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Space Charge in Gamma and Electron-Beam Irradiated XLPE

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Abstract. The current study focuses on the influence of ionizing radiation on the dynamics of space charge in crosslinked polyethylene (XLPE) with the presence of a stored charge. For this purpose, electron-beams have been chosen to implant charges in a regulated manner near to the grounded electrode. At the completion of the irradiation procedure, the Pulsed Electro Acoustic (PEA) technique was utilized to quantify space charge in each sample under ambient circumstances. The measurements of space charges in the presence of a 40 kV/mm electric field reveal the formation of two heterocharges close to the implanted charge and the anode respectively. The charge accumulated persists during the relaxation and electrostatic equilibrium appears to be reached inside the insulation between the various types of charges.

I. INTRODUCTION

Space charges play an essential role in the electrical behavior of insulation materials, the creation and build-up of charges can be complicated by a variety of processes and still poorly understood, which is why a lot of studies [1, 2, 3] have been conducted to determine the origin and influence of space charge formation in insulation material. The presence of ionizing radiation in space for airplanes or in a nuclear reactor for electrical power systems, could alter the dielectric and mechanical characteristics in XLPE resulting of chain scission, crosslinking, and oxidation, which lead to a catastrophic decay in fracture properties [4]. The space charge developed under gamma radiation have been investigated by many studies [5, 6], regarding the effect of electric field and temperature in insulated materials. The present work shows the presence and formation of space charge in cross-linked polyethylene (XLPE) under nuclear radiation and electron beam irradiation, the focus of the study is on the effects of electric field. The presence of electron beam provides an alternative technique to build up space charge in insulation materials. Its allows to deposit charges at specified location and adjust the amount of charges.

This paper reports on the effect of gamma and electron beam radiation on XLPE. Furthermore, based on space charge measurement we discussed the behavior of the charge implanted by the electron beam in both gamma irradiated and virgin XLPE samples.

II. EXPERIMENTAL SET-UP

A. XLPE Samples

The test material for this study was cross-linked polyethylene (XLPE), which was taken from peeling high

voltage cable. The HVAC cables were developed as part of the European Artemis project [7, 8], and some part of the cable were exposed to electrical and thermal aging. To establish the impact of aging, the cables were exposed to a range of electrical and structural characterizations in previous experiments. Following the completion of the experiment, samples were used to investigate ageing under various electrical, thermal, and radiation conditions. The XLPE samples used in this investigation came from the peeled cable. The rolls had a thickness of 150 μm and a width of 80 mm.

Gamma rays were used to irradiate the sample in room temperature at air. Irradiation was carried out using a ⁶⁰Co source at a dose rate of 22 Gy/min for a total dosage of 60 kGy. We noticed a slight change in color after the irradiation: the samples turned more yellowish. A. Charlesby et al. found comparable yellowing after gamma irradiation [9].

The gamma-irradiated XLPE was then subjected to electron beam irradiation in MATSPACE irradiation chamber equipped with an electron gun with an energy range of [10-100 keV] [10]. The irradiation was performed at a vacuum of around 10^{-6} mbar, and a flux of 1 nA/cm². The irradiation time was limited to 5 minutes to minimize surface discharges. Both gamma-irradiated and virgin XLPE were subjected to electronic irradiation.

B. Space charge measurements

Space charge measurements were performed using the standard pulsed electro acoustic (PEA) [11, 12] provided by TechImp, Italy, which was appropriate for the 150 μm thick samples used in this study. The specimen was placed between a layer of high-voltage semiconducting material (carbon black doped polymer) and an aluminum ground electrode. The experiments were conducted in an air environment with a controlled temperature of 25 °C and a direct current field of 40 kV/mm. All samples were polarized and depolarized for a duration of 3600 seconds.

III. RESULTS

A. Charge implantation profiles

The space charge distributions obtained in air shortly after electronic irradiation with a 30 keV irradiation energy in XLPE and gamma irradiated XLPE are shown in Fig. 1. The image charges are represented by the peaks measured on the electrodes (abscissa 0 and 150 μm). In both virgin and gamma irradiated XLPE, a broad negative charge peak is seen in the bulk at the surface, with greatest peaks recorded at 16 μm

from the irradiated surface. For the same irradiation time, the quantity of charge implanted in the gamma-irradiated sample is larger than that reported in the virgin XLPE, which is probably due to the ionizing radiation's alteration of the XLPE, allowing a considerable quantity of charge to enter inside the material.

Under post irradiation, we noticed that some charge was formed during the implantation of charges in the gamma irradiated XLPE, negative charge was found at the top electrode, and positive charges next to the implanted charges (Fig. 1 (b)). The presence of a local electric field formed by the implanted charge and the top electrode as much as the implanted charges are important compare to the virgin sample, can explain the appearance of thus charges. The same think was observed in the virgin sample, a small negative charge was detected near to the top electrode, in contrast to the gamma irradiated XLPE sample, we note the absence of positive charges. The charge implanted in the virgin XLPE was less relevant than that recorded in the gamma irradiated XLPE, which produces a weaker electric field that fails to generate enough charges.

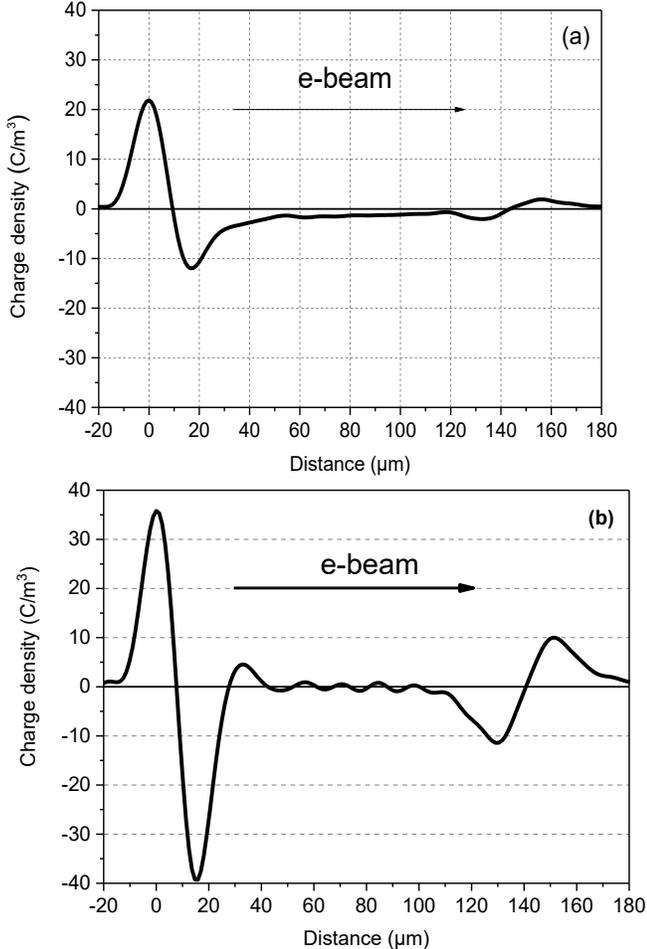


Fig. 1. Fig. 1. Space charge profiles recorded on XLPE 150 μm-thick films: (a) irradiated by electrons under 30 keV for 5 min, (b) XLPE irradiated (gamma 60 kGy + electrons under 30 keV for 5 min). Space charges under DC fields

Fig. 2 (a) shows space charge measurements on virgin XLPE done for 1 hour under polarization with a DC field of 40 kV/mm. As previously described [13], The injection of negative charge is the major mechanism found on the recorded profiles. The negative charge injected builds up with time, followed by trapping near the ground electrode. The injection of a small amount of positive charges near the anode is also seen, however with no significant temporal alterations. Because of the impact of the negative injection that causes positive image charges at both electrodes, the influence charge on the ground electrode drops with time, whilst the one on the HV electrode grows. We noticed that the fluctuation is greater in the grounded electrode than in the anode, which might be due to electrode location in the PEA cells; the charge is better resolved at the cathode because the grounded electrode is closer to the piezoelectric sensor than the anode electrode.

The space charge profiles obtained during 1 h of charging time of the sample irradiated at 30 keV are plotted in Fig. 2 (b). The distribution of the space charge do not shows much changes during polarization, as soon as the field is applied, the peak initially stored grows continuously, negative charge buildup is added to the already stored negative charge near to the ground electrode. As seen in the virgin sample the injection of negative charges is the principal mechanism of the charges generated during the polarization. The influence charges on ground electrode drop continuously during the polarization due to internal charges redistribution that causes positive image charge on the ground electrode.

During 1 h of polarization, the measurement results of space charge distribution in XLPE irradiated by gamma rays of 60 kGy and electron beam of 30 keV, under applied DC field of 40 kV/mm are shown in Fig. 2 (c). The profile acquired before to DC stress (see Fig.1) demonstrates that there is small amount of charges formed in the material indeed of the charge implanted by the irradiation.

Negative and positive charge zones gradually emerge during DC stress from the initial minutes, and the quantity of heterocharges develops fast and continuously during this period. For negative charges, the charge peaks on the recorded profiles are next to the anode, while for positive charges, they are next to the charge implanted by the irradiation. It is also worth noting that the charged areas have symmetrical peak shapes, but with a difference in maximum charge density values, negative charges are more important than the positive ones. The negative charge implanted by electron beam still present after 1 h of polarization (Fig. 3 (c)). The peak drift slightly to the ground electrode, were the maximum of the peak in the end of polarization was found at 10 μm from the irradiated surface (the initials peak was at 15 μm).

The influence charge on the anode side increase during DC stress, the image charge created by negative heterocharge was added to the influence charge peak. On the other hand, we note the absence of influence charge at the cathode, as well as the presence of a significant negative charge (implanted by irradiation) near the grounded electrode that avoid the emergence of this peak at the electrode interface. The negative charges have produced a significant amount of positive image

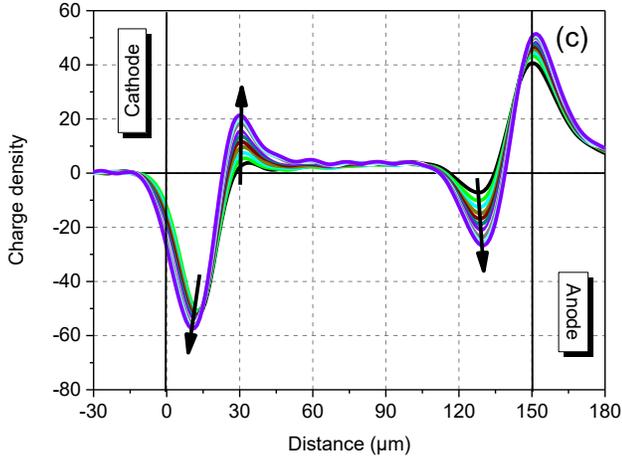
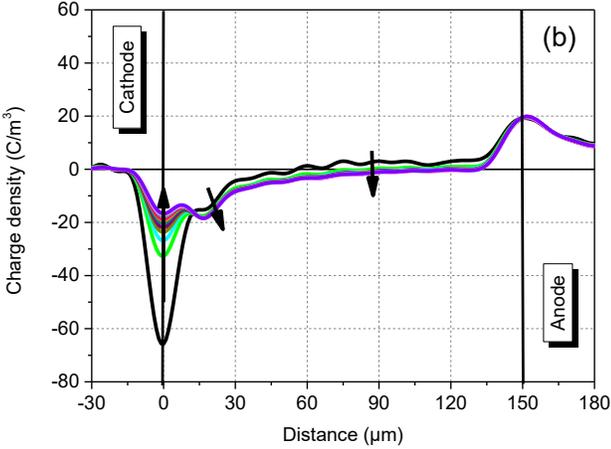
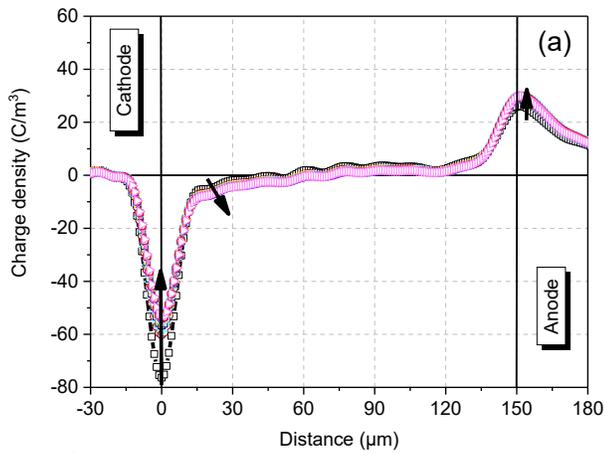


Fig. 2. Space charge profile recorded during 1 h of polarisation under 40 kV/mm and (a) non-irradiated XLPE (b) XLPE irradiated by electrons under 30 keV (c) XLPE irradiated gamma 60 kGy + irradiated by electrons under 30 keV.

charges, which are neutralizing the influence charge.

B. Space charges during relaxation

Fig. 3 depicts the space charge distribution acquired in Volts-off for 1 hour.

The negative charges injected during the polarization process in virgin XLPE (Fig. 3 (a)) appear to be distributed relatively uniformly across the insulator. With time, the charge decays evenly. The positive charges generated on the electrodes represent the image charge, they gradually decrease

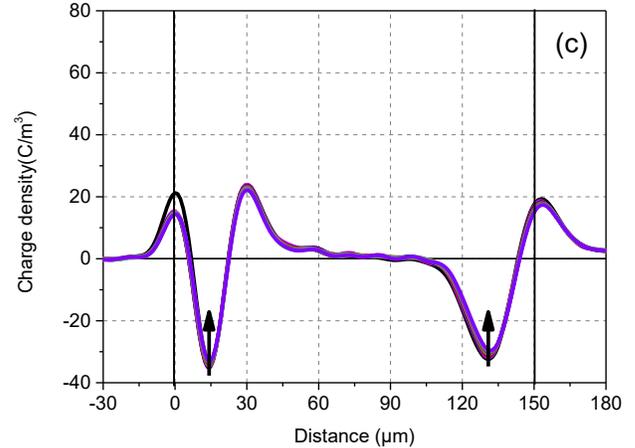
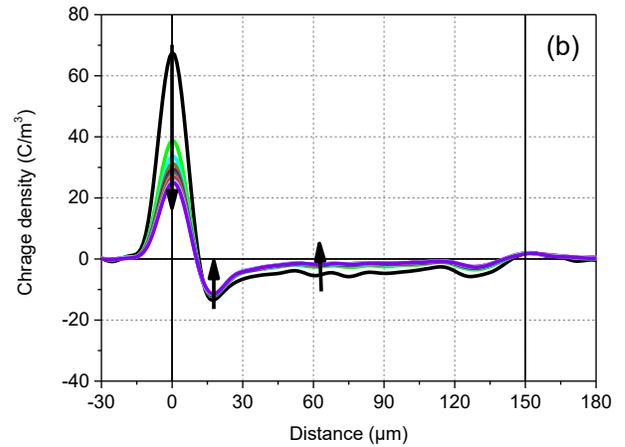
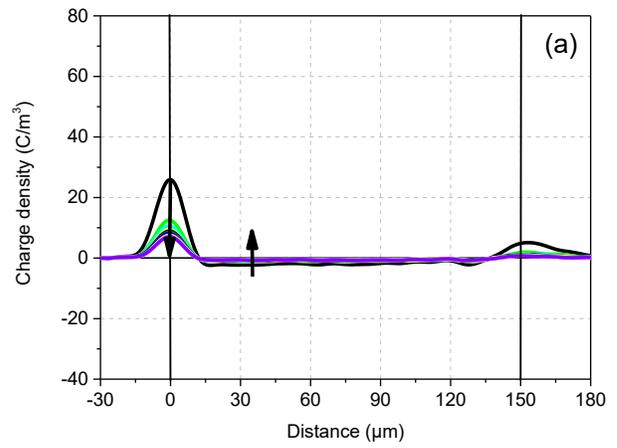


Fig. 3. Space charge profile recorded during volt-off after 1 h of polarization under 40 kV/mm: (a) non-irradiated XLPE (b) XLPE irradiated by electrons under 30 keV (c) XLPE irradiated gamma 60 kGy + irradiated by electrons under 30 keV

following the main distribution of charges inside the material. After 1 hour of relaxing, a small amount of negative charges is still identified in the bulk, implying that the charges have been completely recombined or removed.

During vot-off in XLPE irradiated using electron beam at 30 keV Fig. 3 (b), The negative charge injected when the DC field is applied decreases slowly and vanished completely with time. At last only the implanted charge at 15 μm remain. The charge implanted seems to be stable without evolving much in

time. The distribution of space charge during relaxation is identical to that found in the previous profile during polarization.

The space charge distribution recorded during relaxation in XLPE irradiated with gamma rays at 60 kGy and electron beam at 30 keV are shown in Fig. 3 (c). In 1 h, the charges formed during relaxation is identical to that found in the previous profile during polarization (the different charges decrease very slowly). an electrostatic equilibrium appears to be attained inside the insulation between the various types of charges. A peak of induced charges appears clearly on the electrode (cathode side) to maintain this equilibrium.

IV. DISCUSSION

In the virgin XLPE the apparent mechanism responsible for space charge build-up is the injection of homocharge (fig. 2 (a)). In comparison to the XLPE irradiated with electrons, we see the same behavior in term of evolution of the space charge during polarization (Fig. 2 (b)), therefore in addition to the charge implanted, the injection of negative charge from cathode is the primary process in the evolution of the space charge. As the electronic irradiation was limited to the surface no space charge was detected outside the irradiated zone of the material, that explain the gathering of the behavior of the charge distribution with the virgin sample.

In XLPE irradiated with gamma rays and electrons, we observe the creation of a considerable quantity of negative and positive heterocharges (Fig. 2 (c)) witch was different from virgin XLPE (Fig.2 (a)). As seen in previous work [14] the appearance of heterocharge is a completely novel phenomenon. When compared to the virgin sample the charge observed seems to be generated from the bulk of the gamma-irradiated sample, and the charge recorded prior to voltage application (Fig. 1 (b)), confirm that. The change in the behavior in space charge is probably due to deposited energy by gamma ray in the material, which causes reconfiguration in the electrical and structural characteristics of XLPE. As the gamma irradiation was done in air, the oxidation is one of most processes responsible of this changes as reported by Fu et al [15]. On the other hand, the presence of the implanted charges allow to observe the injection of negative charges from the cathode, which was previously difficult to see in XLPE treated simply with gamma ray.

V. CONCLUSION

The charge cloud have been observed in virgin and gamma irradiated XLPE after e-beam irradiation. The implanted charge appears at the same depth in both sample. The injection of homocharge is the primary processes responsible for space charge build-up in virgin XLPE. Significant heterocharge build-up was seen at the anode and adjacent to the stored charge in gamma irradiated XLPE. The observed behaviour might be attributed to the oxidation introduced in the material. In comparison to earlier research, the singularity is the revelation of another mechanism involved in the space charge

distribution during Volt-on, due to the presence of implanted charge, it was possible to observe injection of negative charge.

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