City Research Online

City, University of London Institutional Repository

Citation: Fu, M., Chen, G. & Fothergill, J. (2005). The influence of residue on space charge accumulation in purposely modified thick plaque XLPE sample for DC application. Paper presented at the 14th International Symposium on High Voltage Engineering, 25 - 29 August 2005, Tsinghua University, Beijing.

This is the unspecified version of the paper.

This version of the publication may differ from the final published version.

Permanent repository link: https://openaccess.city.ac.uk/id/eprint/1396/

Link to published version:

Copyright: City Research Online aims to make research outputs of City, University of London available to a wider audience. Copyright and Moral Rights remain with the author(s) and/or copyright holders. URLs from City Research Online may be freely distributed and linked to.

Reuse: Copies of full items can be used for personal research or study, educational, or not-for-profit purposes without prior permission or charge. Provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

City Research Online: http://openaccess.city.ac.uk/ publications@city.ac.uk

The Influence of Residue on Space Charge Accumulation in Purposely Modified Thick Plaque XLPE Sample for DC Application

M. Fu[1]*, G. Chen[2] and J. C. Fothergill[1]
[1] Department of Engineering, University of Leicester, UK
[2] School of Electronics and Computer Science, University of Southampton, UK
* m.fu@le.ac.uk

Abstract: Effects of cross-linking by-products (residues) of polyethylene on space charge accumulation and decay are investigated in the paper using the pulsed electro-acoustic technique. Space charge profiles have shown a great variation both in the charge initiation over the voltage ramping up process and later on long term stressing and decay (volts off) among the samples subjected to different conditioning, which results in diverse residues content (fresh, 0.5% residue and thoroughly degassed). The results show that by-products of cross-linking or the residual impurities play a key role in the space charge accumulation in cross-linked polyethylene. On the removal of impurities by degassing, small homocharge was built up in the vicinity of the electrode. It is concluded that space charge accumulation is governed by the charge injection through dielectric/electrode interface when sample is thoroughly degassed.
Key Words: Space charge; Cross-linking by-products; XLPE and PEA.

INTRODUCTION

Numerous investigations had been carried on the mechanism of space charge accumulation in polymeric insulations under the motivation of High Voltage Direct Current (HVDC) application over last two decades. In the light of better understanding of this subject, the material (most prominent is cross-linked polyethylene-XLPE) modification has been made on the purpose of space charge suppression in HVDC power cable insulation.

This paper presents the research on space charge characteristics within XLPE purposely modified for HVDC power cable insualtion. A batch of thick plaque samples made of different amended XLPEs is experimentally studied using the pulsed electroacoustic (PEA) method. As the sample has to be prepared in the similar material processing procedure to that in cable manufacturing, it is inevitable to have a bigger thickness (~2mm) than most film samples used in other experimental work. As a consequence, a relatively high external voltage is required across the sample to obtain an adequate stress field for the space charge measurement. By virtue of sample's big thickness, the attenuation and dispersion of the acoustic signal propagation through the sample's thickness has to be another consideration in the space charge distribution measurement [1, 2]. Some points on electrode design and data processing in the concern of thick sample have been addressed in the paper.

The space charge results among these samples have shown a great variation in the fast charge initiation in the voltage ramping process, in the charge accumulation over the stressing term and in the following decay test after the removal of the applied voltage. The samples subjected to different degassing treatment, i.e. at the conditions of fresh (undegassed), partially degassed (0.5% residue) and thoroughly degassed were studied in terms of space charge accumulation and decay.

EXPERIMENTAL

PEA system for thick plaque samples

To satisfy the requirement of a relatively high stressing voltage across the sample, besides the application of voltage bushing on the high voltage electrode, adequate flashover distance is required for the sample along its surface from high voltage electrode to the ground electrode (as the photo shown in Fig 1). This big size requirement both for sample and top electrode make it difficult to maintain an even contact between the sample and the electrode insulator surfaces. Some air gaps may inevitably form between them. At the beginning of the test, flashover frequently occurred through this air gap path over the surfaces of sample at a voltage over 50kV. Smearing silicone grease around the embedded semiconducting electrode of the sample successfully blocked the discharge path. The design of this PEA system enables a dc voltage as high as 100kV to be applied across the sample.

Fig. 1 Photograph of PEA electrodes system for thick plaque samples

Acoustic wave propagation in the thick plaque samples is significantly attenuated and dispersed due to the lossy and dispersive properties of the polymeric material. As a result, these features will wreck the detecting sensitivity and spatial resolution and give a poor

measurement result for the space charge in the location far away from the transducer. A data compensation algorithm was developed to correct the effects caused by the acoustic pressure wave attenuation and dispersion [1, 2].

Samples

Samples tested in the research were purposely modified XLPE for HVDC power cable application. The semiconducting electrodes were embedded by cross-linking method to the planar sample. Fig. 2 illustrates a sample's dimensions and its cross-section. The residue concentration in the sample was controlled by degassing treatment, i.e. fully degassed at 90°C in an oven for three days, partially degassed with 0.5% of impurities. For the reference, the space charge distribution and its evolution were also measured on a low-density polyethylene (LDPE) sample. The sample was prepared by thermal press thus is regarded as additive free.

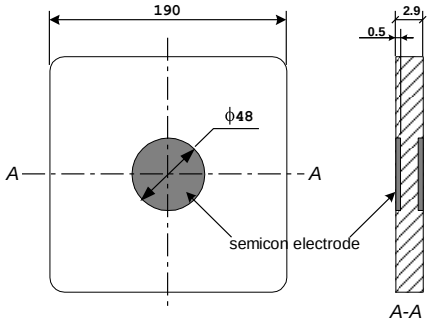


Fig. 2 Sample dimension and cross-section

Measurement procedure

Space charge measurements started with a voltage ramping up test in which external voltage was gradually increased from zero to the required stressing voltage and the magnitudes of the induced surface charge on two electrodes were recorded. The intention of this experiment was to find the threshold voltage at which space charge starts to accumulate. This experiment was then followed by space charge distribution measurement at field of 40kV/mm over a certain period of time until up the equilibrium status of space charge. The decay test was conducted afterwards to study the depolarisation characteristics of the material.

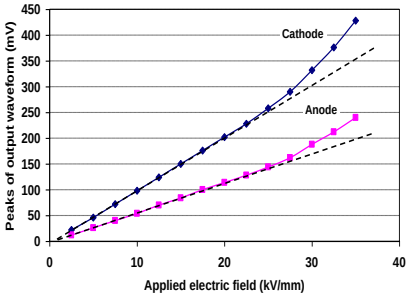
RESULTS

Threshold field for space charge generation

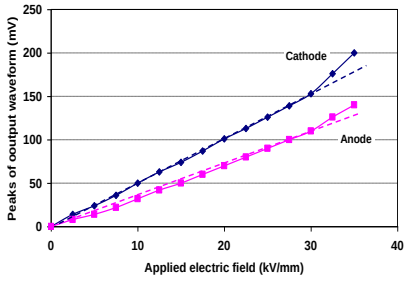
As the results shown in Fig. 3, there is a linear correlation between the induced surface charge on electrodes and relatively low external stressing field for samples with three different impurity concentrations, which obeys capacitor principle about the stored charge on electrodes as given by

$$\sigma = \varepsilon_0 \varepsilon_r E$$

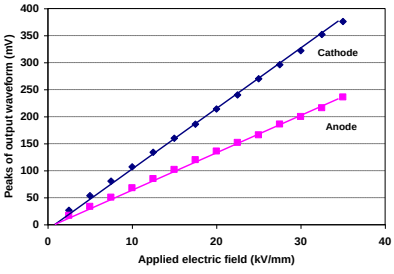
where σ is charge density on electrode, ε_0 permittivity of free space, ε_r the relative permittivity of the dielectric and E the electric field strength. The results indicate no space charge having been generated at the electric field below 25kV/mm for fresh sample and 30kV/mm for partially degassed sample, whilst for the entirely degassed sample, the linear segment is up to the value of 35kV/mm, the maximum field applied in the experiment. When the field is beyond the two values mentioned previously for fresh and partially degassed sample respectively, i. e 25kV/mm and 30kV/mm, the line presenting the relationship of electrode charge and the stressing field starts to bend up-toward as seen the solid line in Fig. 3 (a) and (b) deviating from linear tendency illustrated by the dotted line. This accelerated induced charge increment is attributed to heterocharge accumulation at this voltage ramping up process and it is predictable that the increase tendency line will bend down-towards if homocharge is being generated. These fast charge accumulations during voltage stepping up would also been observed in the following space charge distribution measurement.



(a) Fresh (undegassed) sample



(b) Partially degassed sample (0.5% residues)



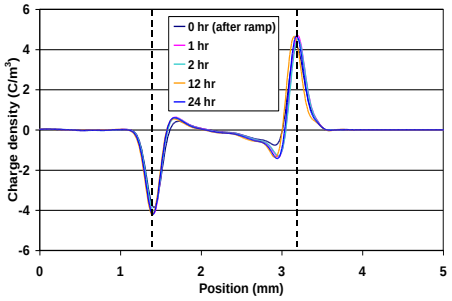
(c) Degassed sample

Fig 3. Relationship between the induced charges on electrode and the external voltage

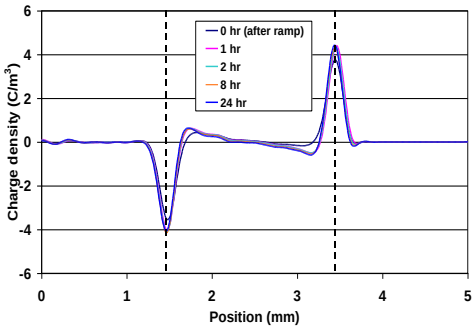
In order to get rid of the influence of stressing time on charge formation, the measurement at each field was quickly carried out within the time less than 30 seconds so that only the peak heights of the induced surface charges at the upper and the ground electrodes were read directly from the oscilloscope in units of voltage. Due to the attenuation of the acoustic signal across the sample, the reading of the upper electrode (away from the transducer) is lower than that from the ground electrode.

Space charge development

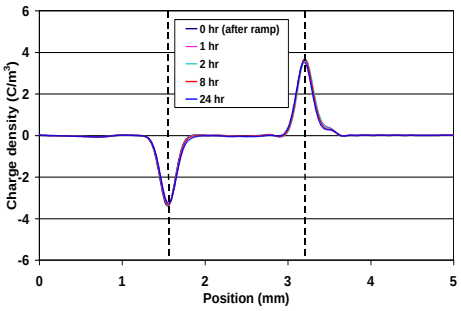
The space charge profile and the evolution of XLPE taken with external voltage application are shown in Fig. 4. Space charge in the fresh and partially degassed samples shows a very dynamic accumulation, which has led to a considerable amount of heterocharge during the voltage ramp test, as shown by profiles of 0 hr in Fig. 4 (a) and (b). It then quickly reaches equilibrium almost within the first hour in the following stressing process as further accumulation of charge from one hour to the end of 24-hour long experiment is hardly observed. The fresh sample shows a slightly higher charge density than the sample with 0.5% residue. For the fully degassed sample, it is hard to discern any charge formation over the stressing term from results in Fig. 4 (c).



(a) Undegassed sample



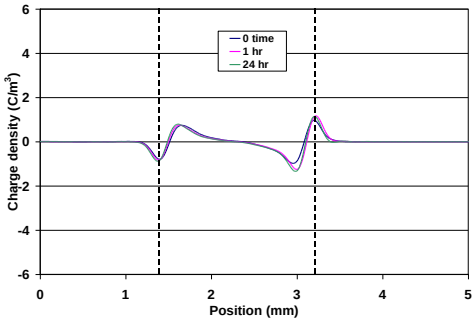
(b) Partially degassed sample (0.5% residue)



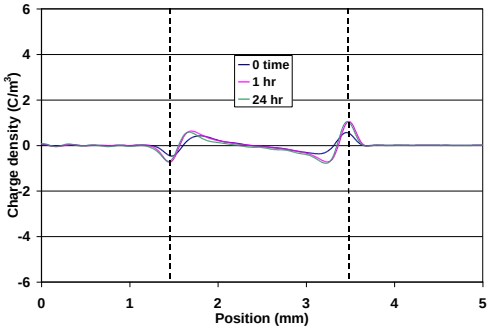
(c) Degassed sample

Fig. 4 Space charge development of XLPE

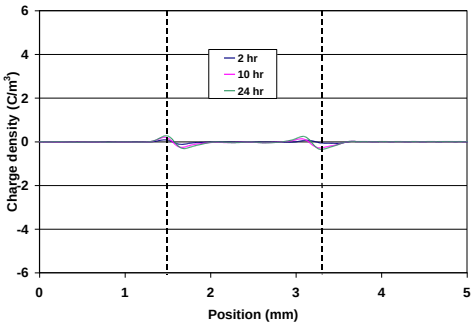
To check the homocharge presence that may be merged into the surface charge due to the external voltage application, the space charge measurement was also conducted with voltage removal at different time over the whole stressing period and the results are shown in Fig. 5. Apart from the show of heterocharge in sample with residues in (a) and (b), small homocharges are clearly revealed in Fig. 5 (c) both at anode and cathode but shows a slow and constant building up rate.



(a) Undegassed sample



(b) Partially degassed sample (0.5% residue)

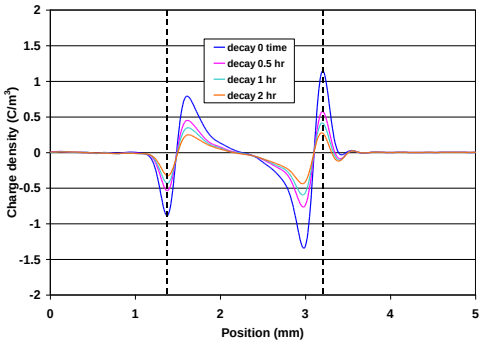


(c) Degassed sample

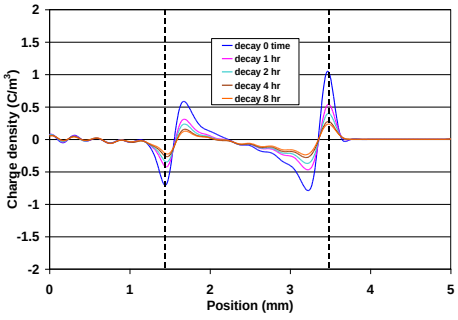
Fig. 5 Space charge profiles of XLPE measured at volts off

Space charge decay

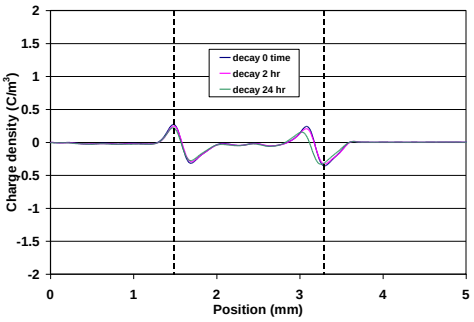
The space charge decay feature is displayed in Fig. 6. Both the fresh and the partially degassed sample exhibit a fairly high decay rate, as seen by the profiles in figures (a) and (b), whereas the homocharge generated in the degassed sample possesses a high stability after the external stressing voltage was removed.



(a) Undegassed sample



(b) Partially degassed sample (0.5% residue)

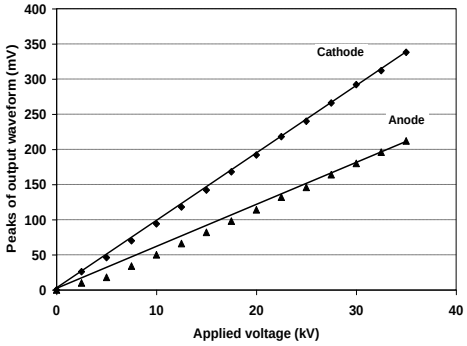


(c) Degassed sample

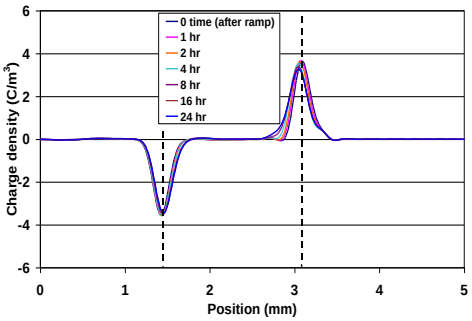
Fig. 6 Space charge decay of XLPE

Results of LDPE sample

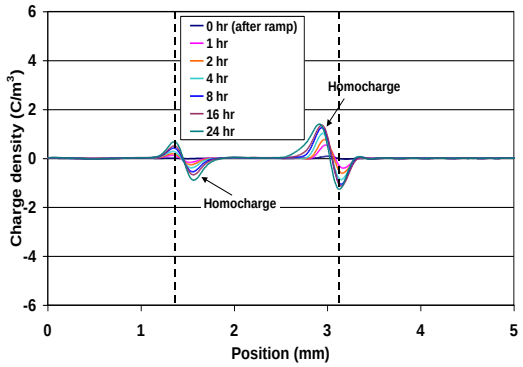
From the ramp test result shown in Fig. 7 (a), the linear relationship between the induced surface charge and the external voltage suggests no space charge appearing in the voltage increasing process. Within the following ageing period, homocharges gradually accumulated in at the vicinities of electrodes, as shown in Fig. 7 (b) and (c), latter one shows more clearly the presence of homocharge in the sample when the external voltage was removed. Like all the homocharges observed in the degassed XLPE sample, the homocharge in this LDPE sample also showed a very slow decay speed that is illustrated in Fig. 7 (d).



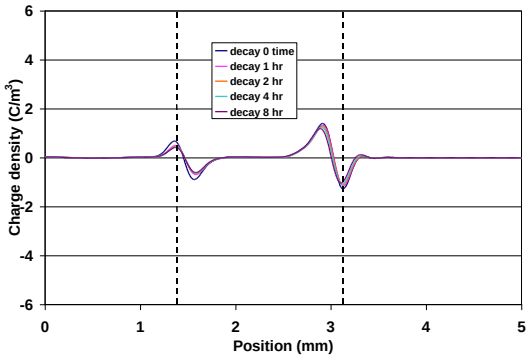
(a) Ramp test



(b) Space charge profile (volts on)



(c) Space charge profile (volts off)



(d) Space charge decay

Fig. 7 Space charge behaviour of LDPE sample

DISCUSSIONS

Threshold field for charge formation and charge polarity after long term stressing

The relationship between the induced surface charge and the external voltage in Fig. 3 (a) and (b) indicates that the undegassed and partially degassed XLPE samples are seemingly to have heterocharge accumulation during the voltage ramp process. This fact is clearly presented in the non-linear relationship between the induced surface charge and the stressing voltage (field). The threshold stress, above which space charge starts to generate, are 25 and 30kV/mm respectively for these two samples with residues, while for the degassed XLPE sample and LDPE no space charge was obviously observed in electric ramping field up to 35kV/mm.

It is evident that specimens with various thermal treatments (degassing) possess different space charge development speeds and final charge distributions. In specific, samples with and without residues may have space charge of opposite polarities in the volume of the material adjacent to the electrode. Table 1 summary above discussion regarding threshold stress for charge formation and charge polarity.

Table 1. Threshold stress (kV/mm) of space charge formation and charge polarity

	Un-degassed	0.5% residue	Degassed
XLPE	25 (hetero)	30 (hetero)	>35 (homo)
LDPE	>35 (hetero)		

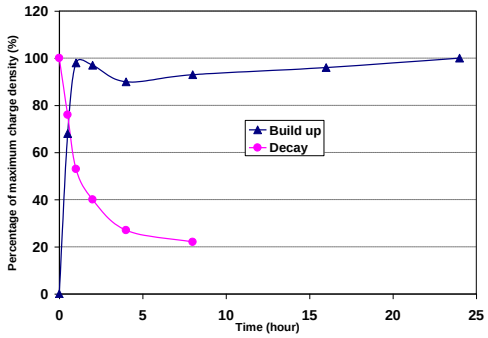
The results obtained so far indicate that the impurities within XLPE, no matter how high its content, are the main source of the heterocharge generation. In samples like pure LDPE or the degassed XLPE, it is very difficult to develop heterocharge under the electric stress applied in this research, except for the small homocharge accumulation in some samples. Moreover, the fact of the longer time requirement for the small homocharge to develop in the degassed sample or LDPE sample may suggest that homocharge formation is more difficult than heterocharge [3, 4]. The former case may need higher electric stress or longer time under the same electrode and dielectrics arrangement to develop same amount of space charge.

Space charge building up and decay speed

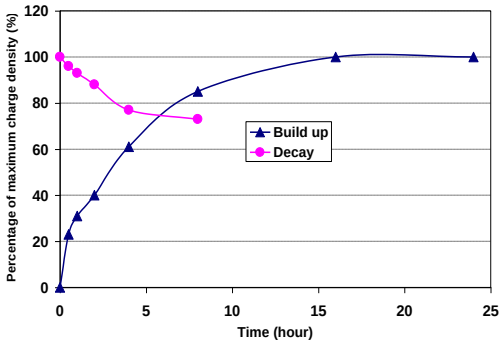
The time for the space charge to reach its saturation is a practicable method to describe the charge building up speed. Fig. 4, 5 and 7 (c) reveal that for the samples having residual impurities (normally developing heterocharges as discussed) show a faster charge accumulation in comparison with the degassed XLPE or LDPE sample where homocharges appears. In fresh sample and sample with 0.5% residues, the space charge reached its saturation distribution within 1 hour, whereas homocharge in degassed XLPE and LDPE held a continuous accumulating process.

By inspecting the space charge measurements of all modified XLPE samples, among which some of their results are not available for publication for the commerce confidential reasons, it is noticed that in most cases the space charge decay speed closely corresponds to its building up speed, the faster the space charge accumulates, the faster it decays, or vice versa. Typical results that lead to this conclusion are presented in Fig. 8 in which two XLPEs are regarded as typical fast charging and slow charging examples respectively.

Same rule could also be applied to space charge evolution and decay in LDPE sample. It is obvious that homocharge in the degassed XLPE and LDPE holds a much slower decaying rate than heterocharge in the sample with residues, as Fig. 9 shows.



(a) Fast charge build up and decay



(b) Slow charge build up and decay

Fig. 8 Space charge accumulation rate in accordance with decay rate

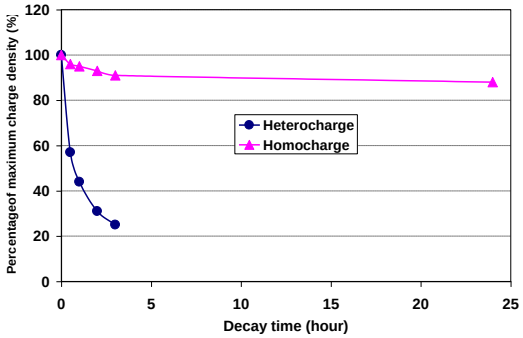


Fig. 9 Comparison of homo and hetero charge decay speed

CONCLUSIONS

Following conclusions may be obtained from this work.

Firstly, the PEA system introduced here is ideal for measuring space charge in thick plaque sample, which may be prepared in the manufacturing process of polymer cable.

Secondly, by-products of cross-linking or the residual impurities play a key role in the heterocharge accumulation in fresh XLPE, while when it is partially degassed to leave 0.5% of residue the space charge density was reduced. In the fully degassed sample a small homocharge was built up in the vicinity of the electrode. In the research quick charge accumulating speed has been observed amongst all the samples with residues, which leads to the heterocharge getting saturated within the first hour of stressing. However, the homocharge appeared in all degassed samples and LDPE as well showed a fairly slow formation speed. At this stage, space charge accumulation is governed by the charge injection through the electrode/insulator interface.

Finally, the space charge accumulation speed corresponds well with the decay speed. In other words, the faster the space charge accumulates, the quicker it decays. It is also found that homocharge in degassed material decays much more slowly than the heterocharge in the same undegassed material.

REFERENCES

1. M. Fu and G. Chen, "Space charge measurement in polymer insulated power cables using flat ground electrode PEA system", IEE Proc. –Sci. Meas. Technol. Vol. 150, No. 2, pp.89-96, 2003
2. Y. Li, M. Aihara, "Space Charge Measurement in Thick Dielectric Materials by Pulsed Electro-acoustic Method", Rev. Sci. Instrum, Vol. 66, pp.3909-3916, 1995
3. T. Tanaka, A. Greenwood, *Advanced power cable technology, Volume II*, CRC Press Inc., USA, 1983
4. B. Sanden, E. Ildstad and R. Hegergerg, "Space charge accumulation and conduction current in XLPE insulation", 7th Inter. Conf. on Dielectric Materials, Measurements and Applications, Bath, UK, 1996