

Surface Recovery of Silicone Rubber Used for HV Outdoor Insulation

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ABSTRACT

Results of a study performed to obtain a better understanding of the material characteristics responsible for hydrophobicity recovery leading to a high wet surface resistance in silicone rubbers used for outdoor HV insulation, are reported. The samples were obtained from new and artificially aged HV insulators using HTV silicone rubbers (3 different formulations) as weathershed and RTV silicone rubbers (2 different formulations) as a protective coating. The main experimental facilities employed consist of a salt fog chamber for artificially aging the insulators, and a scanning electron microscope (SEM) for material studies. New results of practical significance that have emerged from this study are: (1) hydrophobicity recovery, predominantly due to diffusion of low molecular weight (LMW) silicone polymer chains, occurs with only a fraction ($< 20\%$) of the total LMW polymer content initially available in an unaged material surface, (2) LMW chain regeneration and hence surface hydrophobicity recovery occurs even after the initial supply of LMW polymer is depleted, and (3) hydrophobicity recovery is significantly affected by ambient temperature. The results show the same pattern for different formulations of HTV and RTV rubber materials studied. The X-ray Mapping feature in the SEM provides a visual indication of the diffusion process which is a noteworthy contribution.

1. INTRODUCTION

HV outdoor insulating systems such as line and station insulators, cable terminations, surge arresters and bushings, using silicone rubbers for external insulation have become very popular. Presently there are two forms of silicone rubbers that are widely used for outdoor HV insulation, namely, high temperature vulcanizing (HTV), used mainly as weathersheds; and room temperature vulcanizing (RTV), used mainly as a protective coating on a ceramic surface. The driving motivation for their increased use is the unique characteristic of hydrophobicity, which provides a high surface resistance, even in the presence of moisture and contamination, thereby suppressing the leakage current to low values. Uncontrolled leakage current promotes intense dry

band arcing, which on polymers, can ultimately lead to material degradation in the form of tracking and erosion, and/or flashover at the operating voltage [1].

It has been observed both from service and laboratory tests that prolonged dry band arcing causes the surface of all polymers used for outdoor insulation to lose their initial hydrophobicity and become wettable [2, 3]. But if there is a dry period of > 8 h, the silicone rubber materials recover their lost hydrophobicity [4]. It has also been observed that the hydrophobicity is maintained in silicone rubber materials even after many years in service, and it is this attribute that is responsible for the superior contamination performance of silicone rubber family materials when compared to other polymer families and traditionally used porcelain and glass [1].

Earlier studies have shown that the recovery of hydrophobicity is mainly due to a diffusion process [2,4], whereby low molecular weight (LMW) polymer chains from the bulk migrate to the surface to recreate a low energy surface. Because outdoor insulation devices in service are subjected to numerous wet and dry cycles, it is important to know how long does the surface remain hydrophobic and provide superior contamination performance. It is of interest to determine the source(s) of LMW chains and explore if, during service, it is possible that all the LMW chains are used up, which could then impact the electrical performance under contaminated conditions. It is also useful to determine the role of ambient temperature on hydrophobicity recovery as, insulating devices are used in a wide range of climatic conditions. This study was performed to obtain a better understanding of these practical issues.

2. EXPERIMENTAL

Non-ceramic insulators using three different formulations of HTV silicone rubber for weathersheds, and porcelain insulators bells coated with two different formulations of RTV silicone rubber, were evaluated. The test setup used to artificially age these devices was a salt-fog chamber [5]. Samples were subjected to a combination of salt water spray (conductivity 300 $\mu\text{S}/\text{cm}$) and ac electric stress (35 V/mm, average) for 8 h continuously, and both the voltage and fog were turned off for the remaining 16 h in the day, to allow the silicone rubber to recover its hydrophobicity that is temporarily lost due to dry band arcing. The total exposure to electric stress and fog was 500 h. The samples for the salt fog exposure were 3 to 5 skirt sections from full scale insulators, and 2 unit porcelain insulator bells coated with RTV silicone rubber. Typical physical changes that were observed at the end of the aging period were surface roughening and slight erosion. The leakage current on the samples was initially very low (< 5 mA peak) and increased to ~ 25 mA during the test, and this range of leakage current magnitude has been measured in the field in several contaminated locations [1,2]. Although there is no established method to determine the time equivalence between laboratory test duration with field exposure, it is worthwhile to mention that the experimental conditions used in the fog chamber were those which previously have been shown to produce a ranking in the test that is consistent with many years of field experience [1,2,6].

The different HTV silicone rubbers and RTV silicone rubbers have been designated by numbers. For HTV silicone rubber sample HTV1, the weathershed material was also made available in the form of thin rectangular slabs, which made it possible to perform the tensile tests. Except for the tensile strength test which was performed

only on HTV1, the other tests were performed on more than one type of material composition.

2.1. MATERIAL ANALYSIS TECHNIQUES

The principal tool used for material analysis was the scanning electron microscope (Model JEOL 840 JXA). Three types of measurements were performed in this study: the cross over voltage (COV), energy dispersive X-ray (EDX) and X-ray mapping (XRM). A brief explanation of these techniques is provided below and more details are available in the literature [7].

The COV technique has been used successfully to indicate the degree of hydrophobicity of polymeric materials [8]. Samples for this measurement are cut from the insulator surface and the dimension is typically $1 \times 1 \times 0.1$ cm^3 . It has been shown in earlier papers that the COV can be related to the surface resistance under wet conditions [9] and the contact angle made by a water droplet on the surface [8].

The COV refers to the acceleration voltage of the incident beam at which there is a balance between incoming and exiting electrons from the sample surface; in other words, an acceleration voltage where there is no net charge accumulation. The measurement is done by varying the acceleration voltage of the incident electron beam, while checking the change in contrast of the scanned area upon demagnification. A sample that charges positively yields a black square when demagnified, and a sample that charges negatively yields a white square. The acceleration voltage at which the transition of the image from white to black occurs is noted as the COV. There is no need for a conductive coating on the sample surface, because the electron beam voltage is low (< 1.5 keV).

The EDX technique was used in the present study to detect the Si X-rays from the silicone polymer, which can be used as an indicator of the LMW polymer content on the surface. The samples were coated with a spectroscopic grade graphite paste, ~ 2 μm thick. The graphite paste serves two purposes. First, it provides a conducting surface, thereby preventing surface charging and associated problems with secondary imaging that occur when high accelerating voltages are used. Secondly, if the depth of the coated surface analyzed is less than the coating thickness then any Si X-ray detected is due to diffusion of LMW chains from the material into the graphite layer. Because studied samples have silica powder as a reinforcing filler, without a nonsilicon, conducting coating, it would be difficult to perform HV scanning electron microscopy and distinguish Si from the polymer vs. the filler.

A beryllium (Be atomic number 4) window is used to ensure proper vacuum around the detector. This instrument is not sensitive to elements with atomic numbers

< 11; and the use of graphite paste (atomic number 6) does not interfere with the measured results. EDX is a technique by which the sample surface is bombarded with an electron beam. The X-rays generated, as result of the interaction between the electron beam and the material, are collected and sorted along a spectra of characteristic X-ray energies. This incident beam is rastered across the surface line by line. Since each element has a characteristic X-ray, the chemical components of a given sample can be found along the energy scale of the abscissa, with the numerical count of each element compiled along the ordinate.

The depth of the surface that is analyzed is a function of the accelerating voltage and the element of interest (in this case silicon), and is given by [10]

$$Z = 0.035(V_o^{1.65} - V_q^{1.65})(1/\rho) \quad (1)$$

where Z is the depth (μm) of penetration, V_o the accelerating voltage, V_q the characteristic X-ray energy of Si and ρ the density of the graphite paste. At an accelerating voltage of 5 keV, the interaction volume between the incident beam and matter takes on a teardrop shape, and the penetration depth of the electron beam was calculated to be 0.36 μm . This means that the X-ray signals collected are gathered from a depth of up to 0.36 μm into the graphite paste.

The XRM technique was used in this study to provide a visual image of the elemental distribution on the surface being analyzed. By this method the characteristic X-rays collected from EDX measurement are mapped out in an image corresponding to the secondary electron image. Because the mapping process uses the signals obtained from X-ray collection, it operates only when distinct elemental peaks are detected by EDX. The signal collection is similar to that of EDX, except that, in the case of XRM, the photographic image of the surface being examined is digitized by a computer, and the image is projected onto a computer screen. The elemental identification is performed beforehand, via EDX, and each element receives a color code. During the mapping process, the primary beam scans across the surface of the material, and collects the X-rays which correspond to the previously identified element. The element is then labeled with the respective color dot on the digitized computer image. With XRM, one can obtain the distribution of any element of interest on the surface. FlextranTM software was used for the XRM experiments.

3. RESULTS AND DISCUSSION

3.1. XRM AND EDX RESULTS ON UNAGED AND AGED SAMPLES

Insulators in service are contaminated from a variety of sources. A common component found on insulator surfaces is sand [11], silicon dioxide, and silicon is also an integral part of the silicone rubber material. This causes complications if it is required to study the hydrophobicity recovery characteristics under contaminated conditions. Coating the surface with graphite, a non-silicon containing material, may not be fully realistic, but to perform HV scanning electron microscopy a conducting layer is needed to avoid surface charging. Other types of conducting surfaces such as gold, gold-palladium were attempted, but due to the higher density of these materials in comparison with carbon, a considerably longer time was needed for diffusion of LMW polymer chains even when the coating thickness was ~ 10 nm (commonly obtained thickness with sputtering). With a graphite paste of ~ 10 nm, previous studies using ESCA [4, 12] showed that the LMW polymer chains could diffuse through it in ~ 24 h, which is roughly the same time obtained when the insulator surface was coated lightly with mineral deposits consisting of calcium and magnesium, other commonly found contaminants on field exposed insulators [11].

For the EDX and XRM studies, a graphite paste of 2 μm thickness was used as the coating. This could be considered as a fairly thick contaminant on the surface of silicone rubber. The samples for these measurements were graphite coated and were left in the laboratory at room temperature for several days. The EDX and XRM data illustrating typical increase in the surface LMW content by diffusion is shown in Figures 1(a) to (d). The corresponding Si X-ray count, obtained by the EDX technique as an indicator of the surface LMW content, is plotted in Figure 2. It can be seen that diffusion tends towards a steady state on the virgin samples after several days. A similar pattern can be observed for the different types and compositions of silicone rubber materials evaluated. The differences in the rate of diffusion and the steady state value of the silicone count could be due to differences in the material composition.

The surface recovery characteristics of aged samples is also shown in Figure 2. The samples were obtained from the surface near the HV electrode region which had the most discharge activity. The specimens for the SEM studies were typically 1 cm^2 and 2 mm thick pieces. It can be observed that rate of recovery is reduced significantly with aging. It is interesting to note that the trend in the results is consistent for the different types of HTV and RTV silicone rubbers. These results concur with

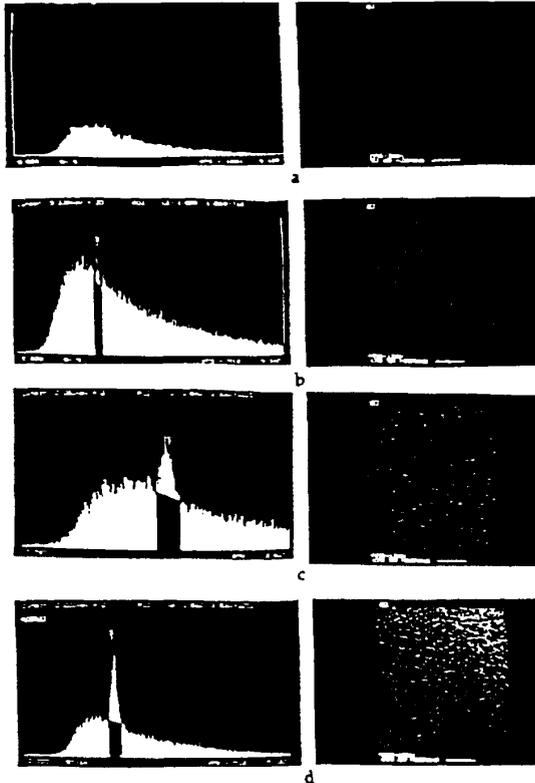


Figure 1.

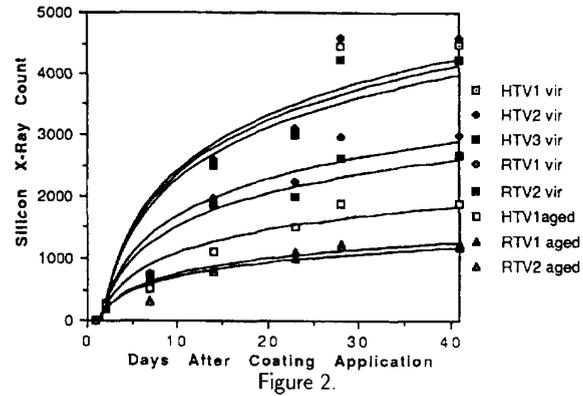
EDX (right) and XRM (left) pictures illustrating increase in surface silicon content with time for unaged silicone rubber sample HTV1. (a) Immediately after coating, (b) 6 days after coating, (c) 12 days after coating, and (d) 24 days after coating.

the hypothesis of a recently published paper that aging produces a reduction in the surface LMW content [13].

3.2. EFFECT OF TEMPERATURE ON LMW DIFFUSION

To determine the effect of ambient temperature on the diffusion process, a set of virgin samples of HTV1 were graphite coated ($2\ \mu\text{m}$ thick) and subjected for several days to different ambient temperatures in a temperature controlled oven. The temperature range evaluated was from -4 to 60°C , which covers a wide range of geographic locations. Some samples were exposed outdoors when the maximum and average temperature was 28 and 24°C , respectively. The samples were examined daily with EDX and XRM, and put back in the oven after the measurement which lasted for ~ 1 h.

Table 1 shows the Si count obtained at different periods. For samples exposed outdoors (with a maximum



EDX data showing increase in Si X-ray count with time for all materials evaluated in the virgin (vir) or unaged and aged condition.

temperature of 28°C), it was seen that after just 2 days exposure, the silicon count on the surface reached almost the steady state value observed after 40 days in samples subjected to room temperature of 20°C . For samples subjected to an ambient temperature of 7°C , there was a slight amount of silicon detected after 2 weeks. There was no silicon detected in this period for the samples subjected to -4°C . It was intended to expose some samples to lower temperatures, such as -10 to -40°C , but the results obtained indicated that not much additional information could be obtained. For the sample subjected to an ambient temperature of 60°C , a very high silicon count was observed after just one day which suggests that major recovery must have occurred in less than a day. These results demonstrates the significant role of ambient temperature on the hydrophobicity recovery.

Table 1.

Surface silicon X-ray counts at different ambient temperature and time for unaged silicone rubber samples HTV1, HTV2 and RTV1.

Sample	Temp. $^\circ\text{C}$	Exposure h	Si X-ray count	Steady state %
HTV 1	20	960	4466	100
HTV 2	20	960	4610	100
RTV 1	20	960	3000	100
HTV 1	28	24	2427	54
HTV 1	28	48	4287	96
HTV 2	28	24	2756	60
HTV 2	28	48	4469	97
HTV 1	60	24	4390	98
HTV 1	7	168	89	2
RTV 1	7	168	100	3
HTV 1	-4	168	0	0
RTV 1	-4	168	0	0

It is important to mention that at higher ambient tem-

perature $> 100^{\circ}\text{C}$ another mechanism, namely, the chain reorientation, which results in a rapid (within ~ 5 min) hydrophobicity recovery has been observed [14]. The temperature range and the coating of a thick graphite paste used in the present study ensured that the diffusion of LMW chains and not the chain reorientation, was the dominant mechanism in the hydrophobicity recovery.

3.3. MECHANISMS OF LMW CHAIN REGENERATION

Silicone rubber materials for insulators have polymer chains of varying molecular weight distribution. It has been demonstrated that the shorter LMW chains are responsible for diffusion, owing to their higher mobility. However, the source of the LMW chains has not been well understood. One possible explanation is that when new, there is always a certain amount of LMW chains that is present which will provide the long term surface recovery or hydrophobicity. This suggests that with time the reservoir of LMW chains could get depleted, and in a finite time the material will lose its ability to recover its hydrophobicity. However, if there is a possibility of a continuous supply of LMW chains then the material could be expected to exhibit the hydrophobicity recovery for longer periods of time. Possible mechanisms for LMW chain regeneration are scission of the longer high molecular weight (HMW) chains into shorter LMW chains, evolution of unreacted polymer chains and cyclic silicone polymers, interaction between the polymer and filler, *etc.* [15]. These reactions are temperature sensitive. Higher temperature should accelerate the appearance of LMW chains on the surface, and this has been demonstrated in the previous Section. In addition, some of these reactions involve the polymer back bone and should affect the mechanical strength.

In order to verify the above explanations, virgin silicone rubber samples were immersed in hexane for varying periods of time. Hexane is known to remove the extractables, that is, the smaller more fluid polymer chains from the silicone rubber material. The amount of extractables that are removed is a function of the concentration of LMW chains initially present in the material by virtue of the manufacturing process. Removal of extractable species should result in a weight loss. Figure 3 shows the loss of weight of virgin silicone rubber materials subjected to hexane for varying periods of time. The weight loss measurements were conducted on a high precision balance (Mettler, accuracy 10^{-5} g) in a semiconductor clean room, and were performed ~ 24 h after the swelling, that occurs due to absorption of hexane by the silicone rubber, had subsided.

It can be noted from Figure 3 that there is a loss of weight in the first few hours, but then a steady state

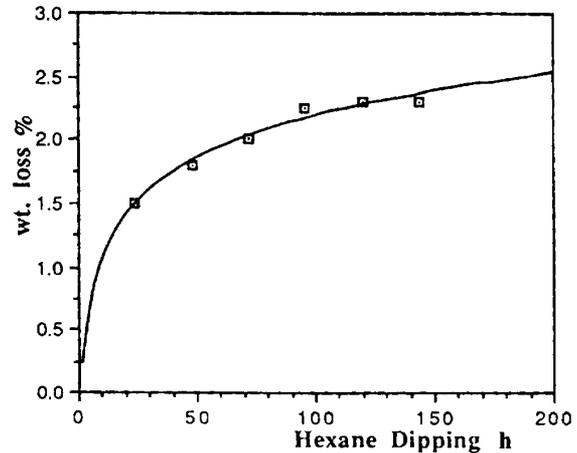


Figure 3.

Weight loss with time of dipping in hexane for unaged silicone rubber sample HTV1.

is reached in a few days. This indicates that most of the extractable LMW chains have been removed from the material. Such a sample should be expected to show little or no surface recovery if the only source of LMW is that present during material processing. These samples, which were dipped in hexane for 168 h (1 week), were coated with a $2\ \mu\text{m}$ thick graphite paste and examined under XRM. It was observed that even after 40 days, there was no trace of silicone that had diffused through the paste. During the entire measurement, the samples were kept at 20°C . The SEM and EDX data that were obtained were very similar to Figure 1(a), and have not been shown separately to avoid repetition.

Another set of hexane treated graphite paste coated samples were placed in an oven at 30°C for 1 day and examined with EDX and XRM methods. Figure 4 shows that in a short time, the elevated temperature can regenerate and mobilize the LMW chains and cause them to appear on the surface. These results are valuable to users of silicone rubber insulation (especially in warmer climate) as they suggest that surface recovery can occur even if the initial LMW content present when new is depleted.

Tensile strength tests were performed on virgin and samples soaked in hexane for varying periods of time in order to determine the change in mechanical properties. The tensile strength is only one aspect of the mechanical property and is a good indication of mechanical changes. The samples (about 20 pieces of HTV1) were first cut into a dumbbell shape for the tensile strength test, and then dipped in hexane for 1 day to remove the bulk of the extractable LMW polymer chains. After this step, the samples were heated for 1 h at 60°C to regenerate more

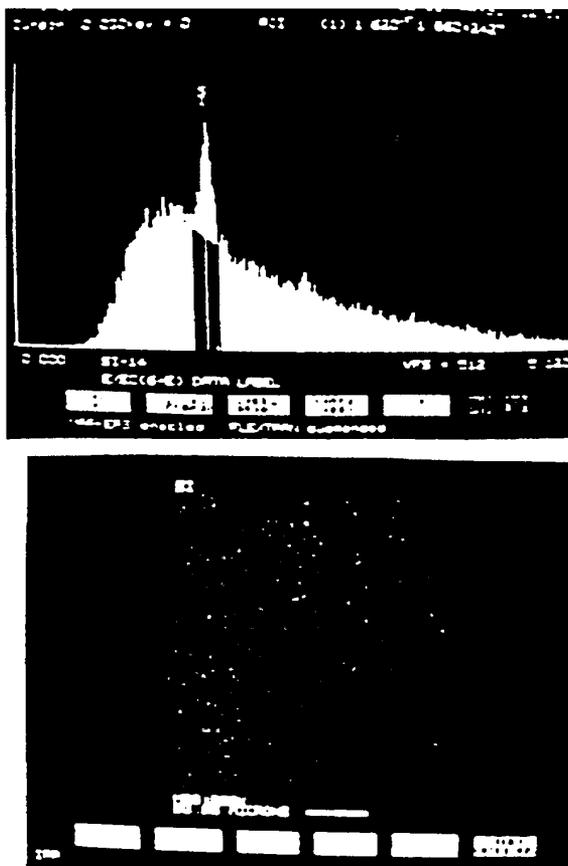


Figure 4.

EDX (top) and XRM (bottom) pictures of unaged silicone rubber sample HTV1 on heating a hexane dipped sample at 30°C for 1 day.

LMW chains. This cycle of hexane dipping and heating was continued for several weeks. The tensile strength was tested in the virgin state (without any hexane dipping or heat treatment) and after 1, 2, and 3 weeks of hexane dipping and heat treatment. The results of the load to tensile failure as a function of time of hexane dipping and heat treatment, is shown in Figure 5. It can be seen that there is a gradual reduction in the load to failure. This behavior confirms that a reduction in mechanical strength is obtained as expected from the various mechanisms responsible for LMW chain regeneration.

3.4. THRESHOLD LEVEL OF LMW CHAINS FOR HYDROPHOBICITY RECOVERY

It has been established that there is a loss of LMW chains on the surface with aging. It is of practical interest to determine the threshold level of LMW chains needed for hydrophobicity recovery. This can provide a qualitative indication on the duration for which these materials

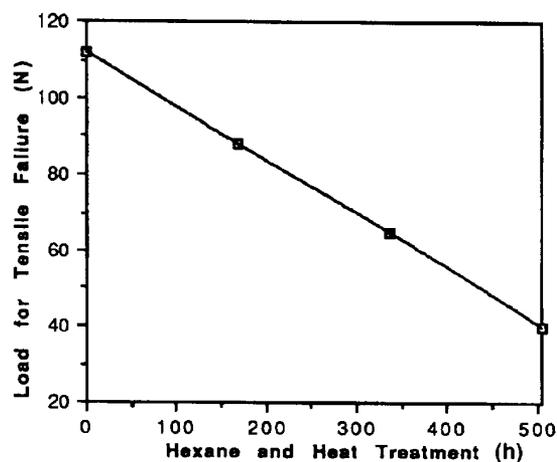


Figure 5.

Reduction in tensile strength with hexane dipping-heating cycles for unaged silicone rubber sample HTV1.

will provide the superior contamination performance. In order to determine this, the COV technique was used to characterize the degree of hydrophobicity. It has been shown in an earlier paper that the COV can be related to the surface resistance under wet conditions. Surfaces on which a high COV is obtained show higher wet surface resistance than those surfaces which yield a low COV. For the virgin surfaces of the samples evaluated the COV was in the range of 900 to 1100 eV. Once hydrophilic after prolonged exposure in the salt fog chamber, their COV dropped to a low valued of 200 eV. The surface usually regains the hydrophobicity within a 24 h dry period and the COV is known to reach the value obtained for the virgin sample [8].

Samples were dipped in hexane for a period of 7 days. Due to the loss of the LMW chains these samples were completely hydrophilic even at 6 weeks after removal from hexane. The virgin and the hexane treated samples were sputter coated with a graphite paste of thickness 10 nm, and analyzed 30 min after the coating application and after 6 weeks, during which time they were stored in the laboratory at 20°C. The main reason for choosing a coating thickness of 10 nm instead of 2 μ m was to minimize the effect of the coating on the diffusion process. It must be mentioned that with such a low coating thickness part of the silicone rubber material is analyzed, and the Si X-rays would be generated both by the polymer and the silica filler. But the use of the same coating thickness for all the samples analyzed facilitates relative comparison of the results.

Another complication in determining the threshold level of LMW chains for hydrophobicity recovery arises from

the fact that the COV measurements are meaningful only on an uncoated sample, but XRM cannot be done without first coating the sample with a conducting medium. The results of the COV and XRM study is shown in Table 2. For samples which have the X-ray count and COV data, they were obtained from two different sets of samples subjected to the same treatment, one uncoated (COV) and one graphite coated (Si X-ray Count). It can be seen that subjecting the silicone rubber in hexane results in a substantial reduction in the Si X-ray count of 20000 from 32000 to 12000. This is indicative of the quantity of the LMW mobile species in the virgin sample extracted by hexane. It can also be observed that even a prolonged period of 6 weeks after removal from hexane at an ambient temperature of 20°C did not increase the Si X-ray count, indicating that hydrophobicity recovery had not occurred. This was in fact verified by COV measurement, and visual observation of a water spray on another uncoated sample subjected to the same hexane treatment.

Table 2.
COV and X-ray silicon count of unaged silicone rubber sample HTV1 subjected to hexane and heat treatment.

Treatment	Si X-ray count	COV eV
None (virgin)	32000	900
Hexane dipped for 7 days	12000	200
Hexane dipped for 7 days and stored for 6 weeks at 20°C	12000	200
Above sample, 60°C heat treated for		
5 min	—	300
10 min	—	400
15 min	—	500
20 min	—	600
25 min	—	700
30 min	—	800
35 min	—	800
24 h	15000	900

To facilitate a quick diffusion induced recovery of hydrophobicity, the hexane treated samples were subjected to a constant temperature (60°C) in the oven and removed at 5 min intervals for COV measurement. Subsequently the same sample was put back in the oven for another 5 min. The oven and the SEM were in close proximity and the time taken for the COV measurement from the time the sample was removed from the oven was ~ 10 min. Table 2 shows the COV measured after every 5 min of oven heat treatment. It can be seen that the

COV recovers back to the original value in ~ 30 min of total heat treatment at 60°C.

In order to determine the threshold quantity of LMW chains needed for hydrophobicity recovery, the hexane dipped and 30 min heat treated samples that had the same COV as the virgin sample, were now sputter coated with a 10 nm thick graphite paste. These samples were examined by the XRM technique. Table 2 shows that the Si X-ray count corresponding to the new LMW chains generated which is responsible for hydrophobicity recovery is $15000 - 12000 = 3000$. This suggests that only a portion ($3000/20000 = 15\%$) of the initial LMW chains originally present on the unaged surface is needed for hydrophobicity recovery.

Similar results were obtained on other types of RTV and HTV silicone rubbers evaluated. The variation in the threshold quantity of LMW needed for hydrophobicity varied between 15 and 20% of the initial LMW chains present in the virgin material surface. These results suggest that during service, hydrophobicity recovery can occur for extended periods of time. However, further work is needed to obtain a more reliable estimate of this time.

4. CONCLUSIONS

1. Hydrophobicity recovery in silicone rubber insulators, which is predominantly due to the LMW polymer chains, can occur with only a fraction (~ 20%) of the LMW present initially in an unaged material surface.
2. Hydrophobicity recovery is shown to be affected significantly by the ambient temperature, with higher temperatures causing a more rapid recovery.
3. LMW chain regeneration and hydrophobicity recovery has been shown to occur even after the initial supply of LMW polymer chains is depleted. There are several mechanisms that contribute to LMW chain regeneration. The net result of the LMW chain regeneration is a weakening of the mechanical properties which has been demonstrated by a reduction in tensile strength.
4. The pattern of the results was consistent for the different formulations of HTV and RTV silicone rubbers evaluated.
5. The use of the XRM feature in the SEM as a visual indicator of the diffusion process has been demonstrated. This method could be employed for surface studies of insulating materials.

REFERENCES

- [1] R. G. Houlgate and D. A. Swift, "Composite Rod Insulators For ac Power Lines: Electrical Performance at a Coastal Testing Station", IEEE Trans. Power Delivery, Vol. 5, No. 4, pp. 1944-1955, 1990.

- [2] A. E. Vlastos and S. M. Gubanski, "Surface Structural Changes of Naturally Aged Silicone and EPDM Composite Insulators", *IEEE Trans. Power Delivery*, Vol. 6, No. 2, pp. 888-900, 1991.
- [3] H. M. Schneider, W. W. Guidi, J. T. Burnham, R. S. Gorur and J. F. Hall, "Accelerated Aging and Flashover Tests on 138 kV Non-ceramic Line Post Insulators", *IEEE Trans. Power Delivery*, Vol. 8, No. 1, pp. 325-336, 1993.
- [4] R. S. Gorur, E. A. Cherney, R. Hackam and T. Orbeck, "The Electrical Performance of Polymeric Insulating Materials Under Accelerated Aging in a Fog Chamber", *IEEE Trans. Power Delivery*, Vol. 3, No. 3, pp. 1157-1164, 1988.
- [5] R. S. Gorur, L. A. Johnson and H. Hervig, "Contamination Performance of Silicone Rubber Cable Terminations", *IEEE Trans. Power Delivery*, Vol. 6, No. 4, pp. 1366-1373, 1991.
- [6] H. Dietz, H. Karner, K. H. Miller, H. Patrunky, G. Schenk, P. Verma and H. J. Voss, "Latest Developments and Experience with Composite Long-rod Insulators", *CIGRE Paper No. 15-09*, 1986.
- [7] R. J. H. Clark and R. E. Hester (editors), *Spectroscopy of Surfaces*, New York, John Wiley, 1988.
- [8] R. S. Gorur, J. Chang and O. G. Amburgey, "Surface Hydrophobicity of Polymeric Materials used for Outdoor Insulation", *IEEE Trans. Power Delivery*, Vol. 5, No. 4, pp. 1923-1933, 1990.
- [9] A. De La O, R. S. Gorur and J. Chang, "Ac Clean Fog Tests on Non-ceramic Insulating Materials and a Comparison with Porcelain", *IEEE Trans. on Power Delivery*, Paper No. 94 WM 048-9 PWRD.
- [10] J. D. Andrade (editor), *Polymer Surface Dynamics*, Plenum Publishing Corporation, 1988.
- [11] *Transmission Line Reference Book, 345 kV and Above*, Electric Power Research Institute EL-2500, Chapter 10, 1985.
- [12] R. S. Gorur, S. Cooper and D. Latta, "Polymer Insulation", *Proceedings of the NORD-IS Electrical Insulation Conference*, Denmark, 1990.
- [13] R. S. Gorur, G. G. Karady, A. Jagota, M. Shah and A. Yates, "Aging of Silicone Rubber used for Outdoor Insulation", *IEEE Trans. Power Delivery*, Vol. 7, No. 2, pp. 525-538, 1992.
- [14] J. W. Chang and R. S. Gorur, "The Role of Backbone Chain Rotation in the Hydrophobicity Recovery of Polymeric Materials for Outdoor Insulation", *Proceedings of the 4th International Conference on Conduction and Breakdown in Solid Dielectrics*, Italy, pp. 270-274, 1992.
- [15] J. S. Kummins, J. A. Thorne and A. R. Huntress, "Space Grade Silicones for High Vacuum Electronic Applications", *Symposium on Electronic Materials, Part III*, Paper 29 B, 1968.

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