Effect of Semiconducting Screen on the Space Charge Dynamic in XLPE and Polyolefin Insulation under dc and 50 Hz ac Electric Stresses Conditions

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ABSTRACT

In the past two decades, significant advances in space charge measurements in polymers have resulted in a better understanding of charge dynamics and their effect on material selection and processing. However, little attention has been given to the effect of semiconducting screens on space charge formation in the bulk insulation. This paper reports on space charge measurements on ~1.5 mm thick XLPE and polyolefinic plaques with different treatments and semicon electrodes, using the modified laser induced pressure propagation (LIPP) system. Samples were subjected to dc or 50 Hz ac electric stresses in the region of 25 kV/mm at ambient temperature. Emphasis has been placed on comparing the space charge characteristics of the two insulation systems with different semicon electrodes using an established method termed "X-plots" for analyzing data. The effects of sample treatment (i.e. degassing) on the space charge dynamics are also presented.

Index Terms — **Semiconducting screen, space charge dynamics, XLPE, Polyolefin, insulation, cables.**

1 INTRODUCTION

SOLID extruded polymeric materials such as crosslinked polyethylene (XLPE) and uncrosslinked polyolefins are used widely for underground HV power transmission cables. The advantages of such materials are their excellent electrical properties combined with good physical properties. However, under certain HV operating conditions, trapped or low mobility electrically charged species within the bulk can give rise to space charge, resulting in localized electric stress enhancement which may lead to premature failure of the cable well below the anticipated and designed values.

In the past two decades, numerous studies have been carried out to develop further a better understanding of the build up of trapped space charge within solid dielectric materials [1–9] which has resulted in a better understanding of charge dynamics and their effect on material selection and processing. However, little attention has been given to the effect of semiconducting screens on space charge formation in the bulk insulation [10–11].

This paper reports on space charge measurements on 1.5 mm thick XLPE and polyolefinic plaques with different treatments and semicon electrodes using the modified laser induced pressure propagation (LIPP) system [12–13]. Samples were subjected to dc and 50 Hz ac electric stresses in the region of 25 kV/mm at room temperature. Emphasis has been placed on comparing the space charge characteristics of the two insulation systems with the different semicon electrodes by using "X-plots" [12–13]. The effects of sample treatment (i.e. degassing) on the space charge dynamics are also presented.

2 EXPERIMENTAL TECHNIQUES, PRINCIPLES OF THE AC LIPP SYSTEM

The method used for the space charge measurement in this paper was the laser induced pressure propagation (LIPP) technique (Figure 1); its principle has been de-

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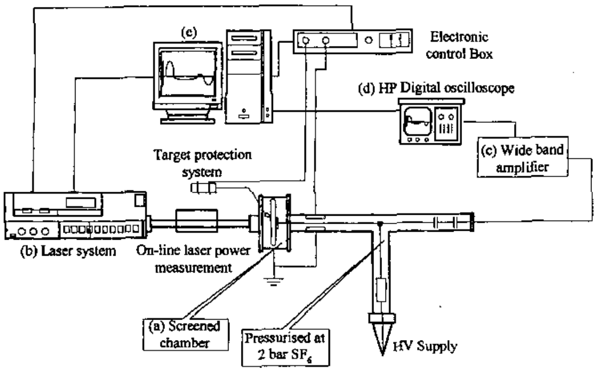

Figure 1. LIPP experimental arrangement.

scribed in details [10, 12–13]. The plaque material with semicon electrodes pressed into the front and rear of the sample was held in a screened chamber with the voltage applied between the front and the rear electrodes of the sample. The ablation of a semicon target by a short duration laser beam (< 5 ns) produces an acoustic wave or pressure pulse which propagates through the electrode and across the sample. This pressure pulse perturbs the space charge in the sample and thereby induces a change in charge on the electrodes and hence a current in the external circuit. Measurement of this time dependent current enables a profile to be obtained, which is related to the amplitude of the space charge coincident with the propagating acoustic pulse. Through the evolution of the current, information on the space charge density distribution within the dielectric sample can be calculated from [14]

$$\rho(z,t) = f(I_{space}, I_{cal}) = \frac{I_{space}(z,t)}{I_{cal}(0,t)} \cdot \frac{P_0}{P_z} \cdot \frac{\epsilon_0 \epsilon_r E_{cal}}{u_{sa}\tau} \quad (1)$$

where $\rho(z,t)$ is the charge density at location z,
$I_{space}(z,t)$ is the current recorded at location z,
$I_{cal}(0,t)$ is calibrated current at the target interface,
p_0 is the amplitude of the pressure wave at the target interface,
p_z is the amplitude of the pressure wave at location z,
ϵ_0 is the permittivity of free space,
ϵ_r is the relative permittivity,
E_{cal} is the electric stress for calibration,
u_{sa} is the velocity of acoustic wave in the sample,
τ is the width of the pressure wave at location z.

For ac space charge measurement studies, considerable care must be exercised to ensure a direct correlation between the "instantaneously" applied electric stress and the measurement taken. This was achieved with "point on wave" control of the applied voltage triggering the laser. Provided the laser was triggered at a specific point on the ac waveform, the applied stress can be considered constant during the period of a measurement. It is possible for an LIPP system to give a space charge measurement profile at a number of different points on the ac voltage waveform; details are given in [12–13].

Table 1. Sample details (T: 1 is as-received and 2 is degassed).

Sample for dc Test	Sample for ac Test	Bulk	Semicon	T	Bulk (mm)	kV/mm
A	F	XLPE	XLPE	1	1.30	23.10
B	G	XLPE	XLPE	2	1.40	21.43
C	H	Polyolefin	XLPE	1	1.29	23.26
D	I	Polyolefin	XLPE	2	1.24	24.19
E	J	Polyolefin	Polyolefin	1	1.56	19.20

3 SAMPLE DETAILS

The samples used to investigate the time dependence of space charge accumulation were as-received and degassed, XLPE and polyolefin plaques with a bulk thickness of between 1.3 mm to 1.6 mm. Both the front and the rear electrodes with thickness ~0.5 mm were hot pressed into the plaque sample. The semicon electrodes were made of the same grade of XLPE or polyolefin material, but were loaded with carbon black to increase its conductivity. The degassing was carried out by heating the sample to 60°C for 48 h to remove the volatile by-products within the bulk of insulation and semicon electrodes. The resultant thickness of the bulk insulation was < 1.5 mm. The samples details are shown in Table 1.

4 dc AND ac EXPERIMENTAL PROTOCOLS

4.1 dc

4.1.1 RAMP RATE TEST (CALIBRATION)

In order to correlate the output current to the charge density and determine the threshold voltage, at which the space charge starts to appear inside the bulk material, ramp rate experiments were performed on the plaque samples with time intervals of 5 s between two successive steps. The applied voltage started from 0 up to 30 kV with voltage steps of 5 kV.

4.1.2 dc AGEING TEST

The plaque samples after the ramp rate experiment were immediately stressed at a dc voltage (30 kV) for a period of 24 h at ambient temperature. The space charge distributions were measured at various times (with and without the voltage applied) within the period of dc aging.

4.2 ac

According to Fanjeau et al [15], the effect of fast charge (charge with high mobility) is expected to be more significant than the slow charge (charge with low mobility) under 50 Hz ac ageing conditions. Consequently, all the measurements were taken with the ac voltage applied

Table 2. ac experimental protocol.

Data	Time (hrs)	Shot no.
1 cycle of data points	0	1–9
1 cycle of data points	4	10–18
1 cycle of data points	8	19–27
1 cycle of data points	24	28–36

across the sample. The as-received and degassed samples were aged at ac stresses at 30 kV_{peak} (in the region of < 25 kV/mm_{peak}) for a period of 24 h at ambient temperature. The charge distribution was measured at various times using the protocols shown in Table 2. Care must be taken to ensure a direct correlation between the "instantaneously" applied electric stress and the measurement taken. This is best achieved with "point on wave" control of the applied voltage triggering the laser [13]. Provided the laser is triggered at a specific point on the ac waveform, the applied stress can be considered constant during the period of a measurement. It is possible to for an ac LIPP system to give a space charge measurement at a number of different points on the voltage waveform. In the present work, nine points were selected in the ac cycle, starting at 0° with a phase shift of 45° for two consecutive points.

Although there is a difference of ~5kV/mm in the applied stress among the samples tested under both dc and ac conditions, the difference among the samples containing XLPE is less than 3 kV/mm, which should not cause significant variation in charge behaviour in the stress range used in this research.

5 DATA PROCESSING AND CORRECTION FACTORS

It is well known that without the presence of trapped charge in the bulk insulation, the magnitudes of the entrance and exit peaks from the current signal (i.e. interfacial stresses) are linearly dependent on the instantaneously applied voltage [10]. With space charge present, the magnitudes of the current peaks deviate from this linear relationship depending on the nature of the charge formation inside the bulk [10–11,14]. Therefore, to analyze the large amounts of ac space charge data without resorting to a complex mathematical treatise, a simple method, termed "X-plots" is used. Details of these data presentation technique are given elsewhere [12–13, 16].

On the other hand, there are several factors, which may cause variations in the magnitude of the current between successive measurements in the LIPP technique. These include shot to shot laser power variation and semicon target ablation [13, 17]. Therefore, in order to ensure that signal magnitude variations and deviations recorded in the current peak heights (i.e. interfacial stress) were caused purely by space charge effects, two correction factors for the laser power variation and target efficiency were used which modify the ac raw current data before any data processing was performed. The variations in laser power may cause changes in the LIPP signal magnitude. This problem was overcome by the introduction of an on-line laser power monitor system [13].

However, in the case of dc space charge measurement, the semicon target on the test sample would need to withstand < 20 shots during an entire experiment (including ageing) and the effect of target ablation to the output signal is insignificant [13, 17]. Therefore, for the dc results presented in this paper, only the variation of laser power is considered.

6 dc RESULTS AND DISCUSSION

6.1 dc RAMP TEST

The results of the ramp rate measurements on sample A to sample E are summarized in Figure 2a to Figure 2e. It illustrates that the magnitude of the entrance peak vs the applied stress for all the samples with XLPE semicons, deviates, positively, from the "extrapolated straight line". This line is obtained from the region over which the entrance peak height of the current signal is linearly dependent on the applied stress. This implies that above the threshold stress, the interfacial stress at the cathode is less than the applied stress, indicating that homocharge has been formed close to the XLPE/semicon interface (cathode).

In order to establish the effect of the sample degassing on the threshold stress, comparisons have been made between the ramp rate results of the as-received and degassed samples (samples A to B and samples C to D). The results show that the degassing process reduced the threshold stress in the samples with XLPE semicons by approximately 30%. This suggests that after the degassing process, which removed the crosslinking by-products, the effect of ionization process in the bulk was minimal and the space charge was mainly due to charge injection from the semicon electrodes. However, in the case of polyolefin samples with XLPE semicons, the threshold stress between the as-received and degassed samples showed only a 4% difference. Since the polyolefin samples have no crosslinking by-products present within the bulk insulation, therefore degassing should not have any significant effect on the threshold stress. The homocharge present is mainly due to the charge injection from the semicon electrodes.

To examine the influence of the semicon material on the space charge, a ramp rate measurement on polyolefin samples with polyolefin semicons (sample E) has been performed (Figure 2e). It illustrates that the entrance peak vs the applied dc stress followed the extrapolated straight line up to a significantly high stress (~19.2 kV/mm), indicating that no homocharge has been formed close to the cathode. By comparing the results between samples C and E, it is reasonable to assume that the source of the negative charge close to the cathode during the ramp rate

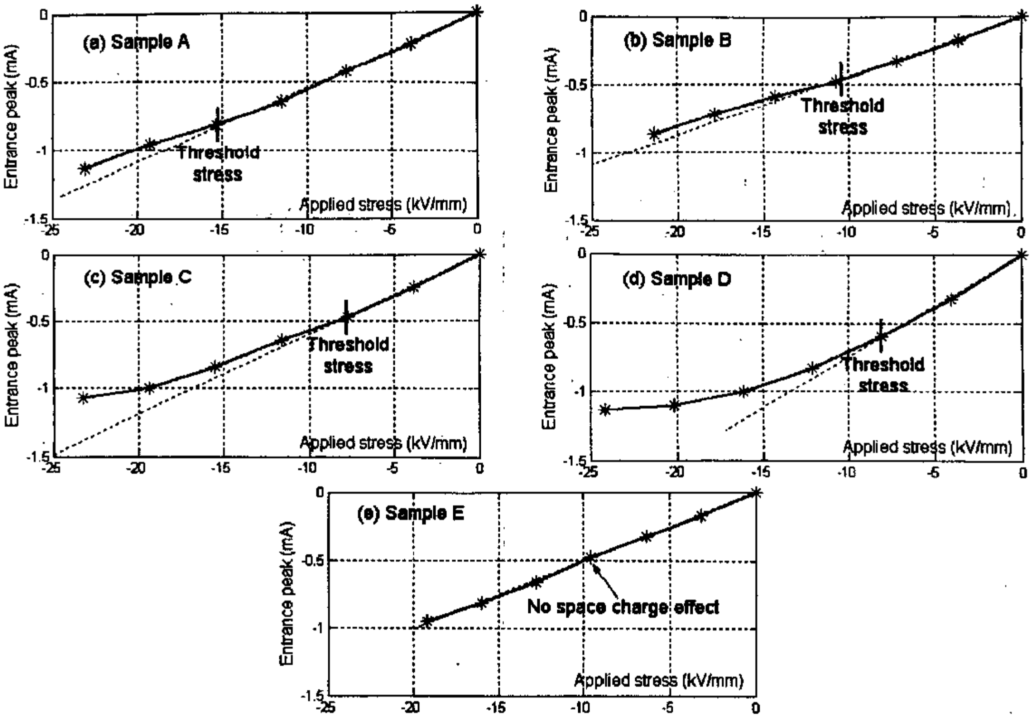

Figure 2. The entrance peak magnitudes of short circuit current vs applied stress for the samples A to E.

measurement in the samples with XLPE semicons was possible due to the homocharge injection from the XLPE electrode (cathode) rather than the ionization process of the by-products inside the bulk, which is strongly dependent on the semicon material.

It is believed that there are two sources which contribute to the formation of space charge. They are charge injection from the electrode and ionization in the bulk. The measured charge in the material is the resultant of two competing processes and the threshold stress will be affected by the rate at which these two processes takes place. It looks as though initially the charge injection dominates the formation of space charge and ionization takes over later (see next section). As a result the threshold stress is determined by charge injection, leading to a decrease in magnitude of the entrance peak. During aging as ionization takes over gradually the magnitude of the entrance peak increases. It is obvious that the amount of charge originated from ionization increases with the amount of by-products present in the material, hence the decrease in threshold stress after degassing.

6.2 dc AGING TEST

6.2.1 Sample A

Figure 3 shows the space charge evolution of sample A over 24 h of dc aging. During the first hour of aging, there was clear evidence of heterocharge accumulation close to both electrodes. This phenomenon is believed to be associated with the electric field assisted ionization process of

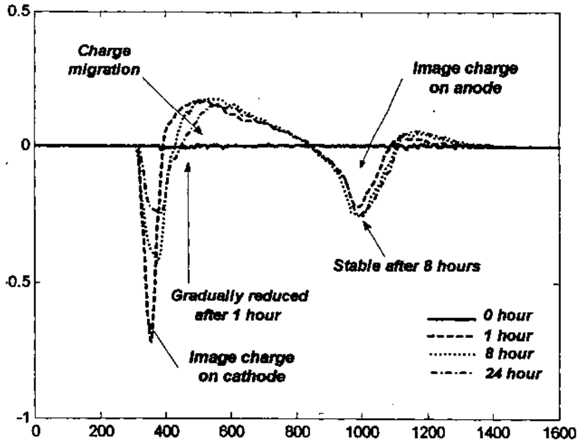

Figure 3. Evolution of the space charge formation of the sample A during 24 h aging process (voltage off).

the crosslinking by-products and impurities inside the bulk. Beyond 8 hours, the positive charge near the cathode reduced gradually and may be due to the negative charge injected from the cathode, which then recombine with the positive charge created from the ionization process. However, throughout the 24 h aging period, the variation of the negative charge accumulated close to the anode was insignificant whilst there was a marked change at the cathode side after the first hour.

The effect of space charge evolution on the interfacial stresses of sample A by using the data processing tech-

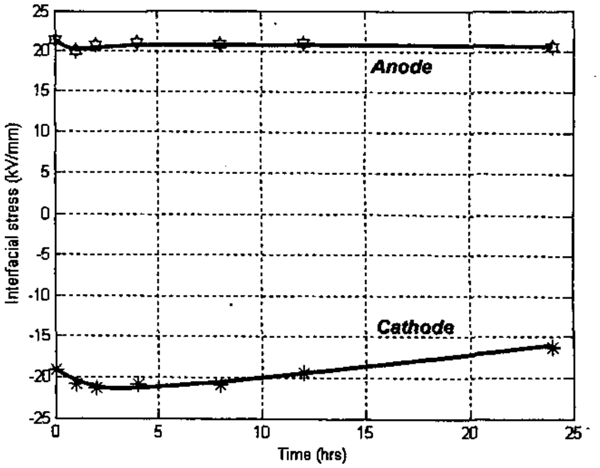

Figure 4. The interfacial stress of the sample A during 24 h aging process (voltage on).

nique described in [13–14] is shown in Figure 4. It can be seen that over the first 8 h aging the stress at the cathode was increased by 9% compared to the value at 0 hour (−19.2 kV/mm up to −21.0 kV/mm); the increased stress at the interface coincident with the heterocharge accumulation in the vicinity of the cathode is shown in Figure 3. However, from 8 to 24 h, the interfacial stress at the cathode decreased from −21.0 to −16.2 kV/mm (−15% compared to that at 0 hour). One possible cause of this is that the stress enhancement caused by the heterocharge (positive charge) close to the cathode initiated the negative charge injection. This recombined with some of the ionized dissociable crosslinking by-products (positive charge) close to the electrode and hence lowered the electric stress at the electrode/XLPE interface. This is supported by the reduction of the positive charge close to cathode from 8 to 24 h shown in Figure 3.

In the vicinity of the anode, there was an obvious heterocharge accumulation (Figure 3) after the first hour of dc aging. However, the interfacial stress reduced by approx 5% compared to the stress at 0 h (Figure 4). This phenomenon may be attributed to the relatively large amount of positive charge rather than negative charge accumulated inside the bulk insulation after the first hour of ageing. In addition, as the position of the positive charge is far away from the anode, the effect of the space charge on the anode (5% stress reduction) should be smaller than that at the cathode (up to 12% stress enhancement). As the amount of positive charge inside the bulk insulation decreased with the aging period, the stress reduction at the anode was reduced from 5% to 2% after 24 hours.

6.2.2 SAMPLE B

Figure 5 shows the space charge evolution of sample B versus aging time up to 24 h. Referring to Figure 2, there has already been clear evidence of negative charge injection at the cathode during the ramp rate measurement. That is, the magnitude of the entrance peak vs the applied dc stress of sample B deviates positively from the "extrapolated straight line" shown in Figure 2b. After the first hour of dc aging there was still no appearance of charge accumulation within the bulk insulation when the dc voltage was removed.

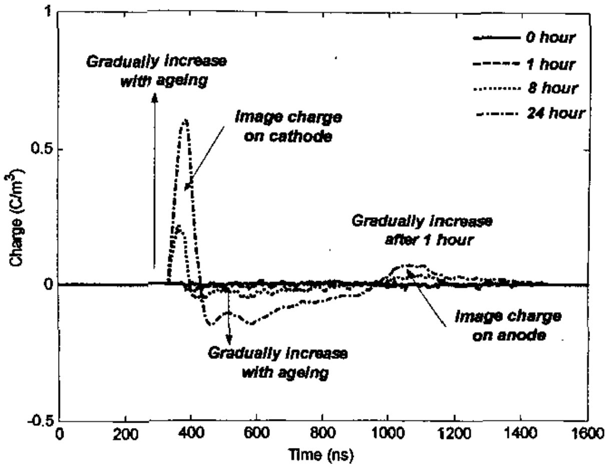

Figure 5. Evolution of the space charge formation of the sample B during 24 h aging process (voltage off).

After 8 hours, it was noticed that there had been a small amount of negative charge (i.e. homocharge) starting to accumulate within the bulk with no indication of any positive charge formation. Judging from the results, it was believed that after the removal of the crosslinked by-products (via degassing process), the injection process governed the space charge dynamics and the source of these negative charges was possibly due to the injection from the cathode. After 24 h, the amount of negative charge increased significantly and became widely distributed within the bulk insulation.

In order to verify the above explanation of the space charge evolution, the interfacial stress at the cathode and anode during the 24 h aging period has been plotted in Figure 6. Over 0 to 8 h aging, in contrast to the results of the as-received XLPE sample (i.e. stress enhancement of 12%), it has been noticed that the stress at the cathode reduced from −16.8 kV/mm to −14.0 kV/mm (approximately 16.7% reduction). The decrease in stress at the interface was believed to be associated with the homocharge (i.e. negative) injection at the cathode.

However, similar to what was observed in the as-received sample A, during the first 8 h, the interfacial stress at the anode was approx 5% reduced with respect to 0 h and remained constant over the next 16 h of dc aging. It was believed that although the amount of negative charge accumulated inside the bulk increased with aging time, the trapping position is far away from the anode, and the effect of the space charge on the interfacial stress at the anode was insignificant.

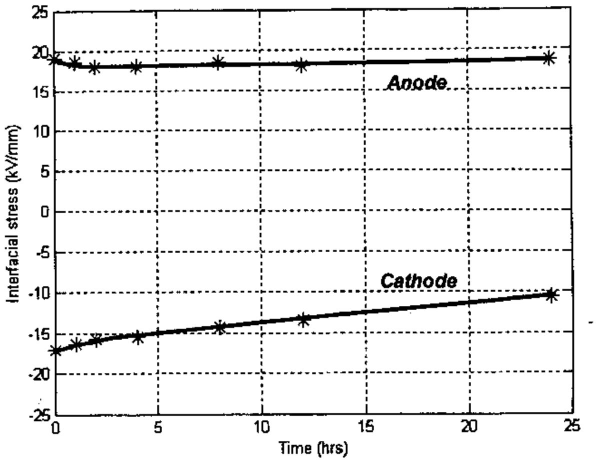

Figure 6. The interfacial stress of the sample B during 24 h aging process (voltage on).

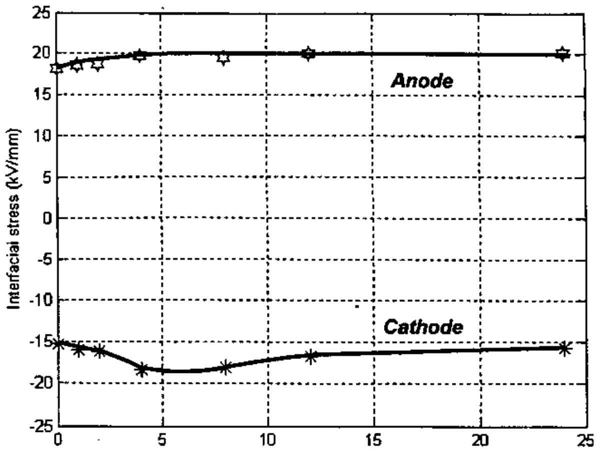

Figure 8. The interfacial stress of the sample C during 24 h aging process (voltage on).

6.2.3 SAMPLE C

Based upon the test results of sample A and sample B, the space charge dynamics in the XLPE materials were significantly affected by the degassing process. In order to examine the effect of semicon on the space charge formation in the different insulation, polyolefin samples with XLPE semicons have been tested. This may give useful information about how to select semicon screens by the cable manufacturers to control the space charge within the bulk. Also, as there are no crosslinking by-products present within the polyolefin insulation, the space charge dynamics is expected to be similar to the degassed XLPE sample, which is mainly controlled by the charge injection process.

Figure 7 illustrates the space charge evolution of sample C within 24 h dc aging. Over 24 h of the aging period, there was clear evidence of negative charge accumulation within the bulk insulation. However, as there were no crosslinking by-products within the polyolefin insulation, the accumulated negative charge is believed to be supplied by electron injection from the cathode.

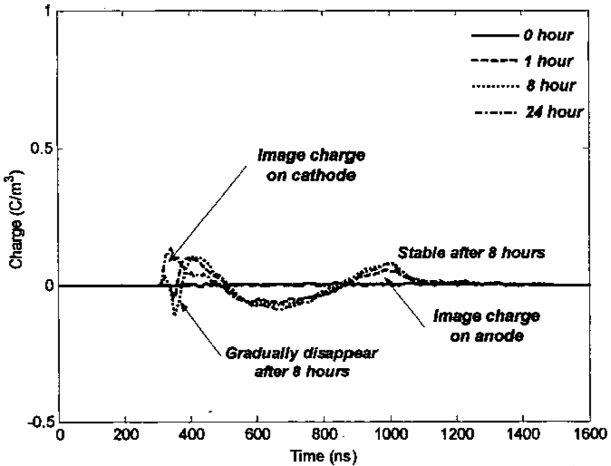

Figure 7. Evolution of the space charge formation of the sample C during 24 h aging process (voltage off).

In the vicinity of the cathode, it was noticed that a small amount of positive charge accumulated after one hour, which became more pronounced after 8 h of aging. However, from 8 to 24 h this small amount of positive charge was gradually reduced and eventually was masked by the positive image charge at the cathode. Considering the above phenomena, a possible explanation, which relates to the sample manufacturing process, is suggested. The semicon electrodes were made from the XLPE material, and during the sample manufacturing process the crosslinking by-products within the semicon diffused into the polyolefin bulk and caused the field assisted by-product ionization close to the interface region to occur.

Figure 8 illustrates the evolution of the interfacial stress at the cathode and anode of sample C over 24 h aging. Over the first 8 h aging, it was noticed that the stress at the cathode and anode increased by +25% (-15 to -18.8 kV/mm) and +11% (18 to 20 kV/mm) compared to that at 0 h. This was consistent with the previous observations of heterocharge accumulation (i.e. ionization) close to the interface. However, from 8 to 24 hours, the interfacial stress at the cathode decreased from -18.8 to -16 kV/mm (+25% to +6.7%). One possible cause was that the stress enhancement due to the heterocharge close to the cathode initiated the negative charge injection and lowered the electric stress at the electrode/polyolefin interface.

6.2.4 SAMPLE D

To examine the effect of the degassing process on the space charge dynamics in the polyolefin sample with XLPE semicons and verify that the source of the small amount of positive charge accumulated in the vicinity of the cath-

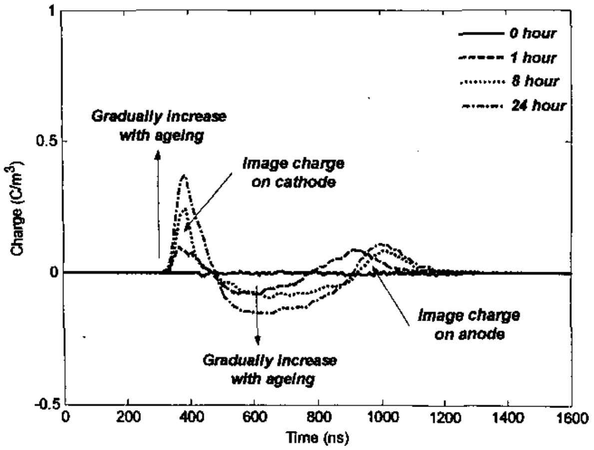

Figure 9. Evolution of the space charge formation of the sample D during 24 h aging process (voltage off).

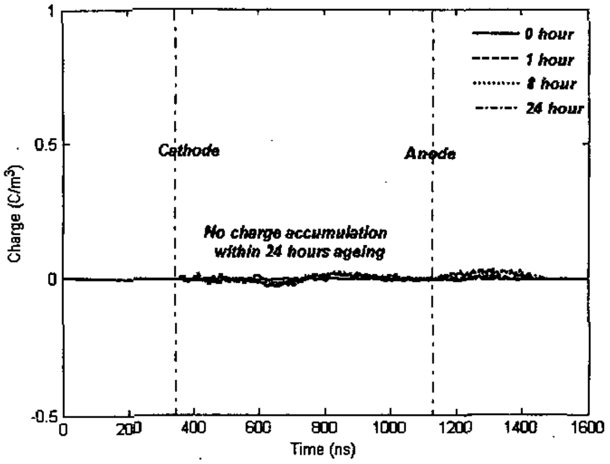

Figure 11. Evolution of the space charge formation of sample E during 24 h aging process (voltage off).

ode was due to the by-products diffusion, a degassed polyolefin plaque with XLPE semicons (sample D) has been tested. Figures 9 and 10 illustrate the space charge and interfacial stress evolution of sample D within 24 h aging.

It can be seen from Figure 9 that in the degassed sample D there was only negative charge accumulation throughout the 24 h aging period. In addition, the evolution of the space charge accumulation inside the bulk was similar to that encountered in the as-received sample C. However, in contrast to what was observed in the as-received polyolefin sample with XLPE semicons, there was no indication of the small amount of positive charge accumulated in the vicinity of the cathode. By comparing the results of samples C and D, the degassing process was responsible for the difference in the observed results. The origin of the small negative peak at the interface region in sample C over the first 8 h of dc aging is possibly due to the image positive charge close to the electrode, which is created by the ionization of the crosslinking by-products diffused from the XLPE semicons into the polyolefin bulk during the sample manufacturing process.

Referring to Figure 10, similarly to what was observed for the degassed sample B, it has been noticed that after 24 h of aging the stress at the cathode was reduced approximately by 40% compared to that at 0 h. The decreased stress at the cathode agreed with the suggestion that the homocharge (i.e. negative) injection from the cathode and the removal of the by-products via the degassing process from the bulk of polyolefin sample with XLPE semicon was the cause of this effect.

6.2.5 SAMPLE E

To correlate the semicon material selection to that of the space charge dynamics within the bulk insulation, a polyolefin plaque with polyolefin semicons has been tested. Figures 11 and 12 show the space charge distribution and interfacial stress evolution of sample E within 24 h of aging.

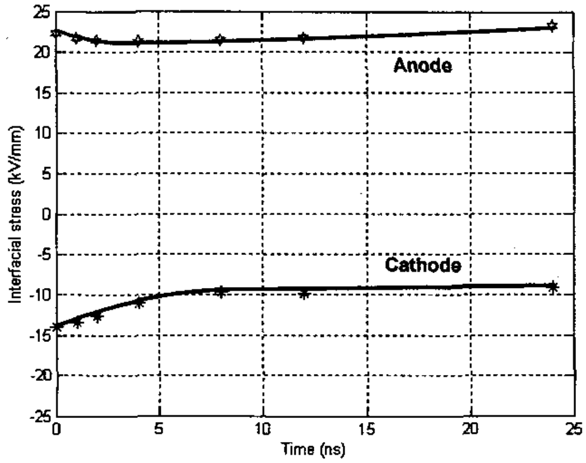

Figure 10. The interfacial stress of the sample D during 24 h aging process (volts on).

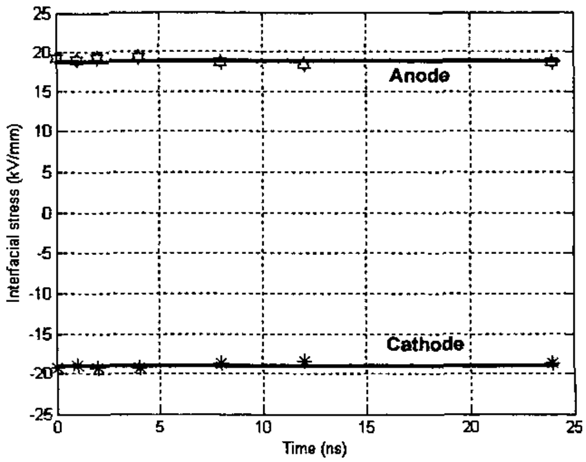

Figure 12. The interfacial stress of the sample E during 24 h aging process (voltage on).

It was noticed that there was no significant trapped charge accumulation within the polyolefin bulk insulation (Figure 11) and electric stresses at both of the electrodes were constant (Figure 12) throughout the whole period of 24 h dc ageing. By comparing the aging results between samples with XLPE semicons and polyolefin semicons, it is confirmed that the negative charge injection from the cathode only takes place in the samples with XLPE semicon electrodes, not with polyolefin semicon electrodes.

7 ac RESULTS AND DISCUSSION

7.1 SAMPLES F AND G

The X-plots of samples F and G at 0 and 24 h ac aging are shown in Figure 13. The results show that during the positive half ac cycle at 0 h (Figures 13a and 13c), the magnitude of the entrance peak (cathode) of the as-received and degassed XLPE with XLPE semicons both deviate positively from the extrapolated straight line by 30% at +30 kV_{peak}. It can be concluded that above the threshold voltage (+17 kV_{peak} or +11.3 kV/mm_{peak}), the interfacial stress at the cathode is less than the applied stress, indicating homocharge (injection) has been formed close to the semicon/XLPE interface (cathode).

For the negative half ac cycle at 0 h, the magnitude of the entrance current peak (anode) follows the extrapolated straight line and the exit peak (cathode) deviates positively from the extrapolated straight line by 15% at −30 kV_{peak} (i.e. the interfacial stress at the cathode has decreased by around 15%). The change in the stress is believed to be similar to the phenomena encounter in the positive half cycle in that negative charge (homocharge) developed close to the cathode.

After 24 hours of ac aging, it was found that the deviation (from the extrapolated straight line) of the entrance peak on the positive half ac cycle was reduced for both samples. The difference between samples with treatment 1 and 2 was insignificant. Therefore, it may be concluded that the space charge dynamics for the XLPE with XLPE semicon electrodes, subjected to 50 Hz ac electric stress depends on the ac aging period and may be unaffected by the sample degassing process.

7.2 SAMPLES H AND I

The X-plots of samples H and I at 0 and 24 h of ac aging are shown in Figure 14. Similar to the results encountered in samples F and G, the magnitude of the entrance peak (cathode) deviates positively from the extrapolated straight line by 30% at +30 kV_{peak} during the positive half ac cycle (at 0 h). It means that above the threshold voltage (i.e. +13 kV), the interfacial stress at the cathode is less than the applied stress, indicating that homocharge (injection) has been formed close to the semicon/LDPE interface (cathode).

However, comparing with what was observed in the XLPE samples F and G, there was no deviation (from the extrapolated straight line) of the exit peak (cathode) on the negative half ac cycle. This may be due to the reduction of the measurement resolution at the exit peak because of the high attenuation of the signal through the polyolefin sample or the loss of acoustic energy due to the mismatch of the acoustic characteristic of the polyolefin bulk insulation and the XLPE semicons.

There is no significant difference between the X-plots at 0 and 24 h for both samples H and I (Figures 14b and

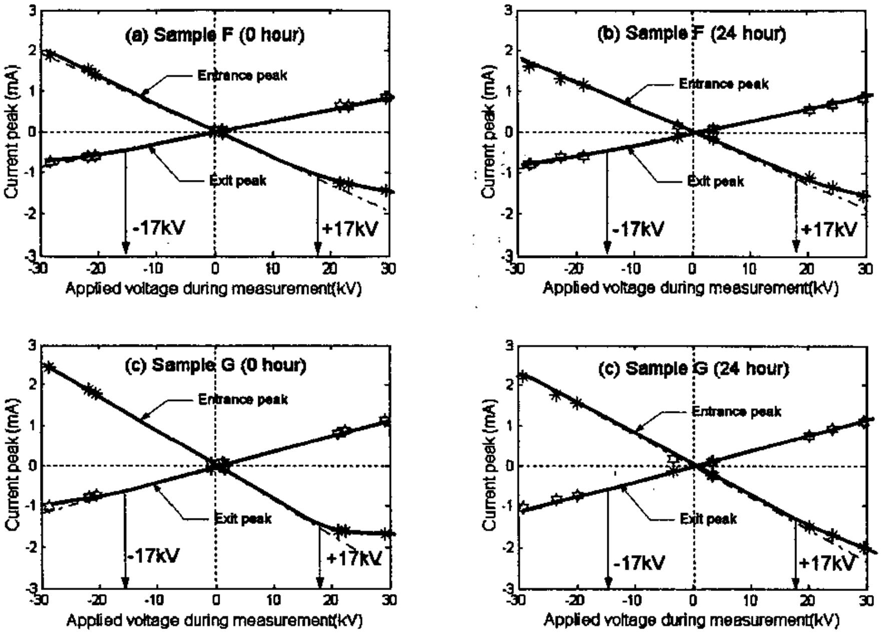

Figure 13. X-plots of samples F and G at 0 and 24 h.

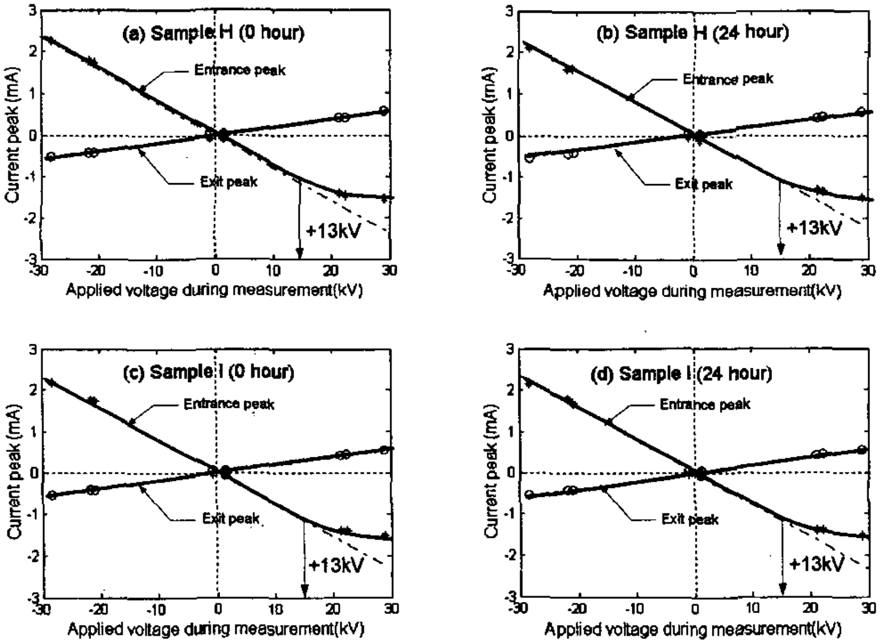

Figure 14. X-plots of samples H and I at 0 and 24 h.

14d). It can be deduced that the space charge effects in the polyolefin with XLPE semicons may be independent on the ac aging period (in the region of 25 kV/mm$_{peak}$) and also is unaffected by the sample degassing process.

7.3 SAMPLE J

Figure 15 shows the X-plots of sample J at 0 and 24 h ac aging. It is observed that there is no peak deviation from the straight line either during the positive or negative half ac cycle at 0 and 24 h (Figures 15a and 15b). These features indicate that there are no space charge effects in the polyolefin sample with polyolefinic semicon electrodes under 50 Hz ac electric stresses. The interfacial stress at the cathode and anode is proportional to the applied stress.

8 CONCLUSIONS

IN this paper, we have reported on the space charge characteristics of XLPE and a polyolefin with different sample treatment and semicon electrodes subjected to dc or 50 Hz ac electric stresses. The main conclusions are as follows.

The degassing process reduces the dc threshold stress for space charge creation in the XLPE samples with XLPE semicons (approximately 30% reduction), but not with

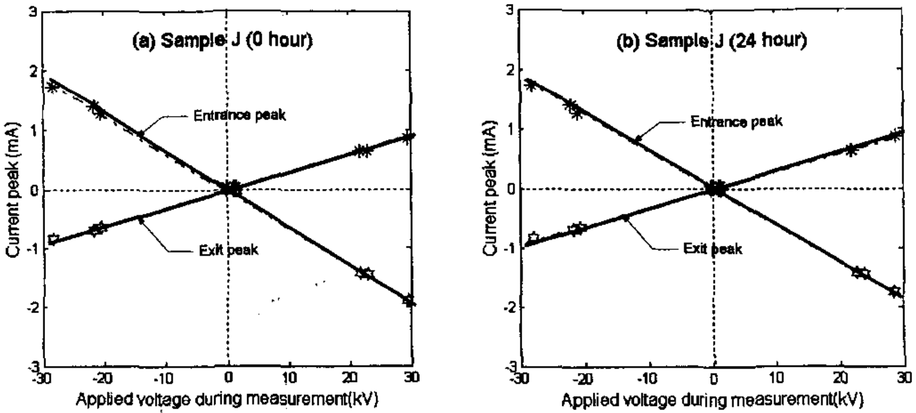

Figure 15. X-plots of sample J at 0 and 24 h.

polyolefinic samples with XLPE semicons. In addition, using polyolefinic semicons with bulk polyolefin insulation, there was no indication of space charge up to ~19.2 kV/mm during the ramp rate measurements.

dc aging shows that the space charge performance of the polyolefin samples with polyolefinic semicons is better than the XLPE samples with XLPE semicons and the polyolefin samples with XLPE semicons. Also, applying XLPE semicons to polyolefin bulk insulation, the crosslinking by-products from the semicons may diffuse across the XLPE/polyolefin interface, and affect the space charge performance.

Space charge effects in XLPE insulation under 50 Hz ac electric stresses are significant when the applied stress is above a threshold value. The presence of charge inside the bulk will modify the electric stress at the semicon/bulk insulation interface. The effect of sample treatment (degassing) on the space charge threshold in the ac case is not significant compared to the dc one, over the 24 h aging period considered here.

The effect of the ac aging can only be found in the XLPE samples with XLPE semicons, but not the polyolefin samples with XLPE semicons. For the polyolefin samples with polyolefin semicons, no significant space charge effect has been detected up to an applied ac stress of 25 $\text{kV/mm}_{\text{peak}}$.

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DEDICATION

It is sad that Professor Tony Davies is no longer here to share our joy for the publication of the manuscript. Let this paper be dedicated to the memory of Professor Tony Davies.

REFERENCES

[1] X. Wang, D. Tu, Y. Tanaka, T. Muronaka, T. Takada, C. Shinoda and T. Hashizumi, "Space Charge in XLPE Power Cable Under dc Electrical Stress and Heat Treatment", IEEE Trans. DEI, Vol. 2, pp. 467–474, 1995.

[2] B. Sanden, "Space Charge Accumulation in Fresh and Degassed XLPE Insulation", 28th Diel. Soc. Meeting, UK, pp. 225–233, 1998.

[3] K. R. Bambery and R. J. Fleming, "The Temperature Dependence of Space Charge Accumulation in Cross-linked Polyethylene", J. Thermal Analysis, Vol. 50, pp. 19–31, 1997.

[4] A. E. Davies and D. A. Hodgson, "Electrical Ageing Effects in Polyethylene", 5th Intern. Conf. DMMA, UK, IEE Publication No. 289, pp. 254–257, 1988.

[5] L. A. Dissado, G. Mazzanti and G. C. Montanari, "The Role of Trapped Space Charges in the Electrical Aging of Insulating Materials", IEEE Trans. DEI, Vol. 4, pp. 496–506, 1997.

[6] P. Notingher Jr., A. Tourelle, J. Santana and M. Albertini, "Space Charge in A.C.-Poled XLPE for HV Cables", Jicable 99, pp. 701–706, 1999.

[7] S. Agnel, A. Toureille, G. Platbrood and G. Geert, "Study of AC Charging Ability of XLPE Insulating for Power Cable", Jicable 99, pp. 656–661, 1999.

[8] S. Hole, C. Alquié and J. Lewiner, "Space Charge Distribution Determination under A.C. Stress", C. R. Acad. Sci. Paris, t. 316, Série II, pp. 157–162, 1993.

[9] M. Mammeri, C. Laurent and J. Salon, "Influence of Space Charge Build up on the Transition to Electrical Treeing in PE under ac Voltage", IEEE Trans. DEI, Vol. 2, pp. 27–35, 1995.

[10] Y. F. F. Ho, G. Chen, A. E. Davies, R. N. Hampton, S. G. Swingler and S. J Sutton, "Do Semicons Affect Space Charge?", IEEE 7th Intern. Conf. Solid Dielectric, pp. 105–108, 2001.

[11] Se-Ondoua Mbarga, D. Malec, N. Zebouchi and Hoang-The-Giam, "Study of Space Charge Effect on Dielectric DC Breakdown of Synthetic Insulators with the Pressure Wave Propagation Method", J. Electrostatics, Vol. 40 & 41, pp. 355–361, 1997.

[12] Y. F. F. Ho, G. Chen, A. E. Davies, R. N. Hampton, S. Hobdell, S. G. Swingler and S. J. Sutton, "Space Charge Measurements in XLPE Insulation under 50 Hz A.C. Electric Stress", IEE Intern. Conference on Dielectric Materials, Measurements and Applications (DMMA), Edinburgh, UK, pp. 68–73, 2000.

[13] Y. F. F. Ho, G. Chen, A. E. Davies, S. G. Swingler, S. J. Sutton, R. N. Hampton and S. Hobdell, "Measurement of Space Charge in XLPE Insulation under 50Hz AC Electric Stresses Using the LIPP Method", IEEE Trans. DEI, Vol. 9, pp. 362–370, 2002.

[14] A. E. Davies, G. Chen, X. Wu, R. N. Hampton, S. J. Sutton and S. G. Swingler, "Calculation of Space Charge Density and Electric Stress in XLPE Compounds", Jicable, pp. 728–732, 1999.

[15] O. Fanjeau, D. Mary and D. Malec, "A Note on Charge Recombination in Low Density Polyethylene under a Moderate ac 50 Hz Field", J. Phys. D.: Appl. Phys., Vol. 33, L61–L64, 2000.

[16] C. Bert, C. Heninion, J. Lewiner, C. Alquié, N. Hampton, J. Freestone and S. Verne, "Measurement of Space Charge Distribution under 50 Hz A.C. Stress", Jicable, pp. 195–199, 1995.

[17] D. Malec, "Design Note Technical Problems Encountered with Laser Induced Pressure Pulse Method in Studies of High Voltage Cable Insulators", Meas. Sci. Technol., Vol. 11, N76–N80, 2000.

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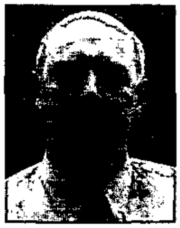

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