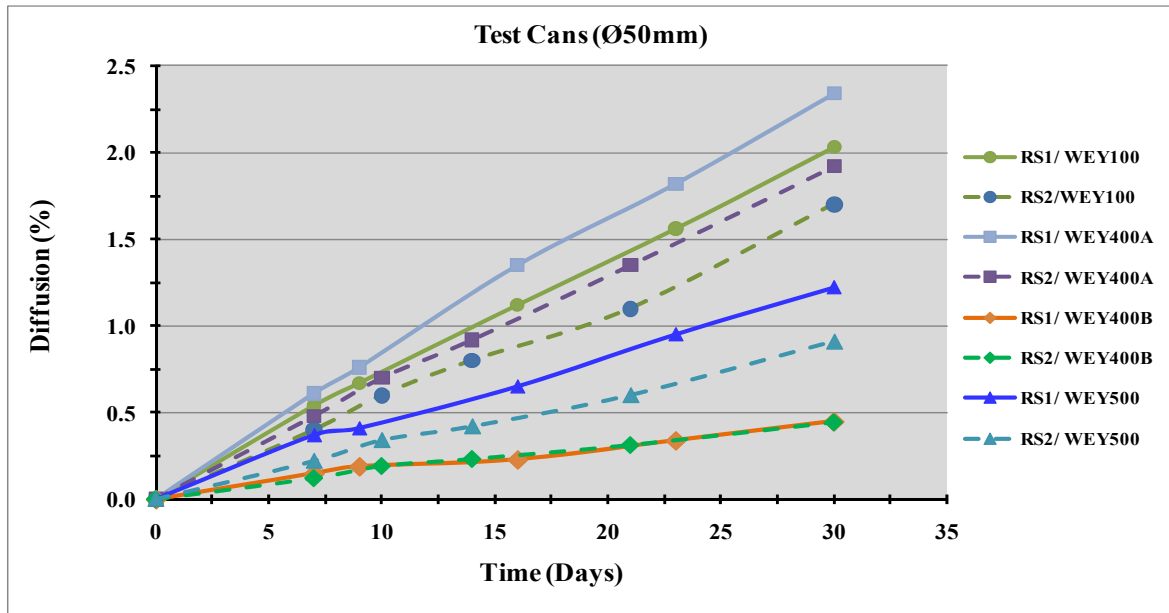


Fig.1. Diffusion through rubber samples (RS1 & RS2) as a function of time.

Figure 1 shows the increase of electrolyte diffusion through the EPDM seal rings with time, using all the test electrolytes. The magnitude of the diffusion depends on the type of electrolyte used. Firstly, EG-based electrolytes (WEY400B) resulted in the lowest diffusion values (less than 0.5% after 30 days of test). This means that EG-based electrolytes have a lower diffusion rate than BLO-based electrolytes (WEY100 and WEY400A in these studies) and electrolytes with both EG and BLO (WEY500). The electrolyte with 1:1 ratio of EG:BLO, i.e. WEY500, was the electrolyte with second lowest diffusion rate. The two BLO-based electrolytes (WEY100 and WEY400A) had the highest diffusion rates, with values above 1.5%. When comparing the latter BLO-based electrolytes, WEY100 led to lower diffusion than WEY400A. This is because WEY100 is a much more concentrated electrolyte (higher concentration of acids, bases, conductive salts, etc) than WEY400A and this means that WEY100 electrolyte produces less free vapour when heated at constant temperature (125 °C). This is very important because the fraction of electrolyte that diffuses through the rubber seal rings is the vapour fraction of the electrolyte. Generally, electrolytes designed for high voltage applications (e.g. WEY400A, designed for 400 V) have a much lower concentration of solutes. This is required to ensure suitable (sufficiently high) dielectric breakdown voltage values. In contrast, electrolytes used for low voltage applications (WEY100, designed for 100 V) can have relative high concentration of solutes, hence increasing the conductivity of the electrolyte. The *highly concentrated* electrolytes will cause less vapour and therefore less electrolyte diffusion.

As stated above, the diffusion of the BLO-based electrolytes is much higher than that using the EG-based electrolyte. This is because of the different vapour pressure of the two solvents. At 125°C the vapour pressure of EG is ca. 7.58 kPa and BLO is ca. 10.00 kPa.<sup>10</sup> Electrolytes with higher vapour pressure are more volatile at the testing temperature.

The comparison between EPDM rubbers (Figure 1) shows that the electrolyte diffusion is much lower in all cases when using RS2 rubber, with the exception of the EG-based electrolyte (WEY400B), where the diffusion is practically the same using RS1 or RS2 seal rings. This means that RS2 is likely to perform better than RS1 in real capacitors working at 125°C. This agrees with the compression set results (section 3.1.1) and the rubber weight and thickness tests (section 3.1.2).

### 3.2 Capacitor Performance in Endurance Test

#### 3.2.1 Electrical Parameters of Sample Capacitors

Two types of sample capacitors were prepared with WEY400A electrolyte and using two types of EPDM rubber seal rings (i.e., RS1 and RS2). From the results in the previous sections, BLO-based electrolytes and especially electrolytes for high voltage applications are more likely to show differences in terms of rubber seal ring performance. The initial capacitor electrical parameters were measured as shown in Table 7.

**Table 7.** Initial Electrical parameters of Sample Capacitors

Rubber Seal Ring	Medium Capacitors (Ø50mm) at 20°C				Large Capacitors (Ø75mm) at 20°C			
	C (µF, 100Hz)	ESR (mΩ, 100Hz)	Z (mΩ, 10KHz)	LC (mA)	C (µF, 100Hz)	ESR (mΩ, 100Hz)	Z (mΩ, 10KHz)	LC (mA)
<b>RS1</b>	275.9	120.3	67.0	0.153	1789.5	17.2	8.0	0.272
<b>RS2</b>	277.3	120.3	67.6	0.152	1794.8	17.5	8.3	0.282

#### 3.2.2 Capacitor Endurance Test at 125°C

##### a) The impact of EPDM rubber sealing materials on the capacitor performance

To evaluate the effects of RS1 and RS2 rubbers on the capacitor performance, a series of capacitors were tested at 400 V DC only (Figure 2) and at 373 V, 1.7 A Ripple for Ø50mm capacitors and 385 V, 5.9 A Ripple for Ø75mm capacitors (Figure 3), continuously at 125°C for 3000 hours. The capacitance, ESR and impedance were measured at 20°C every 1000 hours of test and the results were compared to the initial values. Usually, the capacitance of aluminium electrolytic capacitors decreases after a few thousand hours of endurance test, while the ESR and impedance increase.<sup>9</sup> Figures 2 and 3 illustrate the capacitor parametric change during these tests. In the *DC tests* (Figure 2) and *DC and Ripple tests* (Figure 3), the parametric changes were more pronounced in the medium-size capacitors (Figures 2(A) to 2(C) and 3(A) to 3(C)) than the larger capacitors (Figures 2(D) to 2(F) and 3(D) to 3(F)), with the ESR and impedance showing the most evident differences. Generally, smaller capacitors will show more signs of winding dry-out during capacitor operation at the rated voltages and temperatures. This may be caused by the lower amounts of electrolyte in smaller units, when compared with larger capacitors.

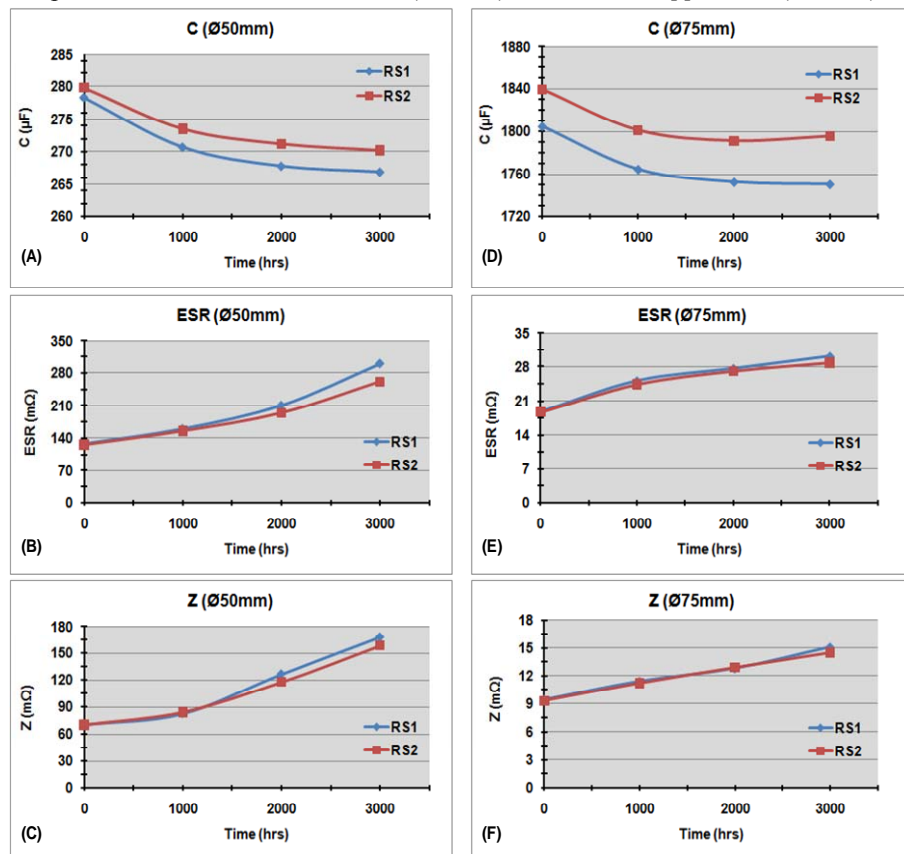
Figures 2 and 3 show significant differences in capacitor performance using RS1 or RS2 seal rings. The main differences using RS1 and RS2 are in the ESR and impedance of the capacitors in the medium-size capacitors (Figures 2(B) and 2(C) and Figures 3(B) and 3(C)). Concentrating on the ESR values, the *DC tests* showed an ESR increase of 134.9 % after the 3000 hours of test when RS1 seal ring was used, whereas it was 106.8 % with RS2

rubber (Figure 2(B)). In the *DC and Ripple tests*, the ESR increase was 184.8 % with RS1 rubber and *only* 120.2 % with RS2 (Figure 3(B)). These differences are very important because these factors will affect the capacitor operating life. In the case of the medium-size capacitors in Figures 2 and 3, the RS2 seal ring may result in several thousand hours of extra life, when compared to RS1, and taking into account that the capacitor definition of end of life (due to parametric drift) is when:

- The final capacitance is outside the  $\pm 10\%$  of the initial value.
- The final  $ESR_{final} > 3$  times the initial value or  $ESR_{final} > 2$  times the initial limit.
- The final impedance is  $> 3$  times the initial value.

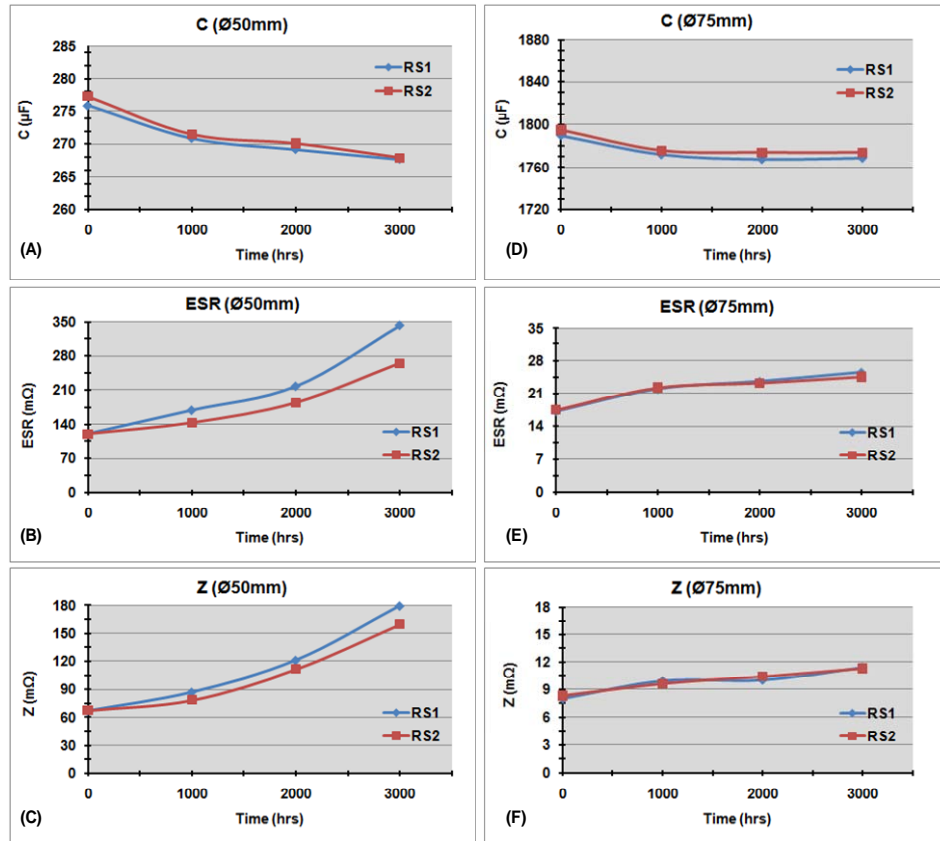
In aluminium electrolytic capacitors, the ESR and impedance increase with time, during capacitor operation at the rated voltages and temperatures. The ESR and impedance increase is mainly due to the electrolyte ageing at such operating conditions. The conductivity of the electrolyte tends to decrease due to acid-base neutralisation; degradation of certain chemicals in the electrolyte; etc. As a result, the capacitor ESR and impedance increase. However, another cause of ESR and impedance increase is the capacitor dry-out mentioned above. This explains the differences in ESR and impedance when different sealing materials are used, despite using the same electrolyte.

In the larger capacitors ( $\varnothing 75$  mm), some differences between RS1 and RS2 were also observed. However, these differences were less pronounced. Tables 8 and 9 summarise the ESR and impedance changes in the  $\varnothing 50$  mm and in the  $\varnothing 75$  mm samples after 3000 hours of *DC tests* (Table 8) and *DC and Ripple tests* (Table 9) at  $125^{\circ}\text{C}$ .



**Fig.2.** Capacitor electrical parameters (C, ESR, Z) as a function of time during  $400\text{ V}_{\text{DC}}$  endurance tests at  $125^{\circ}\text{C}$  for 3000 hours (the results are the average of 8 capacitors for each type of seal ring).





**Fig.3.** Capacitor electrical parameters (C, ESR, Z) as a function of time during *DC and Ripple tests*: 373 V and 1.7 A Ripple for Ø50mm and 385 V and 5.9 A Ripple for Ø75mm capacitors (the results are the average of 8 capacitors for each type of seal ring).

**Table 8.** ESR and Impedance changes after 3000 hours *DC tests*

Endurance Test Time	Capacitors (Ø50mm)				Capacitors (Ø75mm)			
	Rubber RS1		Rubber RS2		Rubber RS1		Rubber RS2	
	ESR (mΩ, 100Hz)	Z (mΩ, 10KHz)	ESR (mΩ, 100Hz)	Z (mΩ, 10KHz)	ESR (mΩ, 100Hz)	Z (mΩ, 10KHz)	ESR (mΩ, 100Hz)	Z (mΩ, 10KHz)
<b>0 hrs</b>	127.5	70.8	126.3	70.2	18.8	9.4	18.7	9.3
<b>3000 hrs</b>	299.5	168.0	261.2	158.8	30.1	15.1	28.8	14.5
<b>Variation (%)</b>	<b>134.9</b>	<b>137.3</b>	<b>106.8</b>	<b>126.2</b>	<b>60.1</b>	<b>60.6</b>	<b>54.0</b>	<b>55.9</b>

**Table 9.** ESR and Impedance changes after 3000 hours *DC and Ripple tests*

Endurance Test Time	Capacitors (Ø50mm)				Capacitors (Ø75mm)			
	Rubber RS1		Rubber RS2		Rubber RS1		Rubber RS2	
	ESR (mΩ, 100Hz)	Z (mΩ, 10KHz)	ESR (mΩ, 100Hz)	Z (mΩ, 10KHz)	ESR (mΩ, 100Hz)	Z (mΩ, 10KHz)	ESR (mΩ, 100Hz)	Z (mΩ, 10KHz)
0 hrs	120.3	67.0	120.3	67.6	17.2	8.0	17.5	8.3
3000 hrs	342.6	179.6	265.5	159.6	25.5	11.4	24.6	11.3
Variation (%)	184.8	168.1	120.7	136.1	48.3	42.5	40.6	36.1

*b) Diffusion of electrolyte in Endurance tests*

After the endurance tests at 125°C for 3000 hours, the weight changes of the sample capacitors were measured as shown in Tables 10 and 11.

**Table 10.** Weight loss and diffusion percentage of sample capacitors after *DC tests* at 125°C for 3000 hours.

Rubber Material	Capacitor (Ø50mm)				Capacitor (Ø75mm)			
	0 hrs (g)	3000 hrs (g)	Weight Loss (g)	Diffusion (%)	0 hrs (g)	3000 hrs (g)	Weight Loss (g)	Diffusion (%)
RS1	151.3	143.1	8.2	5.4	699.3	675.5	23.8	3.4
RS2	151.2	144.5	6.7	4.4	694.4	677.3	17.1	2.5

**Table 11.** Weight loss and diffusion percentage of sample capacitors after *DC and Ripple tests* at 125°C for 3000 hours.

Rubber Material	Capacitor (Ø50mm)				Capacitor (Ø75mm)			
	0 hrs (g)	3000 hrs (g)	Weight Loss (g)	Diffusion (%)	0 hrs (g)	3000 hrs (g)	Weight Loss (g)	Diffusion (%)
RS1	152.2	141.8	10.4	6.8	709.6	684.5	25.1	3.5
RS2	152.3	143.2	9.1	6.0	705.5	687.2	18.3	2.6

After 3000 hours of endurance test, the weight loss / electrolyte diffusion were higher when RS1 seal ring was used in both capacitor sizes. The capacitor weight loss is mainly due to the electrolyte vapour loss through the rubber seal rings, as well as other vapours or gases that may be generated in the endurance tests and other organic substances that may come from other capacitor parts such as the paper separators, deck material or plastic insulating sleeves.

Since RS1 seal ring leads to more electrolyte loss due to diffusion, the internal capacitor winding will dry-out quicker than when RS2 is used. The capacitor dry-out will in turn cause the ESR and impedance to increase, as in Figures 2 and 3. As stated above, smaller capacitors usually show more signs of winding dry-out during capacitor operation at the rated voltages and temperatures. This was proved by capacitor teardown examinations in this study.

### 3.3 Degradation or Ageing Mechanism of EPDM Rubber

Degraded or aged rubber materials do not have good elasticity, heat resistance or the ability to seal properly. The thermal stability is one of the most important factors for rubber sealing materials in high temperature applications. The degradation of EPDM rubber can be explained by its polymeric properties. This is due to oxidation, cross-linking, etc.<sup>11, 12</sup> and the number of unsaturated carbon bonds composing the hydrocarbon backbones in such materials.<sup>13</sup> However, the EPDM rubber contains an almost saturated hydrocarbon backbone; and only a few branched chains with chemical double-bonds exist on the main backbone, with approximately 200 carbon atoms.<sup>13</sup> Therefore, EPDM rubbers normally have good chemical and thermal resistance.

Previous investigations showed that the ageing process of EPDM specimens proceeded when new cross-links occurred after the EPDM samples were immersed in a solvent over a period of time.<sup>14</sup> The absence of the carbon-carbon double bonds in EPDM rubber may be a key requirement for a good sealing function.<sup>15</sup> The compression set tests (section 3.1.1) show that RS2 rubber had significantly lower compression set values. This suggests that RS2 rubber may contain fewer double bonds on its backbone than RS1. However, the precise compositions of these rubbers are unknown due to industrial confidentiality.

According to the diffusion test results (section 3.1.3), the diffusion rate increases with time. This can be attributed to thermal degradation of EPDM, which is caused by the oxidation of the EPDM rubber as described by Zhao *et al.*<sup>15</sup> The oxidation causes the formation of peroxy radicals, alkyl radicals and alkoxy radicals, which produce various oxygenated species, e.g. ether, ester and  $\beta$ -diketone. This oxidation ageing process will start from the EPDM surface and propagate to the EPDM inner body. Therefore, almost all EPDM rubbers have to be post-cured and/or press cured to avoid such surface oxidation.

In practice, the performance of different EPDM seal rings in aluminium electrolytic capacitors will be essentially influenced by the ageing at high voltages and high temperatures. As the rubber seal ring ages and deteriorates during capacitor operation at high temperatures, more electrolyte vapour will diffuse through the seal ring, thus causing capacitor dry-out and hence contributing to the capacitor parametric changes (ESR and impedance increase, etc) and reducing the capacitor operational life.

## **4. CONCLUSIONS**

Two types of EPDM rubber, namely RS1 and RS2, have been investigated as seal ring materials for screw-terminal aluminium electrolytic capacitors and for high temperature applications. The initial compression set tests showed that RS2 rubber has enhanced elastic properties than RS1, when exposed to high temperatures (125°C) for prolonged periods of time. The compression set values using RS2 rubber were considerably lower than those using RS1. On the other hand, after doing the chemical compatibility tests at 125°C for 30 days, RS1 and RS2 rubber seal rings had some differences in terms of changes of rubber weight and thickness. In addition, the diffusion tests showed less electrolyte diffusion through EPDM rubber when RS2 seal rings were used.

RS1 and RS2 seal rings were used to seal different capacitor samples. The capacitor endurance tests (both *DC tests* and *DC and Ripple tests*) at 125°C proved that RS2 is the best material, since the latter rubber caused less electrolyte diffusion and therefore less capacitor internal dry-out, when compared to RS1. Less capacitor dry-out means less parametric changes (mainly less changes in ESR and impedance). Less parametric changes results in longer capacitor operating life.

Finally, the mechanisms for the degradation / ageing of EPDM rubbers have been discussed. The EPDM degradation is mainly associated with the amount of unsaturations in the polymer and the oxidation ageing process starts from the EPDM surface and propagates to the EPDM inner body.

This paper has proved the importance of the selection of suitable seal ring rubber materials, as these materials will affect the capacitor overall performance and capacitor life.

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## REFERENCES

1. C. D. Gamlin, N. K. Dutta, N. R. Choudhury, *Polymer Degradation and Stability*, 80, 525-531 (2003).
2. F. Delor-Jestin, J. Lacoste, N. Barrois-Oudin, C. Cardinet, J. Lemaire, *Polymer Degradation and Stability*, 67, 469-477 (2000).
3. S.W. Rutherford, D.T. Limmer, M.G. Smith, K.G. Honnell, *Polymer*, 48, 6719-6727 (2007).
4. M.P. Stevens, *Polymer Chemistry*, 3<sup>rd</sup> Edt, 249-250, Oxford University Press (1999).
5. Z. Dou, R. Xu, A. Berduque, *CARTS Europe 2008 Proceedings*, 79-92, October 20-23, Helsinki, Finland (2008).
6. R. Xu, A. Berduque, Z. Dou, *CARTS USA 2009 Proceedings*, 83-94, March 30-April 2, Jacksonville, FL (2009).
7. Z. Dou, R. Xu, A. Berduque, J. Qazi, C. Prince, *CARTS USA 2010 Proceedings*, 203-218, March 15-18, New Orleans, LA (2010).
8. Z. Dou, R. Xu, A. Berduque, J. Qazi, C. Prince, *CARTS Europe 2010 Proceedings*, 155-171, November 10-11, Munich, Germany (2010).
9. A. Berduque, J. Martin, Z. Dou, R. Xu, *CARTS USA 2011 Proceedings*, 265-287, March 28-31, Jacksonville, FL (2011).
10. E. W. Flick. *Industrial Solvents Handbook*. 5<sup>th</sup> Edition (1998). Noyes Data Corporation, Westwood. New Jersey (USA).
11. T. Zaharescu, S. Jipa, M. Giurginca, C. Podina, *Polymer Degradation and Stability*, 62, 569-574 (1998).
12. T. Nakamura, O. Chaikumpollert, Y. Yamamoto, Y. Ohtake, S. Kawahara, *Polymer Degradation and Stability*, 96, 1236-1241 (2011).
13. X. F. Zhu, H. B. Jia, W. Wei, L. Liu, *Electronic Components and Materials*, 02, 1-4 (2002).
14. Q. Zhao, X. Li, J. Gao, *Polymer Degradation and Stability*, 92, 1841-1846 (2007).
15. Q. Zhao, X. Li, J. Gao, *Polymer Degradation and Stability*, 94, 339-343 (2009).