

Modified IEC 5000-h Multistress Aging of 28-kV Thermoplastic Elastomeric Insulators

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Abstract—The 28-kV, novel, environmental-friendly, thermoplastic elastomeric insulators were tested under slightly modified IEC 1109 5000-h (Annex C) conditions for their long-term performance. The modifications were made to more closely represent the actual service environment than the conditions used in the IEC. Various stresses applied include UV-A radiation, heat, rain, clear mist and salt fog, in addition to electrical. After 5000-h aging, there was discoloration, loss of hydrophobicity, and a loss of hydrocarbon bonds. Overall, the insulators looked intact despite the molecular and microstructural changes.

Index Terms—Accelerated aging, equivalent salt deposit density (ESDD), Fourier transform infrared spectroscopy (FTIR), hydrophobicity, multistress, thermoplastic elastomeric insulators, thermoplastic elastomeric (TPE), scanning electron microscopy (SEM).

I. INTRODUCTION

THE INDUSTRY adapted from ceramic to polymeric (non-ceramic) insulators when the opportunity presented itself in the form of lightweight (only about 10% of that of a porcelain insulator of comparable voltage), aesthetic, shatterproof, and superior contamination performance materials [1], [2]. Polymeric insulators and coatings have improved the reliability of transmission and distribution systems by reducing contamination flashovers and pole fires. Polymers are characterized by their very high molecular weight, which gives them their excellent hydrophobicity and low surface energy. Their macroscopic properties are due to their microscopic structure.

These polymers can be classified as either thermoplastic or thermoset [3]. In thermoplastics, the polymer chains are only weakly bonded (van der Waals forces). The chains are free to slide past one another when there is enough thermal energy available, making the plastic formable and recyclable. On the contrary, in thermosets, adjacent polymer chains are strongly cross-linked. When heated, these crosslinks prevent the polymer chains from slipping past one another. As such,

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thermosets cannot be reflowed once they are cured. Instead, they can chemically degrade if reheated.

A thermoplastic-elastomeric (TPE) polymer [3], [4] is a diverse family of rubber-like materials which has desirable features, such as good tracking resistance, good hydrophobicity, UV resistance, a wide temperature performance range, and good electrical properties. Typically, TPEs consist of two polymeric phases, a hard thermoplastic phase, and a soft elastomeric phase. The resulting properties are derived from each phase as well as from the interaction between the two phases (the sum is more than the individual components). The TPE used in this research consisted of polypropylene (PP) and ethylene-propylene diene monomer (EPDM). The PP forms the hard thermoplastic phase and EPDM rubber constitutes the soft elastomeric phase. The two phase alloy results from the use of proprietary additives and/or processing techniques suitable for the combination of a thermoplastic and an elastomer. The two phases of a TPE may be present as alternating hard and soft segments along a common polymer backbone.

TPE is a third generation polymeric material that meets most of the stringent requirements of high-voltage (HV) outdoor insulation, at least for the distribution class and low contamination environments. A very distinct feature of TPE is that it is reusable and recyclable. Additionally, being thermoplastic, it has the benefits of better speed, efficiency, and economy of processing over the well-known silicone rubber (SiR) and EPDM polymers, which are thermosets.

However, being mostly organic in nature, all polymers are susceptible to weathering [5]. Polymeric insulators experience aging and degradation in the field due to both electrical and environmental stresses, such as UV radiation, temperature, rain, fog, and air-borne contamination [1], [2], [5], [6]. In order to understand the kinetics and the mechanism of the aging and degradation of the TPE insulators under a wide spectrum of service conditions, it is necessary to design a meaningful accelerated lab aging test which can simulate the field conditions. While serving their intended function, conventional aging tests, such as the IEC 61109 1000-h salt fog test, the tracking wheel test, the inclined plane test, have the major drawback that they do not represent the synergy of various stresses experienced in any actual service environment [7], [8]. Using the above tests, the compound effects operating on the insulation system in actual service are not reproduced. Additionally, the stresses associated with individual tests are often unrealistic. The modes of failure caused by excessive stresses are not encountered in actual service.

In multistress tests, various environmental stresses are applied in repetitive cycles just as they occur in real-life conditions [7]–[10]. The stresses are created by simultaneous applications

TABLE I
ACCELERATED MULTISTRESS CONDITIONS USED IN THIS STUDY

Aging Period (9h)	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24
Humidification-clear fog: 1-2 μ S/cm			x					x				
Heating: 50°C	x	x				x	x					x
Demineralized Rain: 50-70 μ S/cm								x				
Salt Fog: 16000 μ S/cm				x	x				x	x		
UV Radiation: 0.8mW/cm ²	x	x	x	x	x	x	x	x	x	x	x	x
Voltage: (RMS + 10%)	x	x	x	x	x	x	x	x	x	x	x	x

of combinations of voltage, UV radiation, moisture and contamination. Moisture is introduced in the form of humidity, fog or rain. Contamination is applied by various levels of salinity introduced with moisture. The aging cycles essentially identify the duration and sequence of various stresses. This paper reports the 5000-h aging of 28-kV TPE insulators under IEC 61109 5000-h multistress conditions [11] with slight modifications. The effects of aging and degradation on the physical characteristics and on the surface chemistry and surface morphology were investigated.

II. 5000-H AGING CYCLE

IEC 61109 Annex C provides the specifications for the 5000-h accelerated multistress conditions [11]. These conditions do not represent any particular service environment. Some modifications were made to more closely represent the actual service environment. For example, the IEC 1109 5000-h test specifies the use of peak ac voltage, instead of the conventional root mean square (rms) value used in practice. Hence in this research, root mean square (rms) value +10% was used to accelerate the aging to some extent in line with IEC specifications. The IEC 61109 5000-h test specifies the use of xenon arc lamp at very high intensity to simulate the solar spectra. Since only low wavelength, high-energy UV radiations can break the molecular bonds of polymers; UV-A radiation was used (similar to EPRI Florida study [7]). The IEC 61109 5000-h test specifies a salinity of 7 kg/m³ (10000 μ S/cm). However, a higher salinity of 10 kg/m³ (16000 μ S/cm), the same as that of the IEC 61109 1000-h salt fog test, was used to enhance the aging to some extent. The various stresses applied, their levels, sequence, and duration are depicted in Table I.

III. INSULATORS TESTED

Two 28-kV insulators—one vertical and one horizontal—as specified in IEC 61109, were used in this research. Fig. 1 shows the experimental setup and Table II gives their dimensions.

IV. EXPERIMENTAL

The details of the multistress chamber used for the 5000-h test can be found in a recent publication [12]. A 0-100 kV, 40-kVA, HV transformer was used to energize the insulators at 16.6 + 10% (18) kV. UVA-360 lamps were used to simulate UVA radiation. The industry standard LabVIEW was used for data acquisition every minute and for ON/OFF the various stresses at various times.



Fig. 1. The 28-kV vertical and horizontal distribution/dead end insulators.

TABLE II
DETAILS OF INSULATORS TESTED

ITEM	DIMENSION (mm)
Leakage Distance	645
Diameter of Shed	97.4
Diameter of Sheath	25.0
Dry Arc Distance	285

V. RESULTS AND DISCUSSION

To monitor the condition and identify the threshold of aging/degradation, physical characteristics, such as visual-color change, chalking, cracking, erosion, and equivalent salt deposit density (ESDD), nonsoluble deposit density (NSDD), and Swedish Transmission Research (STRI) hydrophobicity classification [13] for surface wetting characteristics were observed every 200- and 500-h intervals (i.e., at 200 h, 500 h, 700 h, etc.). The surfaces changes are characterized by attenuated total reflectance Fourier transform infrared spectroscopy (FTIR-ATR) [14], [15], [6], and scanning electron microscopy (SEM) [16], [6].

A. Physical Observations

In general, there was no major physical degradation of the insulators. The insulators did not flashover, there was no cracking, chalking, and erosion. The significant changes observed were as follows:

- slight discoloration (aged insulators became paler than the virgin (unaged) insulator);
- there were salt residues all over the insulators;
- HV end fitting of the horizontal insulator hardware had severe corrosion;

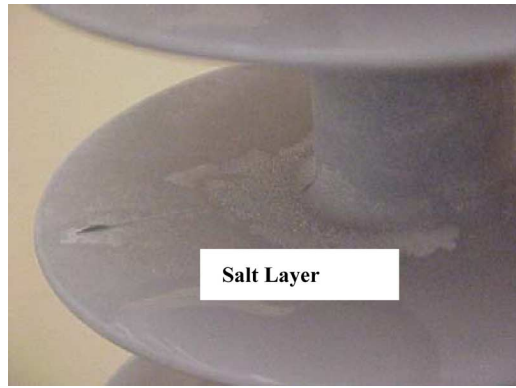


Fig. 2. Vertical insulator surface illustrating salt layer deposition after 5000-h multistress aging.

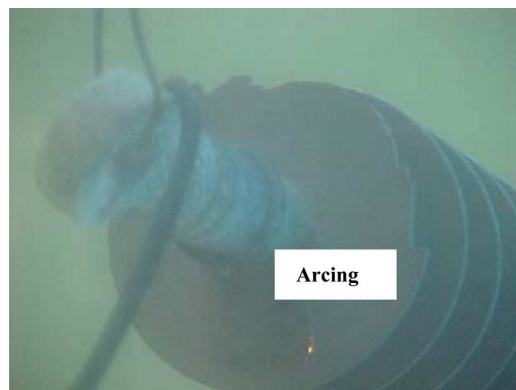


Fig. 3. Arcing observed on the insulator surface after 4000-h multistress aging.

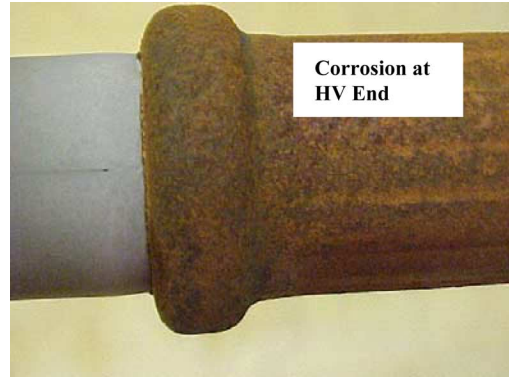


Fig. 4. Horizontal insulator end fitting (HV side) with extensive corrosion after 5000-h multistress aging.

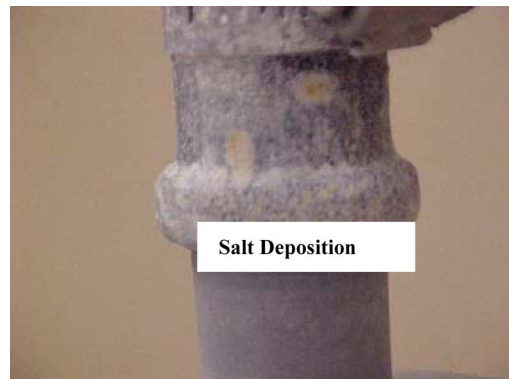


Fig. 5. Vertical insulator end fitting (LV side) with salt residues after 5000-h multistress aging.

- insulators became wettable;
- ESDD measured was light;
- there was light arcing after 4000-h aging;
- very light erosion after 4000 h (using SEM).

Fig. 2 shows a typical shed of the insulator with salt residues. Fig. 3 shows the arcing observed in the insulators after 4000 + h. The arcing occurred only occasionally. Fig. 4 shows the heavily corroded end fitting of the horizontal insulator. Fig. 5 shows the end fitting of the vertical insulator. The contrast between the horizontal and the vertical end fitting are interesting (i.e., there was no corrosion in the vertical insulator). Table III shows the ESDD along with the STRI HC data. It can be seen that the ESDD is very light [17]. [The NSDD values were also very small (data not shown)]. The insulator surfaces became wettable (HC class 6) after 5000 h under multistress conditions. Actually, S, similar to the insulators, began losing their hydrophobicity after about 1500 h, but survived without arcing until 4000 h and then became very wettable after the 4000 + h.

B. Electrical Data

The leakage current (peak values) and the number of pulses of various magnitudes were collected every minute to quantify the aging and degradation of the polymer. Additionally, the surface charge and watts loss [8] were also calculated (data not shown). Figs. 6 and 7 show the peak values of leakage current variation of the vertical and the horizontal insulators for the 3000 h and 5000 h, respectively. The leakage current magnitudes increased

TABLE III
PHYSICAL OBSERVATION RESULTS

Aging Period	ESDD mg/cm ²		Hydrophobicity Classification (HC) class 1 (hydrophobic) to 7 (hydrophilic)	
	Vertical	Horizontal	Vertical	Horizontal
Virgin (0h)	0.00	0.00	1	1
1000h	0.08	0.02	1-2	1-2
2000h	0.005	0.01	5	5
3000h	0.049	0.015	5-6	5-6
4000h	0.017	0.008	5-6	5-6
5000h	0.065	0.008	6	6

up to 50 mA for both insulators and then decreased. The trend of the leakage currents was the same for both insulators and correlates well with that found in the field aging [18].

C. Material Diagnostic Techniques

Polymers surfaces can respond to changes in their environment or to surface modification processes by undergoing rotational and diffusional segmental and chain motions [19]. The microstructural changes can be studied using FTIR and SEM techniques.

FTIR: FTIR can detect changes due to bond shifting, reduction in molecules by means of reduction in peak heights, bond breaking and chain scission [5]. Normally change (reduction (in most cases) or increase) in the peak height is used as a metric to indicate loss (or gain) of molecules. Fig. 8 shows the FTIR spectra obtained for 4200-h-aged samples versus virgin. Both

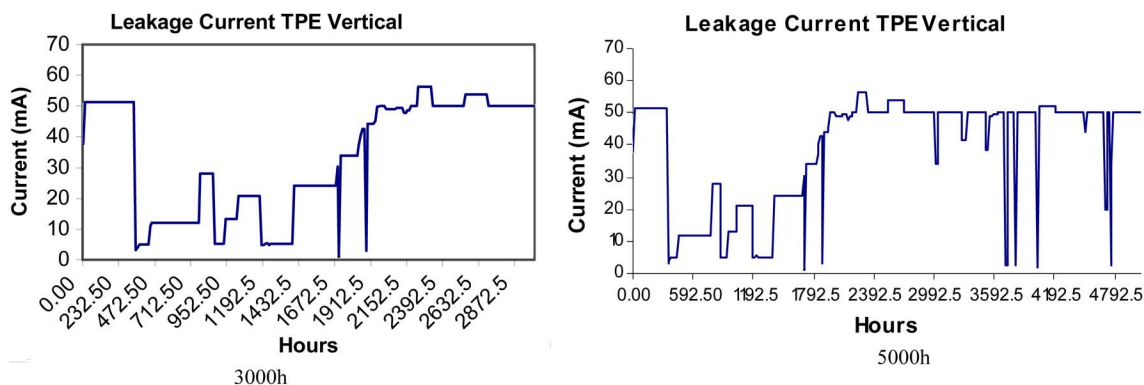


Fig. 6. Leakage current variation due to 3000- and 5000-h aging vertical insulator.

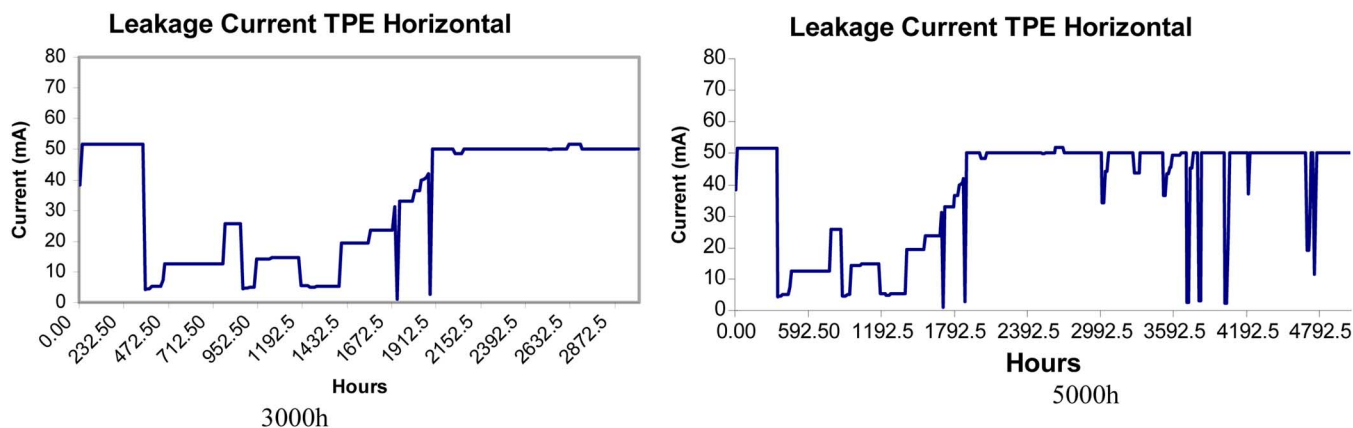


Fig. 7. Leakage current variation due to 3000- and 5000-h aging horizontal insulator.

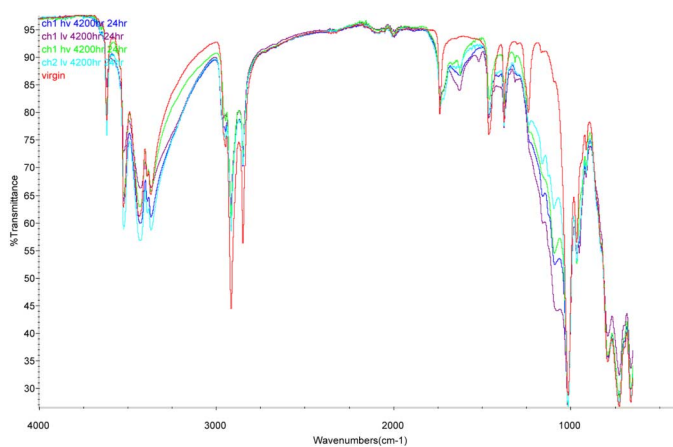


Fig. 8. FTIR spectra of virgin versus aged (4200 h) samples showing the change in peak heights. With aging $C = O$ at wavenumber 1740 cm^{-1} has shifted.

HV and LV samples of vertical and horizontal insulators are depicted against virgin.

There is bond shifting with aging; $C = O$ at wavenumber 1740 cm^{-1} in the virgin is shifted to approximately 1600 cm^{-1} . This is indicated by the 87% reduction in the peak height compared to virgin (Table IV). There are also reductions in peak heights due to aging in several other bonds. It can be seen that

hydrocarbon (CH) groups in their various forms have undergone major reduction in their peak heights indicating the loss of molecules. Maximum changes were observed in 4500 h (data not shown) compared to other hours. The reduction at 4000 h and the recovery in the 5000 h (Table IV) indicates the dynamic nature of polymer surfaces—that they are mobile and unpredictable [19]. The atoms that constitute polymers can change their spatial position with time; electrical and environmental stresses can aid them in this process.

From the peak heights it can be observed that there is a continuous reduction of molecular bonds at wavenumbers 2918 and 2850 cm^{-1} corresponding to CH_2 asymmetric stretch and CH_2 symmetric stretch. There is a loss of 47% and 67% of molecules for these chemical functional groups at the end of the 5000-h aging compared to 31 and 40% at the end of 1000 h. The CH_3 umbrella bend at 1375 cm^{-1} has only a loss of 31% during the 5000-h aging while the CH_3 asymmetric bend at 1464 cm^{-1} has a loss of 64%. The reduction in CH_3 could cause the loss of hydrophobicity. The OH stretch bonds at 3618 and 3523.5 cm^{-1} and the alumina filler at 1014 cm^{-1} remain almost intact indicating the withstanding capability of the material despite loss of hydrocarbons.

Table V illustrates similar data for the horizontal insulator. In this case also, reduction in peak heights to an extent of about 80% was observed for $C = O$. The CH_2 symmetric and asymmetric stretch losses are 30% and 48%, respectively. They show slightly reduced losses compared to vertical ones.

TABLE IV
FTIR PEAK HEIGHTS FOR VIRGIN, 1000-, 4000-, AND 5000-H-AGED SAMPLES—VERTICAL INSULATOR, HV SAMPLES

Group (cm ⁻¹)	Virgin	1000h	4000h	5000h
O-H stretch (3618)	16.4 (100%)	14.75 (90%)	12.75 (78%)	14.56 (89%)
O-H stretch (3523.5)	22.09 (100%)	18.93 (86%)	17.70 (80%)	20.60 (93%)
CH ₂ asymmetric stretch (2918)	30.91 (100%)	21.41 (69%)	16.29 (53%)	16.35 (53%)
CH ₂ symmetric stretch (2850)	22.41 (100%)	13.43 (60%)	7.47 (33%)	7.24 (32%)
C=O (1740)	13.93 (100%)	10.83 (78%)	7.71 (55%)	1.78 (13%)
CH ₃ asymmetric bend (1464)	16.76 (100%)	12.28 (73%)	8.32 (50%)	6.10 (36%)
CH ₃ umbrella bend (1375)	11.96 (100%)	10.06 (84%)	8.54 (71%)	8.24 (69%)
C-O (1240)	12.62 (100%)	6.25 (50%)	1.85 (15%)	3.39 (27%)
Alumina Filler (1014)	42.01 (100%)	37.94 (90%)	35.91 (85%)	38.93 (93%)
CH ₂ Rocking vibration (727)	12.73 (100%)	13.52 (106%)	11.75 (92%)	9.39 (74%)

TABLE V
FTIR PEAK HEIGHTS FOR VIRGIN, 1000, 4000, AND 5000-H-AGED SAMPLES—HORIZONTAL INSULATOR HV SAMPLES

Group (cm ⁻¹)	Virgin	1000h	4000h	5000h
O-H stretch (3618)	16.4 (100%)	14.63 (89%)	8.71 (53%)	17.54 (107%)
O-H stretch (3523.5)	22.09 (100%)	19.87 (90%)	12.13 (55%)	23.72 (107%)
CH ₂ asymmetric stretch (2918)	30.91 (100%)	23.63 (76%)	14.28 (46%)	21.76 (70%)
CH ₂ symmetric stretch (2850)	22.41 (100%)	13.62 (61%)	8.00 (36%)	11.62 (52%)
C=O (1740)	13.93 (100%)	13.28 (95%)	3.59 (26%)	2.88 (21%)
CH ₃ asymmetric bend (1464)	16.76 (100%)	12.54 (75%)	6.76 (40%)	12.01 (72%)
CH ₃ umbrella bend (1375)	11.96 (100%)	10.71 (90%)	6.89 (58%)	12.40 (104%)
C-O (1240)	12.62 (100%)	6.88 (54%)	0.82 (65%)	2.35 (19%)
Alumina Filler (1014)	42.01 (100%)	38.01 (90%)	35.77 (85%)	41.42 (98%)
CH ₂ Rocking vibration (727)	12.73 (100%)	13.26 (104%)	12.82 (101%)	12.33 (97%)

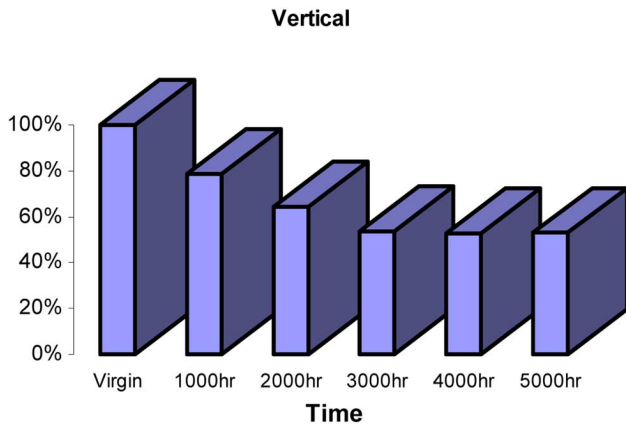


Fig. 9. Peak height variation of chemical molecular group CH₂ (2918 cm⁻¹) over the 5000-h aging—vertical insulator.

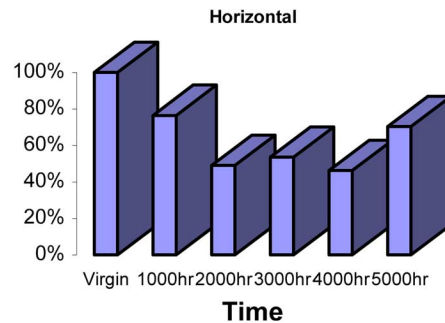


Fig. 10. Peak height variation of chemical molecular group CH₂ (2918 cm⁻¹) over the 5000-h aging—horizontal insulator.

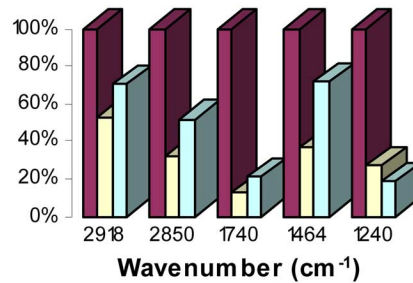


Fig. 11. Peak height variation of several chemical molecular groups after 5000-h aging. From left: virgin, vertical, and horizontal surfaces.

Figs. 9–11 illustrate the above data graphically. For the chemical group CH₂ asymmetric stretch at 2918 cm⁻¹, Figs. 9 and 10 show the changes observed over the 5000-h aging period for the vertical and horizontal insulators, respectively. Fig. 11 shows a comparison of the virgin, vertical, and horizontal insulator samples for five major functional groups due to the 5000-h aging. Chemical groups CH₃ asymmetric bend at 1460 cm⁻¹ and C–O stretch at 1240 cm⁻¹ have a loss of 64% and 73% for the vertical insulator. They are 28% and 82%, respectively, for the horizontal insulator.

Overall, the horizontal insulator performed slightly better than the vertical one. This might be due to better washing off of the horizontal insulator due to its orientation compared to the

vertical insulator. However, these changes have not shown any major physical degradation at the completion of 5000 h.

SEM: SEM is useful to monitor surface microstructural changes (both surface morphology and topographical) as a

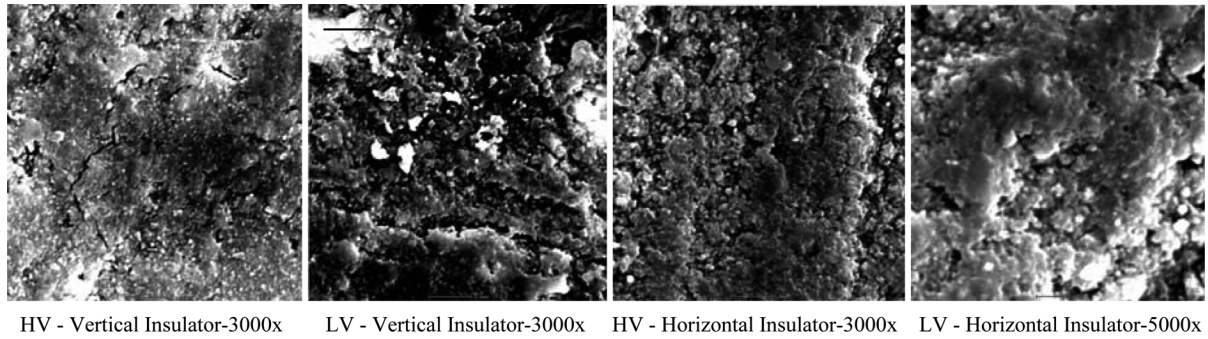


Fig. 12. SEM micrographs of 4500-h-aged TPE samples showing the growth of shallow cracks from the degraded rubber interphase.

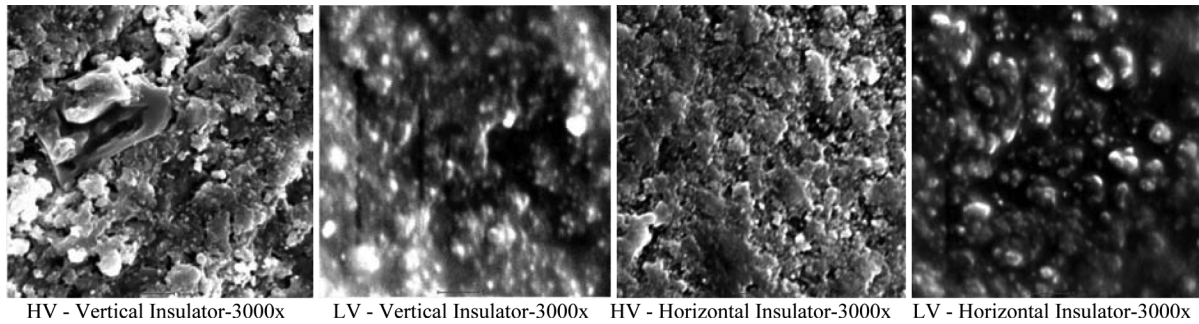


Fig. 13. SEM micrographs of 5000-h-aged TPE samples showing the growth of shallow cracks from the degraded rubber interphase. (Bar = 5 μm for 3000x).

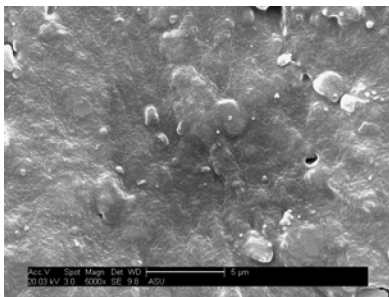


Fig. 14. SEM micrograph of the virgin surface. (5000x, bar = 5 μm .)

function of aging [6], [16]. The surface microstructural changes due to 5000-h aging were also examined using SEM. Figs. 12 and 13 show the scanning electron micrographs of the HV and LV vertical and horizontal insulator modified surfaces. They depict the growth of shallow cracks from the degraded rubber interphase after the 4500-h and the 5000-h aging, at a magnification of 3000x (bar = 5 μm) except the horizontal LV surface whose magnification is 5000x (bar = 2 μm). These micrographs also indicate the changes in the surface morphology, such as the disintegration of the filler and the basic polymer matrix particles. The surfaces of the aged samples showed neither pores nor cracks. However, the virgin surface (Fig. 14 at a higher magnification of 5000x) is more homogeneous and smooth compared to the aged samples.

The aged surfaces exhibit slightly rougher surfaces and phase differences due to changes in the filler and rubber surfaces because of aging. The vertical HV-aged surface showed shallow cracks after 4500-h aging. The 4500-h vertical LV sample showed slightly deeper cracks compared to vertical

HV. The cracks observed were across the entire surface of the sample. The distribution of the particles is not uniform and clustering (lumps) is a common feature in the aged samples. It can be the beginning of the yielding of the surfaces. The 5000-h micrographs illustrate a similar microstructural disintegration of the surfaces. The particle sizes are bigger than they are at 4500 h. Similar changes were also observed in the case of the horizontal insulator, except in the case of 5000-h LV, where the particles exhibit somewhat partial crystalline nature. This could be due to PP, which is partially crystalline. The 1000- to 3000-h samples had fewer changes and no shallow cracks (data not shown). Most of the deterioration seemed to begin after 4000 h, just as in the FTIR.

However, there is no major degradation observed.

VI. CONCLUSION

From our 5000-h continuous multistress lab aging, the following conclusions can be drawn.

- 1) The 28-kV TPE insulators successfully withstood the 5000-h multistress aging under slightly modified IEC 61109 conditions. There was no major degradation, such as flashover, heavy arcing, erosion, cracking, or tracking.
- 2) Physically, there was a loss of hydrophobicity, discoloration, light arcing, and very shallow cracking.
- 3) FTIR spectra and SEM micrographs illustrated the loss of molecules and surface roughness due to the aging.
- 4) There was severe corrosion of the HV end fitting of the horizontal insulator.
- 5) Overall, the insulators seemed to be intact.

Considering the degradations observed due to 1000-h and 400-h aging salt fog tests [4], [20] the multistress tests serve to test the

insulators long term under realistic conditions that more meaningfully and more closely represent the actual service environment.

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