# Application of unusual techniques for characterizing ageing on polymeric electrical insulation

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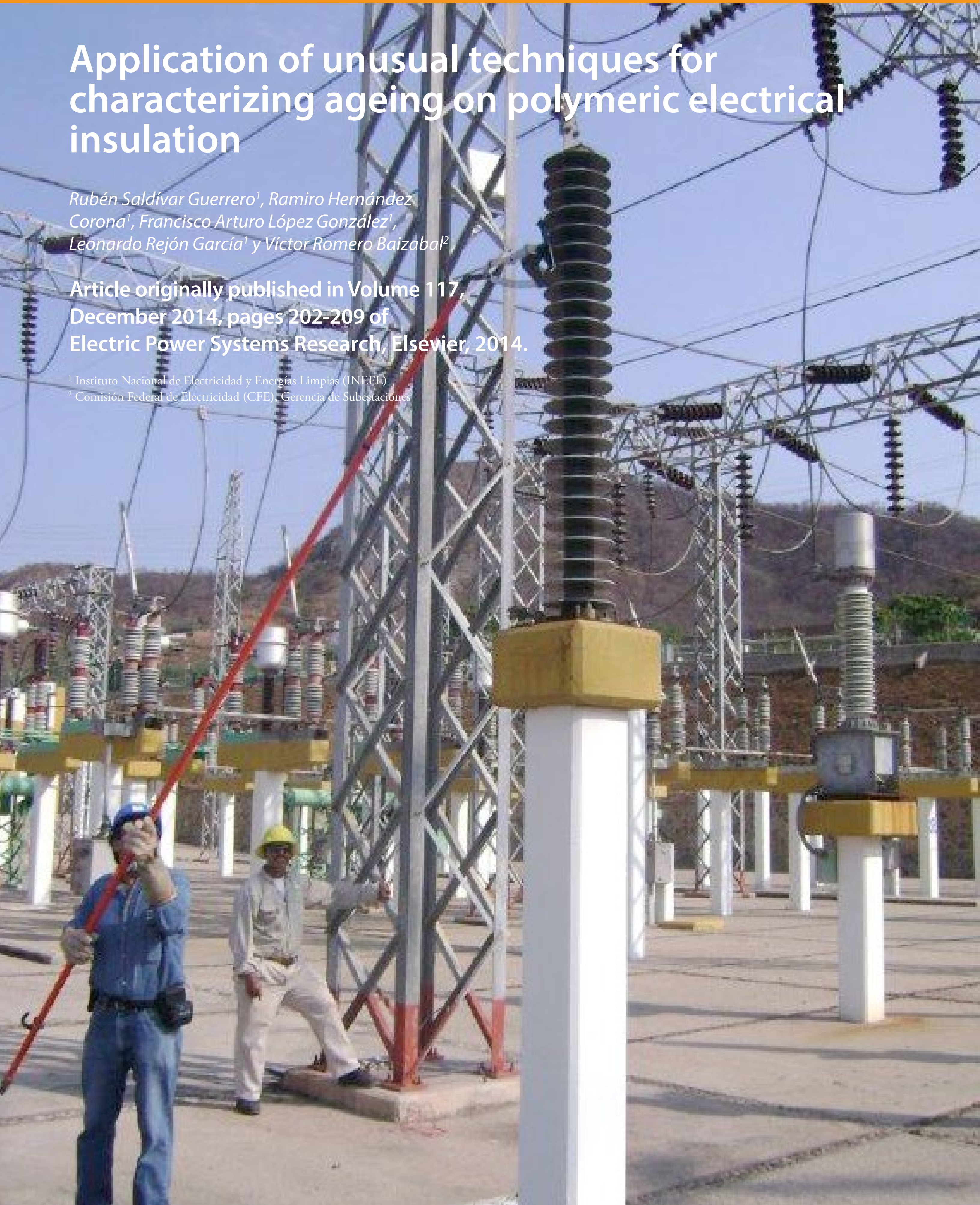

## Abstract

The degradation process caused by electrical stresses and weather conditions on electrical non-ceramic insulation was analyzed with non-destructive techniques. Traditional replica technique was introduced as a novel method to characterize microstructure changes on polymeric insulation. Static contact angle and roughness measurements were also used to characterize non-ceramic insulation. These non-conventional techniques have shown to be appropriate for evaluating aging on electrical insulation surfaces of bushings and surge arresters installed in electrical substations. The replica technique has drawn attention for being an innovative analysis test for characterizing polymeric insulation.


## Introduction

Polymeric composite insulating materials, also known as non-ceramic materials, have been used as housing insulation in high power electrical devices such as: insulators, surge arresters and bushings. Generally, non-ceramic insulation is made of silicone rubber, EPDM and Ethylene Propylene Rubber (EPR)/silicone alloys, and inorganic fillers. They came to have a strong commercial interest and were considered a mature product since the early 1990s [1, 2]. While rubber composites' performance is generally satisfactory, polymeric insulating materials are much prone to aging than their ceramic counterparts. Hence, it is of practical interest to investigate the performance and the chemical changes of polymeric housing insulation under field conditions. A comparison of laboratory aging test results with those obtained in natural environments yield useful information on long term performance.

In order to obtain information of the degradation process, the insulating material must be characterized by different techniques. Visual observation, hydrophobicity classification and surface pollution evaluation are part of the physical characterization for polymeric housing insulation. Some others involve electrical measurements as leakage current measurement and corona monitoring. In addition, material characterization is carried out by Fourier Transform Infrared (FTIR) spectroscopy, chalking analysis and surface microstructure observation. These techniques have been widely used to characterize polymeric outdoor insulation [3–6].

Some other methods that have also been used for characterizing non-ceramic materials include: light emission, thermal imaging, and acoustic measurements [7]. In addition, diagnostic methods as laser induced fluorescence and quality control of internal interfaces are still under development. Each of these characterization techniques reveals a part of the degradation process that is also affected by high pollution, extreme weather conditions and electrical stresses.

However, some of the relevant characterization tests commonly require a sample of housing material to be cut off. Examples of these tests are: chemical analysis, FTIR spectroscopy, sessile drop technique hydrophobicity measurement and scanning electron microscopy microstructure observation. Consequently, it is difficult to use these powerful methods for evaluating aging and degradation process of polymeric housing materials in field.

In this paper, we take advantage of some non-destructive techniques to characterize non-ceramic electrical insulation in laboratory and in field. These include hydrophobicity evaluation by measuring static contact angle, roughness of the polymer surface, and microstructure analysis by the novel application of the replica technique to polymeric insulating materials.

For the polymer microstructure analysis, the replica technique is adapted to non-ceramic insulation. This has shown to be appropriate to follow up structural changes of the housing materials. The materials used for this investigation include polymeric insulation based on EPDM and silicon rubber. They were aged in an accelerated way in laboratory, under different weather conditions and electrical stresses [8]. Moreover, we introduced the evaluation of polymeric insulation within field by using the replica technique, plus the roughness and contact angle measurements. The obtained results have been correlated to electric field distribution and leakage current measurements.

## Unusual techniques used for characterizing aging

In this work, the unusual techniques used for characterizing aging on polymeric electrical insulation are hydrophobicity, surface roughness, and microstructure replication. Additionally, leakage current is monitored by recording frequency and range of peak currents, using a custom-built data acquisition system [9]. The electric field distribution is measured before and over the course of the test period, with an instrument that was originally developed at Hydro-Québec [10].

### Hydrophobicity

A hydrophobic surface has a water repellent property, where as a hydrophilic surface can be easily wetted. The contact angle that a drop makes when it comes into contact with a solid surface is a measure of the surface wettability. The most commonly used method for evaluating hydrophobicity is the so called sessile drop technique. However, it is generally only applicable in the laboratory.

The hydrophobicity of the housing polymer is evaluated by placing a drop of distillated water on the previously cleaned (with ethylene alcohol) polymeric surface. Then, a photograph of it is taken with a high resolution digital camera. By digital image analysis and the use of special software, the contact angle is measured. The data of the contact angle were obtained from the mean of six to nine measurements that were made to different drops placed on the surface.

### Surface roughness

Roughness is the measure of a surface texture. It initially indicates the surface profile that a material has due to the manufacturing process. It could be used to measure the aging degree since an increase in roughness due to surface erosion is expected. The roughness measurements were made with a roughness profile meter (Mitutoyo SJ-201), and at least three evaluations were made for each roughness data point. All measurements and surface characterization were made off-line.

### Microstructure replication

Replication is a non-destructive technique, generally used to evaluate microstructure changes caused by service failures in metallic materials. It records and preserves the topography of a microstructural surface as a negative relief on a thin foil of polymeric material. Replica can be observed with the use of an optical microscope, where standard magnification ranges from 50 to1000×. On the other hand, if the reproduced surface is properly prepared with the application of a conductive support, the replica can also be observed with a scanning electron microscope (SEM). This provides the possibility of observing reproduced microstructure aspects with a higher magnification. While using SEM examination, special care should be taken because the electron beam can produce excessive heating of the surface and then possible deformation of plastic material.

Because of the acceptance of replication as a non-destructive test for metallic surfaces in field, the replica technique has been standardized by international standard organizations like ASTM (E1351), ISO (3057) and NORDTEST (NT NDT 010). However, this technique has not been commonly used for microstructural analysis of polymer insulating materials or for other kind of rubbers and plastics. In this paper, the replica technique is introduced for being used to characterize non-ceramic materials.

The surface microstructure replication of polymeric housing materials is made using cellulose acetate film (0.05 mm thickness) supplied by Good fellow Cambridge Limited. As softening solvent, analytic grade acetone by Aldrich Chemical is used. Replication is made softening an acetate foil of 2 cm × 2 cm in acetone, and then placing it on a cleaned surface of non-polymeric insulation, in order for it to be analyzed. After the solvent is evaporated and the foil is hardened again, the foil is removed and observed by using a Carl Zeiss DSM-960 scanning electron microscope.

## Evaluated equipment and aging methodology

The unusual techniques to characterize aging on polymeric electrical insulation were evaluated on three surge arresters and two hollow core bushings. One surge arrester and one hollow core bushings were installed in field while the other devices were aged in laboratory. The main characteristics of these devices and the place of test are presented in Table 1.

The sample 1 was installed in a 115 kV line of a coastal power substation located in the North of Mexico, where the geographic conditions are Mediterranean-like humid and with low rain. The sample 5 was installed in a 230 kV dead tank breaker at a generation plant also located in the North of Mexico, but far away from the coast. All the conventional outdoor insulation of the substation and the generation plant has been historically washed at least several times per year.

The samples 2–4 were used for accelerated aging tests in laboratory, using a multistress environment chamber (5.1 m wide × 5.7 m high × 7 m long), to promote surface aging of non-ceramic insulation [8]. The chamber was conditioned to apply UVA-340 light exposure with an average of 0.65 W/m$^2$, salt fog: 5150 µS/cm, clear fog: 50–70 µS/cm and water flow rate: 1.35 l/min. The applied voltage was phase-to-ground 66.4 kV rms throughout the test. The used methodology to age the testing samples consists of three cycle sequences [8], as shown in Table 2: the first one consists in stressing the insulation for a period of 24 h in salt fog, followed by a 12 h dry period with UV. Finally, after switching off the UV, 24 h of clean fog is applied. This leaves a total time of 60 h per cycle. Then, the cycle is repeated for a total time of nearly 7000 h with the components continuously energized at the test voltage. All samples are washed off before the aging test.

To accelerate the aging process, only on sample 2 (EPDM arrester) and on sample 4 (the hollow core bushing), the samples were polluted by deposition of a layer on their insulation surface with the solid layer method, applying a

Table 1. Material characteristics of samples.

| Sample No. | Device | Material | Place of test |
|---|---|---|---|
| 1 | Surge Arrester | EPDM-ATH[a] | In field |
| 2 | Surge Arrester | EPDM-ATH[a] | Laboratory |
| 3 | Surge Arrester | Silicone Rubber | Laboratory |
| 4 | Hollow Core Bushing | Silicone Rubber –ATH[a] | Laboratory |
| 5 | Hollow Core Bushing | Silicone Rubber | In field |

ATH[a]=Alumina tri-hydrated

Table 2. Weather cycles designed to the accelerated ageing test.

| Cycle | Cycle time (hours) | Applied AC voltage 66.4 kV rms |
|---|---|---|
| Dry + UV | 12 | yes |
| Clean fog | 24 | yes |
| Salt fog | 24 | yes |

slurry prepared with 20 g of kaolin and 10 g of salt per 50 ml of demineralized water. A sponge is used to apply the slurry by hand. The test insulations were washed off to the 2500 h and 4000 h of testing and after that, pollutant layer was reapplied on the corresponding insulations (samples 2 and 4). After applying the new pollutant layer on the insulation surface, the apparatus is allowed to rest for 48 h prior to restarting the test, thereby allowing the contaminant layer to dry and the hydrophobicity to recover.

## Results and discussion

### Hydrophobicity

Usually, hydrophobicity evaluation of non-ceramic and ceramic housing insulation is made according to STRI guide [11]. The guide provides a set of hydrophobicity pattern photographs in order to determine the hydrophobicity level observed on the insulation surface. This method is commonly used in field. However, it has an intrinsic inaccuracy because of its subjective image analysis which depends on the operator's criteria. In order to analyze hydrophobicity more accurately, the contact angle was measured by using software image analysis, as described in the experimental section. In addition, it has the advantage that a water photograph can be easily taken in field with the portable high resolution camera. Through this method, the operator's criteria were eliminated and detailed changes on hydrophobicity behavior could be observed.

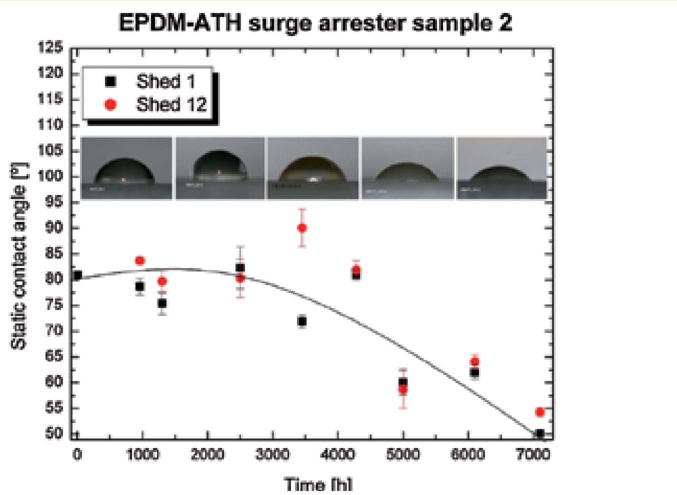


Figure 1. Static contact angle measurement vs. aging time for EPDM surge arrestertested in laboratory.

Figure 1 shows the static contact angle behavior for the EPDM-ATH surge arrester aged rapidly in laboratory. The figure includes some images of water drops on the polymer material for the shed 1. The photographs were taken at the 960, 2500, 3450, 5000 and 7000 h of test. On this figure the contact angle's behavior on different sheds could also be analyzed. Shed 1 corresponds to the top, and the shed 12 to the middle of the insulation's height.

As it can be seen in Fig. 1, the hydrophobicity behavior is mostly independent of the shed's position. This behavior is also shown for the SiR Surge arrester and the Silicon ATH bushing (Figs. 2 and 3, respectively). Some differences in contact angle between shed 1and 12, for sample 2 at 3450 h of test (Fig. 1), could be attributed to the corona activity that occurred around shed 12 of the arrester during this period of test. A corona discharge is a high voltage arc in air. When air is ionized, the electrons collide with the material surface to break the molecular bonds, increasing chains of low molecular weight. It is possible that these chains made the polymer insulation more hydrophobic, increasing the dimension of the contact angle.

Moreover, hydrophobicity is highly related to the nature of the composite material. The hydrophobic properties of EPDM insulating material, sample 2 (Fig. 1), decayed drastically after 3000 h of testing and failed to recover, even after passing some days without any kind of fog. Electrical stresses, strong weather conditions (in terms of solid contamination), salt fog and UV generate polymer oxidation. This produces ester groups and water molecules on the surface as chemical reaction by products [12]. These molecular components make the EPDM composite surface hydrophilic, causing a reduction in contact angle.

On the other hand, silicone rubber material of sample 3 (Fig. 2) showed none or little loss of hydrophobicity up to 5000 h of aging test. It is important to point out that during the first 5000 h of aging; the polymeric insulation was maintained free of contaminant layers. On this clean surface, the reorientation of the polymer methyl groups can occur, which promotes a recovery in hydrophobicity in the fashion of a fast process. That is why the contact angle, during this period of time, remains without change, apart from the time span of 1350 h. It is possible that around this time the housing polymer was more affected by dry band arcing, which was observed on the surge arrester.

For silicones, it is known that heat generated from dry band arcing causes hydrolysis, scission and crosslinking of Si-O bonds. This gives rise to decreased CH groups and increased levels of oxygen in the siloxane bonds [13]. As a result of such increased oxygen levels, high interaction forces between the polymer and water deposited on its surface are formed. This process is called oxidation and leads to easy wetting of surface, promoting lowered contact angles. However, a recovery process of hydrophobicity has been found in the silicon materials tested in laboratory. This is a special characteristic of this material, which promotes chains of low molecular weight from the bulk to the surface, easier than EPDM rubber. This behavior is caused mainly by three types of chemical changes achieved

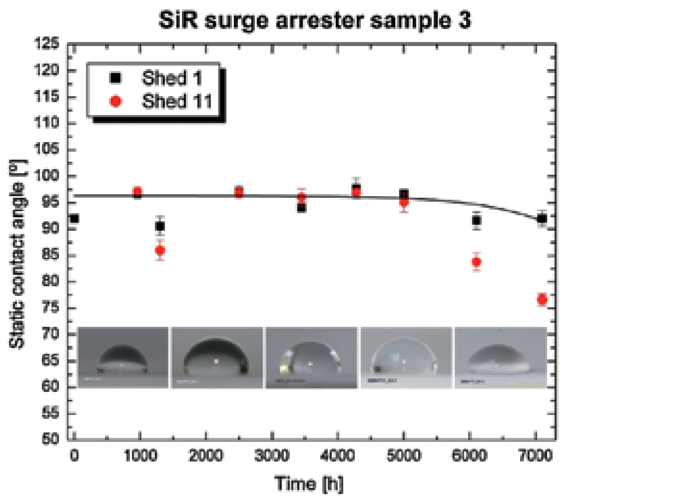


Figure 2. Static contact angle measurement vs. aging time for SIR surge arrester testedin laboratory.

either artificially or naturally: (1) reorientation of methyl and oxidized groups, (2) condensation of silanol groups and, (3) diffusion of PDMS of low molecular weight.

A particular modification on silicon surge arrester test conditions was made after 5000 h of testing; it was also artificially contaminated with the same slurry used to contaminate the samples 2 and 4, containing salt and kaolin, as is described in experimental section. This situation promoted a loss of hydrophobicity by building up pollution layers on polymer surface. This especially occurs on the arrester's lower sheds, as it was shown by lower contact angle values on shed 11, Fig. 2. This loss of hydrophobicity is attributed to high local electrical stresses caused by a non-uniform pollution layer distribution on such shed, where corona activity and higher average temperature were observed. Also, it is important to note that the loss of the static contact angle is double for EPDM composite (sample 2) as compared with silicone rubber composite (sample 3) due to the easier diffusion of low molecular weight (LMW) chains in silicon rubber from the bulk to the surface, as mentioned above.

Figure 3 shows the contact angle behavior for the Silicon-ATH bushing (sample 4). As can be seen, in this material, contact angle increased from 108° to 120° and then decreased down to 90° approximately for both sheds. The increment in contact angle can be explained because of the filler added to the silicon rubber. By infrared spectroscopy and thermogravimetric analyses has been found that this material includes alumina trihydrated in about 50% of

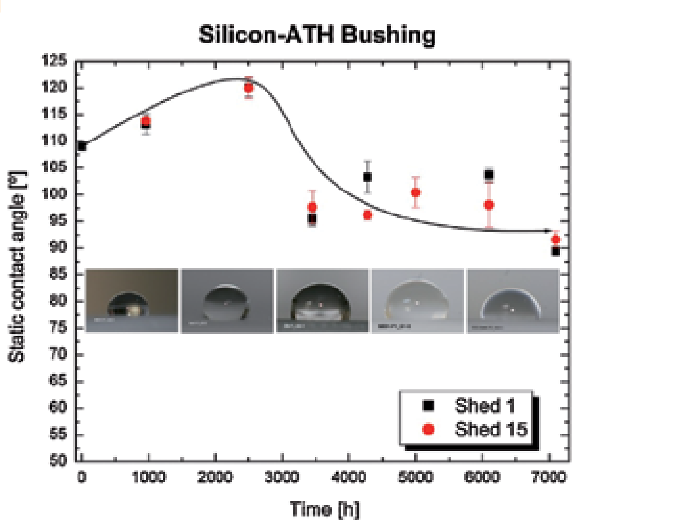


Figure 3. Static contact angle measurement vs. aging time for silicone-ATH bushing sample 4 tested in laboratory.

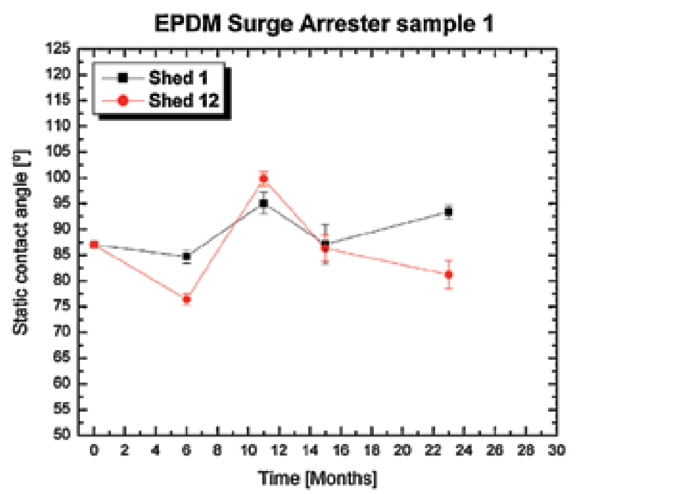


Figure 4. Static contact angle measurement vs. aging time for EPDM surge arrester tested in field.

its weight. Some investigations [14] have shown that the addition of filler to silicon rubbers has very important influence on the performance of SIR insulating material, since they provide an increase in concentration of dynamic LMW components [14, 15].These LMW species migrated to the surface and thus, made it more hydrophobic. However, the accumulation of LMW components on the polymeric surface decreased after 2500 h of aging test presumably because of the cleaning process that was carried out at this time. The EPDM arrester (sample 2) was also contaminated and cleaned at this time of test; yet, similar behavior was not observed on this material. Hydrophobicity was completely lost after 5000 h of test and it was not recovered anymore by the EPDM. This indicated that hydrophobicity behaves differently depending of polymeric material and composition.

It is important to point out that silicon insulation of sample 4 also recovered hydrophobicity after some hours under dry conditions. That is a unique property present in silicon rubber materials, attributed mainly to the diffusion facility of low molecular weight PDMS chains in silicon rubber.

Figure 4 shows the behavior of the static contact angle for sample1, installed in field during a period of 23 months. On this figure, it is observed that no major loss of hydrophobicity has occurred during the testing period. As shown in Tables 1 and 2, this sample has the same material as sample 2, which was put under accelerated aging in laboratory. So, the hydrophobicity behavior can be compared by observing changes in contact angle in both samples, and by correlating these results to establish operational status of housing insulation material installed in field. By this way, it can be said that the EPDM material of sample 1 has presented good performance up to now because the contact angle has not shown yet significant variations.

Table 3 provides the static contact angle values recorded for the silicon bushing installed in field (sample 5). As it can be seen, on almost all sheds the contact angle decreased during the first months, but then increased up to the last evaluation. Similar behavior was found for the silicon arrester (sample 3) tested in laboratory. The analysis of materials on both samples corresponds to silicon rubber without inorganic filler. So, by following the results obtained in laboratory, the end of life may be predicted for the housing materials in terms of contact angle. However it is necessary take into account some other factors like surface microstructure.

As an important point of these results, it is note worthy that while the non-ceramic bushings were never washed during the entire course of the test, they continued to maintain a hydrophobic surface. As a consequence, the reduced risk of leakage current under rain and condensation due to hydrophobic surface of the material helped to preserve the housing's integrity, even within a challenging service environment.

A longer monitoring has to be done on samples 1 and 5 in order to follow up material degradation due to electrical stress and ambient conditions. It is important to note that the contact angle measuring technique was effectively implemented in field and that it can be used for monitoring hydrophobicity in polymeric housing off-line.

## Surface roughness

Figure 5 shows the roughness measurements obtained in terms of the Ra parameter for the polymeric housing materials tested in laboratory. Ra measures average roughness by comparing all the peaks and valleys to the mean line, and then averaging them all over the entire cutoff length.

In Fig. 5, it is observed that for EPDM-ATH surge arrester (sample 2), Ra increases approximately 2 times its original value after1000 h of test. Some investigations have shown similar behavior at the same time span of accelerated aging in EPDM materials [12]. It can be explained with the loss of the polymer outer

Table 3. Contact angle measurements of 230 kV silicon bushing installed in field (sample 5) during different time of test.

| Contact angle (°) | | | | |
|---|---|---|---|---|
| Shed | Begin | 3 months | 8 months | 47 months |
| Bottom | 90.8 | 79.8 | 97.2 | 98.9 |
| Middle | 87.2 | 78.9 | 97.2 | 95.4 |
| Top | 87.2 | 85.3 | 97.5 | 95.6 |

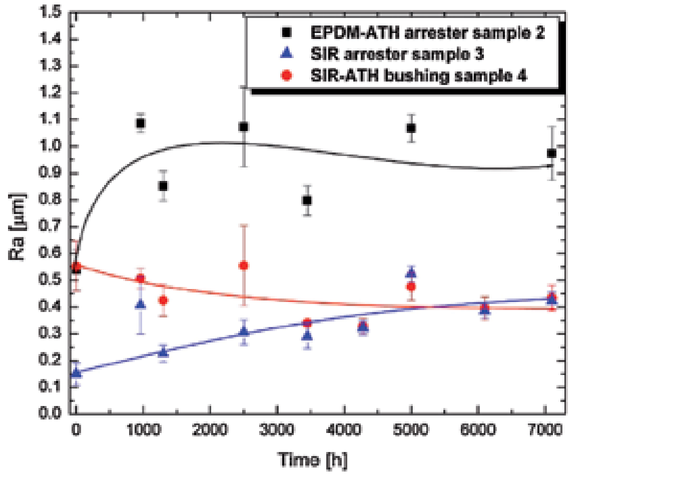


Figure 5. Surface roughness Ra, as a function of aging time for different polymer insulating materials tested in laboratory. Data of roughness correspond to the upper shed.

layer on the surface. This layer resembles the surface finish of the molding process. After this time (1000 h), the data of the roughness test oscillate around a value of 1 μm. With continuously increasing aging time, are placement process of the outer layer is observed due to erosion. It means that the molded outer layer (mostly polymer) is then substituted by a layer composed of polymer and fillers now exposed, as it can be observed in Fig. 8(a). This situation makes the roughness increase its value giving information related to the polymer surface degradation. At this point, it is important to mention that the roughness measurements for EPDM-ATH material aged rapidly in laboratory seem to be more effective than hydrophobicity evaluation to identified degradation on polymer surface. While contact angle results showed decay until 2500 h of test, roughness data identifies surface modification since 1000 h, approximately.

A different behavior can be observed in Fig. 5 for the Ra parameter of the sample 3 that consists of silicone rubber composite. For this material, the surface roughness increases almost linearly up to three times of the initial value at the end of the test. It suggests constant erosion on the polymer housing material.

On another hand, the silicon rubber bushing (sample 4) shows as light decay in roughness: from 0.55 μm to 0.40 μm (Fig. 5). As it can be seen, the initial roughness data for sample 2–4 are different. This could be due to diverse polymer matrix material, manufacturing process or fillers used on each composite. For instance, sample 4 has a conical-helicoidally shape obtained by helical extrusion. In combination with the high content of filler (about 50% of ATH) an initial roughness of 0.55 μm can be observed. Nevertheless, as the test develops, this value slightly decays. This phenomenon, contrary to the expected results, is not yet well understood. It is possible that the original surface came with many imperfections originated by the helical extrusion process, and because of polymer degradation due to weather and electrical stress, these imperfections were lost, making the surface a bit smoother.

When comparing the contact angle and roughness behavior for samples 2–4, it can be seen that they are not well correlated. Sample 4 is the worst correlated: its data tendency for both parameters highly differs. This can be attributed to different composite materials and filler concentration used in these samples. For example, silicon rubber has the property of recovering its hydrophobicity even after losing it, due to migration of LMW species to the surface. However, EPDM does not recover hydrophobicity which is lost after a period of time under environment conditions and electrical stress, as it was shown above.

Figure 6 shows the surface roughness for EPDM composite of the arrester sample 1 installed in field. It can be observed that this value does not increase after 23 months of evaluation. These results suggest that this period of time in field corresponds to less than 1000 h of accelerated weathering aging in laboratory for the EPDM housing material. This idea is supported by microstructure analysis as discussed below.

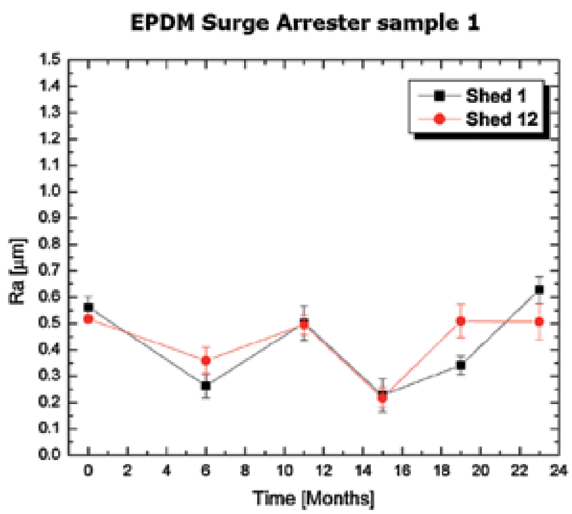


Figure 6. Surface roughness Ra, as a function of service time for EPDM-ATH arrestersample 1 installed in field.

**Microstructure replication**

Taking advantage of the replica technique as a method for reproducing surface microstructure, polymeric housing materials have been analyzed by the means of this technique. In order to validate the replica technique for its use in polymeric surfaces the following was done. A polymeric insulator that had already failed in field was analyzed with direct observation of a housing polymeric sample and with replication by the replica technique. Fig. 7(a) shows the polymeric housing material sample directly observed by SEM, and Fig. 7(b) is the microstructure of the cellulose acetate used to record the topography of the same sample as Fig. 7(a). It can be observed that similar microstructures are obtained by replication and direct observation on the material. The said above demonstrates that replication can be used to analyze surface microstructure of polymeric materials with the advantage of using non-destructive technique.

Based on the good results obtained from the preliminary tests with replication technique, this characterization method was implemented to study the degradation process on the polymeric materials used in our investigation.

Figure 8 shows replica micrographs of samples 2–4 tested under accelerated aging for different testing times. All replica films were taken on the first shed that was close to the conductor side. In the micrographs, the erosion process caused by aging, both in EPDM-ATH composite of the sample 2 as well as in silicone rubber composites of the samples 3 and 4, can be observed. Electrical stress and the harsh environment simulated in laboratory are mainly responsible of this degradation developed on the polymeric composite surfaces. In the case of compounds containing fillers (sample 2 and 4), the fillers are exposed as a function of the aging time due to the loss of polymeric species. Different microstructure was found for the sample 3, because it does not contain microparticles as filler; however, polymer degradation was also observed in it, due to aging.

On the other hand, Fig. 9 shows SEM micrographs of the surface microstructures taken on the shed of polymeric housing material of the sample 1, installed in field and having 23 months in service. The microstructure reveals slight changes supporting a minor variation on contact angle and roughness for the same monitoring timespan. It supports the idea of using these non-destructive tests for evaluating degradation on polymeric housing material.
In addition, a correlation between accelerated aging test laboratory results and field monitored data can be useful to get information of such materials' end of life.

Figure 10 shows the microstructure evaluation of the 230 kV silicon rubber bushing installed in field (sample 5). It is evident that after four years of service, the surface microstructure shows some changes, possibly caused by the

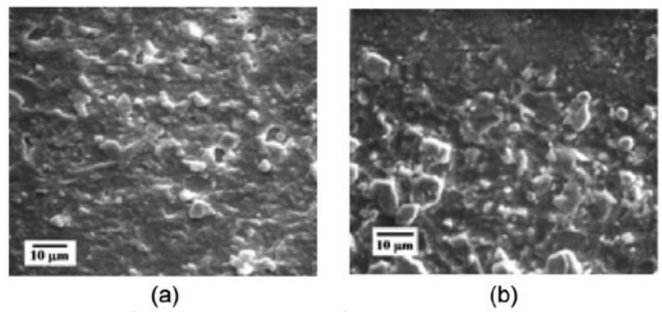

Figure 7. Surface microstructure of polymeric housing material: (a) direct observationand (b) replica technique.

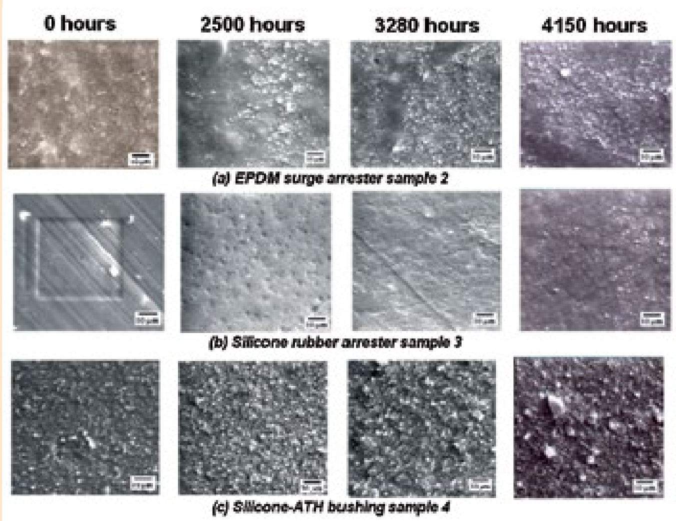

Figure 8. Surface microstructures obtained by replica technique for samples 2–4 at different aging test time.

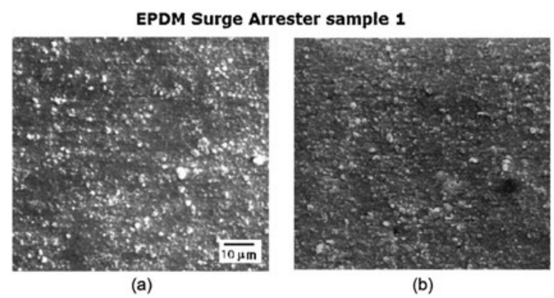

Figure 9. Replica surface microstructures of EPDM-ATH arrester sample 1 installed infield having 12 moths of service.

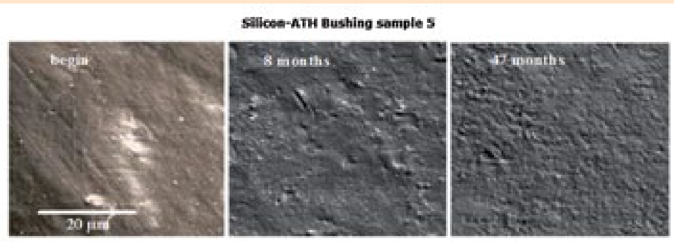

Figure 10. Microstructure images of non-ceramic housing of the bushing during different time of evaluation. Microstructure was analyzed by scanning electronic microscopeusing replica technique.

contamination layer that has not been removed by washing. Nevertheless, these changes are insignificant; according to contact angle measurements (Table 3), the housing polymeric material of this bushing is still in good operational conditions.

It is important to point out that the microstructure analysis, made by using replica technique, can be applied on places where it is impossible to get a sample. This is the case of the polymeric insulation sheath, where housing material covers the composite core with a deep of few millimeters. In Fig. 11, the microstructure of the sheath of sample 4 is shown as it appeared at the end of the accelerated aging test (7000 h). The place where replica was taken on the surge arrester is displayed along. The micrograph shows more degradation than that observed on the shed of the same bushing due to about 3000 h of extra time exposed to accelerated aging (Fig. 8c). In service, it is clear that no other non-destructive test could be used to get information from the microstructure of the housing insulation along the sheath; therefore, the replica technique can be a powerful tool for evaluating polymer degradation of housing insulation in situ.

Surface microstructures obtained on this study have shown similar structures as composite insulating materials studied

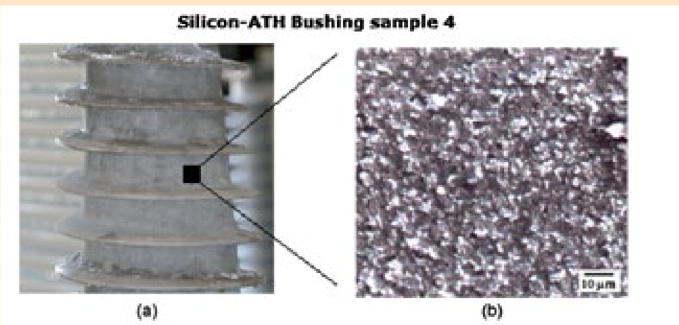


Figure 11. (a) Image showing the point on the sample where replica was taken. (b)Sheath surface microstructure of SiR-ATH housing material sample 4 taken byreplica technique.

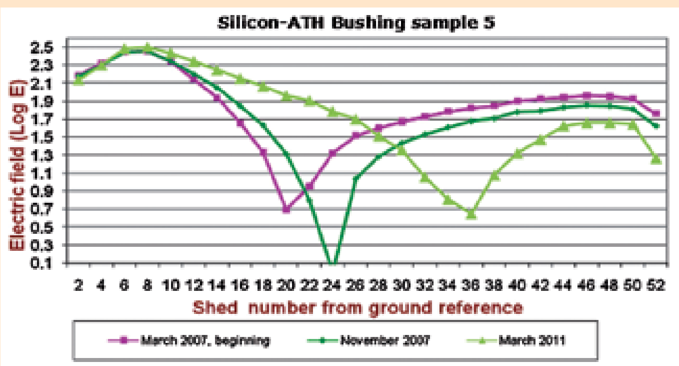


Figure 12. Electric field distribution along the non-ceramic bushing connected to the line.

by different authors [3, 16, 17]. In their studies, direct observation of the composite material was applied. It confirms that replication has a great relevance for following up the degradation process in high voltage insulation installed in field.

Particularly for the 230 kV silicon bushing (sample 5), the characterization was completed with electrical tests. Fig. 12 shows the electric field distribution measured along the bushing for different time spans in service: 0 months, 8 months and 47 months, after the bushing was installed. The measurements were performed with the breaker closed. The principle of measurement is based on the automatic measurement and recording of the tangential electric field strength in different points along the non-ceramic bushing surface. As shown in Fig. 12, the distribution of electric field is more concentrated on the bottom of the bushing (ground side) than on the top of the bushing (hot side). This electric field behavior on the bushing has been similar in the 3 measurements carried on different times and no problem has been detected in the circuit breaker.

By means of the leakage current system installed near the dead tank circuit breaker with non-ceramic bushings, data were downloaded and analyzed. The results showed leakage current peaks around 8 mA. Peaks higher than 50 mA could generate dry band on the surface; however, during sporadic rains, maxima peaks have been of 24 mA, which does not deteriorate non-ceramic housing insulation. These results confirm that the bushing suffered neither internal, nor external, deterioration.

## Conclusions

Microstructural and surface changes of rubber insulating materials due to aging were studied by static contact angle, roughness measurements and micrograph observation. Data of hydrophobicity, surface microstructure and roughness of a period of time infield and of 5000 h in laboratory by multistress accelerated aging were compared. Hydrophobic properties of EPDM housing composite material have been suppressed and unrecovered after 3000 h of accelerated aging. Whereas for silicone rubber composites, the contact angle values were kept in the hydrophobic range. These results showed a dependence of the composite formulation with aging time. Polymer matrix material, manufacturing process and fillers have a strong influence on surface roughness of composite insulation. A replica technique was effectively implemented to evaluate the microstructure of polymeric insulation composites even in field. This makes of this non-destructive technique a novel and powerful tool for polymeric housing material characterization.

Hydrophobicity and structure replication can be used to predict the end of life of non-ceramic housing material if the results are correlated to accelerated aging tests. Material characterization of silicon rubber bushing installed in field has shown to be in good conditions for continuing working after 47 months of service. These results were confirmed with electric field distribution and leakage current measurements.

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