Effect of Long-Time Electrical and Thermal Stresses upon the Endurance Capability of Cable Insulation Material

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Effect of long-time electrical and thermal stresses upon the endurance capability of cable insulation material

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ABSTRACT

This paper presents the results of endurance tests that have been carried out on cross-linked polyethylene (XLPE) cable peelings. The peelings were taken from cables that were manufactured from a single batch of XLPE and subjected to electrical (up to 28 kV/mm), thermal T = 363 K (90 °C) and electro-thermal stressing for at least 5000 hours. The endurance tests of the peelings (thickness 150 µm) were carried out at the same temperature of T = 363 K as the thermally stressed cable, but at two different ac electrical fields of 55 and 70 kV/mm. The resulting life data for the different sample sets are compared to one another and to that of peelings taken from unaged cables. Weibull analysis of the failures shows that only peelings from cables that had experienced a thermal stress component during their time of stressing as a cable, exhibited a statistically significant reduction in endurance capability. Possible reasons for this reduction of life are discussed.

Index Terms — **Thermal stress effect, XLPE, endurance testing, cable peelings, Weibull statistics.**

1 INTRODUCTION

THe replacement of oil-filled cable insulation by polymeric materials and the necessity to ensure equivalent performance and reliability has led to a large amount of research into ageing mechanisms during service and accelerated ageing [1]. Now that such insulating materials have been in service for several decades the opportunity exists to ascertain their current condition so that decisions can be taken regarding replacement. There is therefore a need for an understanding of the degradation process and an identification of diagnostic factors. The EU-sponsored ARTEMIS programme [2] was an attempt to resolve these problems involving the collaboration of a number of research institutes. A feature of this programme was that 90 kV cross-linked- polyethylene (XLPE) cables were manufactured by two different companies using exactly the same batch of XLPE. Samples from the cables were placed under electrical, thermal, and electro-thermal stress for varying lengths of time, up to about two years, after which their insulation was peeled. The peeling was then subjected to a number of diagnostic measurements designed to characterize the state of the insulating material in comparison to its state in an unstressed (i.e. unaged) cable. An analysis of the results did not show significant differences in the properties that were examined. The ARTEMIS project demonstrated a very low rate of degradation of the cable materials in spite of the use of very high electric stress levels at elevated temperatures. Nevertheless, it did provide a definite indication of the techniques that should be used to evaluate the state of the insulation, one of which is its endurance capability. This is reported here.

Endurance life data of unstressed peelings for electric fields varying from 30 to 80 kV/mm (rms) and two temperatures 293 (20^{o}C) and 363 K (90^{o}C) was generated as part of the ARTEMIS programme [3]. This data demonstrates that the endurance life of the peelings from an unstressed cable is lower at the higher temperature in comparison to the lower one. Moreover, this difference is greater at lower electric fields compared to the higher ones where the difference is insignificant. In this work we investigate whether or not XLPE insulation peelings from cable sections with different electro-thermal histories show a statistically significant change in endurance life compared to those taken from unstressed cable. In other words we determine whether or not the electro-thermal stressing that the XLPE material experienced as a cable has altered its inherent endurance capability and whether or not this change is reflected in its peelings.

2 EXPERIMENTAL

2.1 TEST PROTOCOL

The endurance tests, reported here, were conducted under two different conditions **A** and **B** as is shown in **Table 1**. The endurance test under the condition **A** was carried out more than once, and the number of the relevant sample set is denoted by the subscript. Part of this data is also reported by [3]. The alphabetical order of the endurance tests also corresponds to the order in which the tests were carried out. The first test, **A**, was carried out with an AC electric field of 70 kV/mm (rms) and a temperature of 363 K. The second test, **B**, was conducted at the same temperature but with a lower electric field of 55 kV/mm (rms). The materials that were used in each test are listed in Table 2 along with their stressing pre-histories as a cable during the ARTEMIS programme.

The statistical analysis is carried out using extreme value Weibull statistics according to the IEEE P930 standard guide [4]. The expression for the cumulative density function for the two-parameter Weibull distribution is:

$$F(t;\alpha,\beta) = 1 - \exp\left\{-\left(\frac{t}{\alpha}\right)^{\beta}\right\} \qquad (1)$$

where:

t is the measured variable, usually time to break down or the breakdown voltage,

$F(t)$ is the probability of failure at a voltage or time less than or equal to t,

α is the scale parameter defining a characteristic value of the measured variable t and is positive, and

β is the shape parameter and is a positive number.

Table 2. Materials used for the endurance tests defined in Table **1** and their pre-history as a cable.

Ref. name	Endurance test	Pre-history of the material as a cable		
		AC stress (kV/mm)	Temp. (K)	Time (h)
US_a	A_2	-	293	-
US_b	A_2, B	-	293	-
E_S1a	A_2	19.5	293	5000
E_S2a	A_4, B	19.5	293	7747
E_S1b	A_4,	19.5	293	5581
E_S2b	A_2	12.5	293	5000
_TS1a	$A_{1,3}$	0	363	5000
_TS2a	A_3, B	0	363	10000
ETS1a	A_1	19.5	363	5000
ETS2a	$A_{1,3}$, B	28	363	6000
ETS2a	A_4	25	363	6000
ETS3a	A_2	28	363	3000
ETS4a	A_1	12.5	363	5000
SA	B	SERVICE	SERVICE	>18 YEARS

Table 1. Endurance test conditions.

Endurance Test	E-Field AC (kV/mm)$_{rms}$	Temperature (^{o}K)
$A_{1, 2, 3 \& 4}$	70	363
B	55	363

The following equations are used to obtain the bounds of the 90 % confidence intervals for the p^{th} percentile [4]:

$$\begin{aligned} t_l(p) &= \alpha \exp\{Z_l(p)/\beta\} \\ t_u(p) &= \alpha \exp\{Z_u(p)/\beta\} \end{aligned} \qquad (2)$$

Where:

t_l (p) and t_u (p) are the lower and upper bounds of the confidence interval for the p^{th} percentile.

Confidence interval tables have been calculated in [4] and have been used in this study to estimate the 90% confidence limits according to the number of specimens used and failed/suspended for each test. In this study four specimens were used for each material (n=4) and the test was terminated once three of them failed (r=3). The values for the factors $Z_l(p)$ and $Z_u(p)$ were extracted from the confidence interval figures in [4] for the percentiles p=0.1 %, 1.0 %, 5.0 %, 10 %, 30 %, and 95 % and the bounds of α (63.2%) are also included for n = 4 and r = 3 as presented in Table 3.

Table 3: Factors $Z_l(p)$ and $Z_u(p)$ extracted from [4] in order to calculate the confidence limits for n=4 and r=3.

Percentile p	$Z_l(p)$	$Z_u(p)$
0.1 %	**-15.1**	**-2.3**
1 %	**-9.9**	**-1.1**
5 %	**-6.4**	**-0.65**
10 %	**-4.84**	**-0.415**
30 %	**-2.431**	**0.08**
63.21 % (α)	**-1.17**	**0.99**
95 %	**-0.55**	**2.98**

Such confidence limits enclose any particular percentile of the true population with 90 % probability. The greater the number of specimens tested, the closer the upper and lower curves. Confidence intervals are also calculated for the shape parameter β, using the following equation:

$$\begin{aligned} \beta_l &= W_l \beta \\ \beta_u &= W_u \beta \end{aligned} \qquad (3)$$

Where:

β_l and β_u are the lower and upper limits, respectively for the interval.

The factors W_l and W_u for $n = 4$ and $r = 3$ are obtained from [4] and are *0.456* and *4.67* respectively.

2.2 MATERIALS

All the materials used for the endurance tests were peelings of XLPE insulation with a thickness of 150 μm but different stressing pre-histories as a cable, see **Figure 1**. The insulation for the cables was manufactured by two different companies, which can be distinguished by the small case letters, “a” and “b” in the reference name column in Table 2. The rest of the reference name of the materials under study is constructed according to acronyms of the stress that they experienced as a cable, i.e. US stands for Un-Stressed, ETS for Electro-Thermally-Stressed and so on. Peelings from a service aged, SA, cable are also used for comparison. The same batch of XLPE was supplied to the cable manufacturers, thus the inherent differences between the insulation peelings, if any, come from the cable manufacturer’s processes and the electro-thermal stressing that they experienced as cables.

The peelings were thermally conditioned prior to the endurance testing. The conditioning occurred at 323 K at ambient pressure for 48 hours. The conditioning of the tapes was a feature of the ARTEMIS programme [2] to remove volatile by-products to ensure reproducible results [5].

2.3 SAMPLE HANDLING

In the ARTEMIS programme, one material supplier provided two cable manufactures with the same batch of XLPE resin in order to make model cables for Extra High-Voltage (EHV) with an insulation thickness of 14 mm corresponding to a 90 kV cable construction, as shown in **Figure 1**a. After these cables had been electro-thermally stressed, the insulation was peeled (peeling thickness of 150 μm) with a specially designed cryotome. The peelings were rolled into tapes with a width of 8cm as is shown in **Figure 1**b and were distributed to the rest of the ARTEMIS partners inside polyethylene-bags completely enclosed within aluminium bags, for investigation [3]. From then onwards the tapes were stored at a temperature around 278 K in order to prevent any further changes. The properties of the peelings were then investigated using samples taken from between 2 mm to 4 mm (or as close as possible to those margins) from the inner semiconductive screen. **Figure 2** shows the sequence in time that each process took place in a rough scale.

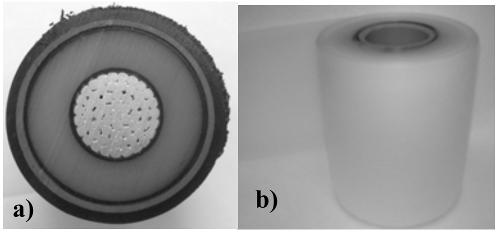

Figure 1. a) Section of the cable after any kind of stressing during the ARTEMIS programme and b) a tape roll after the insulation was peeled.

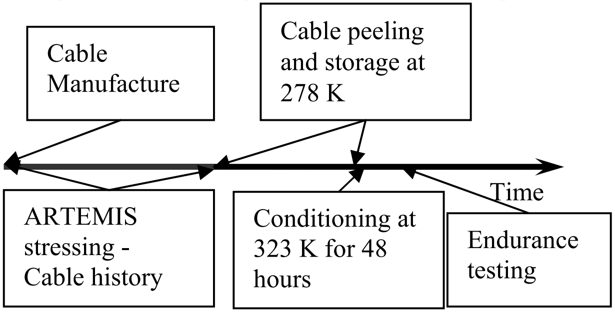

Figure 2. Time line of material used.

Before carrying out any experiments the samples were conditioned [4] (see Figure 2) so as to remove any volatile chemicals that are known to influence the behaviour of XLPE in an undefined manner [2].

After the conditioning process the samples used for the endurances tests **A** and **B** were placed between the electrodes and immersed in silicone oil as shown in **Figure 3**. The tray could accommodate up to four specimens of three different materials each, which means up to twelve specimens. In order to avoid air bubbles being trapped between the specimen and the electrode interfaces the whole tray was placed under vacuum till no air bubbles were observed and then was moved to the HV rig. The temperature was controlled via a Eurotherm controller at 363 K. The specimens were not removed from the HV rig till three out of four samples failed for each material.

The time to breakdown was recorded by a high voltage circuit breaker with an accuracy of 1/100 of an hour. Once a specimen failed the power was cut off for all the specimens. The specimen was identified using a Mega-ohm meter, and then isolated from the high voltage rig, so that the power could be switched back on by carefully ramping the voltage up to the desired value. This means that the failed specimen remained in the tray shown in **Figure 3** till three specimens of all the materials have failed, as removing would disturb the remaining on-going specimens.

2.4 ELECTRODE DESIGN

The HV electrodes were brass of a cylindrical shape with a radius of 2.5 cm, height of 3.0 cm and with rounded edges to minimize corona discharges. The bottom electrode was an aluminium plate with a thickness of 5mm, where up to four HV electrodes can be placed. A good contact was ensured by placing a Perspex glass plate with thickness of 5mm above the brass electrodes and screwing the plate onto the electrodes, thereby pressing them onto the XLPE samples, see **Figure 3**.

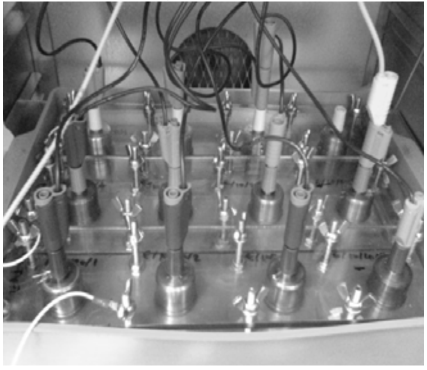

Figure 3. HV electrode set up at the start of an endurance test.

3 RESULTS

3.1 HIGH ELECTRICAL AND THERMAL STRESS: ENDURANCE TEST A

The results of the endurance test, which was carried out at an electric field of 70 kV/mm (rms) and a temperature of 363 K, are shown in Figure 4. The estimated Weibull distribution for the samples with the most severe electro-thermal pre-history **ETS2a** is shown by the solid continuous line, together with its associated 90% confidence limits (dashed lines). The data of the **ETS2a** is represented in Figure 4 by filled triangles. In Figure 4, the filled solid symbols represent the materials that have been stressed as a cable for around 5000 h at 363 K and the unfilled ones represent the materials that have experienced no thermal stressing i.e. T = 293 K. It is observed that all the filled symbols lie within the 90% confidence limits of the most severely stressed material. However, the first failure of the 3000 hour electro-thermally pre-stressed material **ETS3a**, represented with the “✖” symbol does lie within the limits although the other two lie outside. The endurance life of all the materials that experienced no stress or just electrical stress as a cable lie outside the 90% confidence limits, except for the first failure of the electrically pre-stressed material, **E_S2a**. Thus, the thermal stressing that the peelings had experienced as a cable seems to be the dominating process causing a reduction in their endurance life. The electric field levels that were applied to the XLPE cable insulation as a cable in the ARTEMIS programme seem to have no significant effect. The data from the samples with 3000 h of electro-thermal pre-history of stressing (**ETS3b**) indicates that this amount of time was insufficient to affect the material.

In general terms, the failures in Figure 4 can be separated into two groups with very similar statistical properties, one group with the filled symbols and another group with the hollow ones. The group with the filled solid symbols, indicated by the continuous-line circle, contains failures of samples that have been stressed at least thermally (363 K) as a cable more than 5000 h. The group with the unfilled symbols, grouped by the dashed circle, contains failures of samples that have experienced no stress or just electrical stress as a cable. The endurance lives of the samples from electro-thermally stressed cables are compared those from unstressed cables in Figure 5. This shows that the electro-thermal cable stressing has significantly reduced the ability of the insulation material to withstand electrical stress, resulting in a shift of the main part of the failure distribution to shorter lifetimes. The two data sets presented in Figure 5 are collations of life data from peelings from different cable/tape all of which had either experienced electro-thermal stress of varying magnitude or zero stress. The failures of the electro-thermally pre-stressed materials that are represented with the filled triangle in Figure 4 are used in conjunction with other endurance data from replicate tests on electro-thermally pre-stressed samples to form the failures of the electro-thermal data set. The suspended samples of each material set are censored. Both sets of materials have very similar shape parameter values,

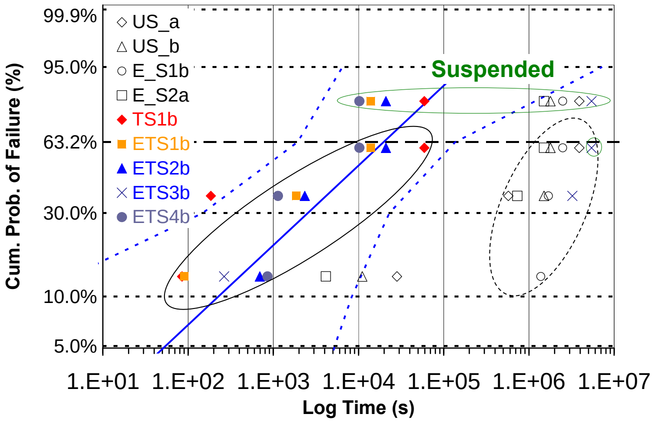

Figure 4. Weibull plot of the times to failure of the peelings with different electro-thermal histories as a cable, including data that was obtained during endurance tests A1 & A2.

denoted on the figure as ***β***, but clearly very different characteristic values ***α***. This plot implies that the electro-thermal stressing carried out during the ARTEMIS programme did in fact alter the endurance capability of the materials with respect to the unstressed ones.

The characteristic values, *α*, in conjunction with the corresponding 90% confidence limits of each material set that participated under the endurance test A are plotted in **Figure 6**. On the left hand-side of the black vertical line in **Figure 6** the characteristic values are for materials with either unstressed or solely electrical stress histories as a cable and have very similar characteristic values. Materials with thermal and electro-thermal histories are shown on the right hand side of the black line and can be seen to have characteristic values that generally are less than those to the left. There are two sets of material characteristic encircled in black whose values are similar to the unstressed ones, and are therefore exceptions to the general trend. There are also materials with narrow confidence limits. These indicate that the failure generating feature possesses only a small sample-to-sample variation in these sample sets. One such set (ETS3b) has a short lifetime which suggests that it contains many severe defects of the same type, whereas the other is an exception to the general trend and hence has hardly any failure generating features.

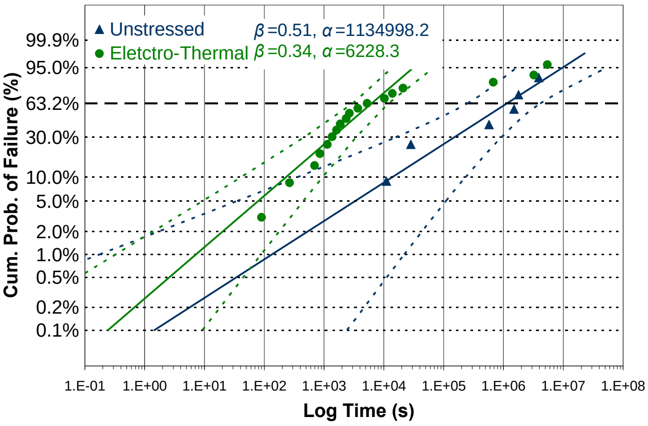

Figure 5. Comparison of the electro-thermally pre-stressed and unstressed (US) material failures that occurred during endurance test A. The 90% confidence limits of the Electro-Thermal data are estimated using only those failures enclosed by the 90% confidence limits.

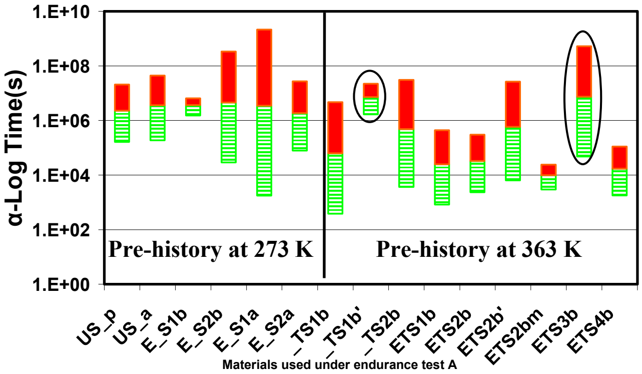

Figure 6. 90% confidence limits for the scale parameter α. The horizontal line is the estimated value of α and is the separation point between the striped and the solid boxes.

3.2 LOW ELECTRICAL AND HIGH THERMAL STRESS: ENDURANCE TEST B

This test uses an ac field of 55 kV/mm (rms) and a temperature of 363 K, and involves five sets of peelings with very distinct cable pre-histories in the ARTEMIS programme. These are peelings from: an unstressed, US_b, an electrically, E_S2a, an electro-thermally, ETS2a, and a service stressed, SA cable. The failures of these materials are presented in Figure 7b. Eight failures have occurred by $1.8\text{x}10^7$sec, but only seven are presented in Figure 7b. The first failure of the service aged material was eliminated because it occurred immediately after switching on the voltage. The only material that had not failed by $1.8\text{x}10^7$sec is the unstressed material. On the other hand two out of four specimens of the thermally stressed material as well as the electro-thermally and service stressed ones have failed. Regardless of the different electrical stresses that these three materials may have experience as a cable they all have experienced thermal stress at 363 K for samples from the ARTEMIS programme and 343 K or more for the service stressed material. Thus the effect of the stressing pre-history of the materials upon the endurance life follows the same trend as that found in endurance test **A** at high field and temperature,

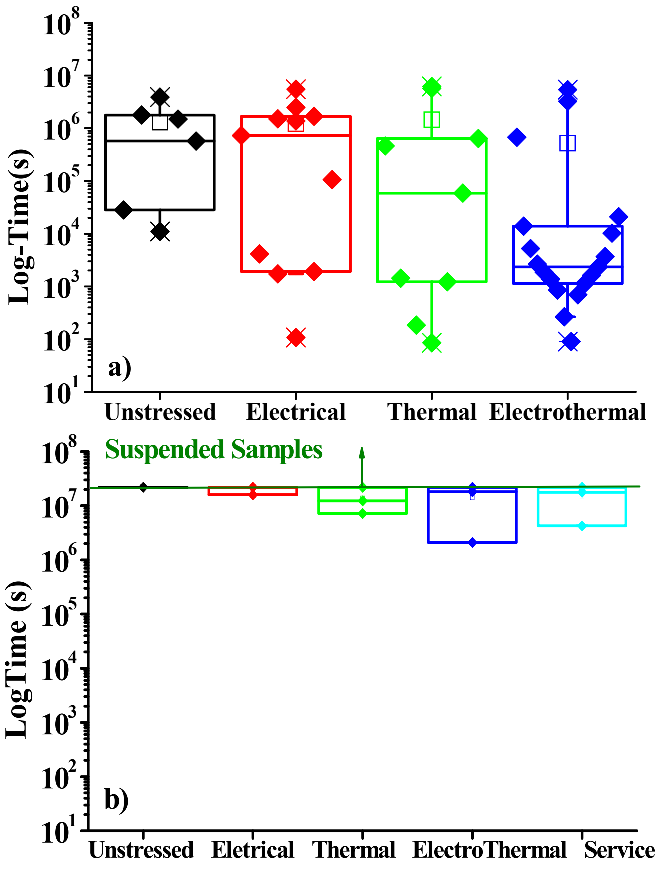

Figure 7. Box and whisker presentation of all the failures that occurred a) at 363 K and 70 kV/mm (rms) b) at 363 K and 55 kV/mm (rms) of groups of

materials not necessary from the same cable but having experienced the same type of cable stress.

where the materials with a thermal and electro-thermal stressing pre-history fail sooner than the others as is shown by the box and whiskers representation, given in Figure 7. The box is determined by the 25th and 75th percentiles. The whiskers are determined by the 5th and 95th percentiles.

4 DISCUSSION

The endurance tests, A and B, at high electrical fields (70 kV/mm and 55 kV/mm) and high temperature (363 K) showed that the pre-stressing history of the peelings as a cable did reduce the inherent endurance capability of the material especially when the pre-stressing was either just thermal or combination of electrical and thermal. These findings also agree with the endurance test data reported previously in [3]. Peelings with only an electrical pre-history did not demonstrate a significant decrease in the inherent endurance capability under these endurance tests. According to Figure 7 the influence of the pre-histories on the inherent endurance capability could be ranked from the least severe to the most severe one as follows:

0. no stress
1. electrical stress
2. thermal stress
3. electro-thermal/service stress

The ranking suggests that electrical and thermal stress on their own seem to degrade the XLPE insulation less than both combined together. This suggestion also comes into an agreement with the thermodynamic based life models where the electrical field acts as an accelerator of the ageing process [6, 7]. The influence of the pre-stressing histories on the cable peelings has also been detected by space charge measurements during the ARTEMIS programme [2, 8, 9] and after the ARTEMIS programme [10-13]. Quantities that were extracted from space charge measurements on the pre-stressed cable peelings, such as dc injection voltage threshold, charge mobility and trap depth distribution were able to detect intrinsic degradation. Furthermore, the endurance data presented in this paper has identified the consequence of such changes. The statistical difference of the endurance test data can only be assigned to the intrinsic changes that occurred in the materials during cable stressing as the base resin that was used to manufacture the cables as well as the manufacturing and peeling process was identical in all cases.

The reasons that lead a dielectric insulation to age and ultimately fail are multiple as Dissado and Fothergill [1] have discussed. The theoretical models by Crine [14], Dissado et al [15], Mazzanti el al [7, 16], Paloniemi [17], Wu and Dissado [18] and Lewis et al [6], show that the attempt to describe it is very complex. These models approach a scientific explanation from different points of view; electrical, chemical, mechanical, electromechanical, etc, by the choice of the dominant mechanism that leads to failure. Nonetheless they all present a good fit to experimental data [7, 14, 19] and they all share a common characteristic; they are all dependent on temperature variations as well as the history of the polymeric materials that they attempt to describe. The dependence of the state of the polymeric materials on thermal exposure is an intrinsic phenomenon.

Much research [1] has been carried out in order to understand and evaluate the effect of temperature [20-22], on the material properties, such as crystallinity, conductivity, ability to accumulate and transport space charge [23, 24]. For example, Vaughan et al [25] found that the conductivity of the electrical trees that he studied changed when the temperature at which they were grown increased from 293 to 303 K under the same field conditions. The material properties of polyethylene and especially cross-linked polyethylene insulation may be strongly dependent on temperature for a number of reasons. Heating will lead to morphological changes such as modification of lamella thickness and interfaces. By-products from the cross-linking will move more easily within and out from the insulating layer and so any beneficial effects that they may have will be reduced. It should be noted that the conditioning applied to the cable peelings eliminates any potential effect of test temperature on this mechanism. Additives such as the antioxidant [26] can be consumed under continuous high thermal stress [24,27]. Therefore such additives may have lost their effectiveness during the period of cable stressing possibly allowing some regions of the cable insulation to become oxidised and/or chemically degraded. A spectroscopic analysis of cable cross-sections has also shown that acrylates migrate from the semiconductor screens into the insulation with a migration rate and penetration depth that increases as the temperature increases [28]. Such migrating chemical species may locally alter the electrical properties of the insulating material. Each or all of these features in combination could have contributed to the reduction of the insulation life of the peelings from cables samples that had experienced a thermal stress component.

It is certain that electrical and thermal stress do influence the life time of polymeric insulation. Here it has been shown that under endurance testing conditions, polymeric materials that are exposed to thermal and electro-thermal pre-stressing are more susceptible to failure than those pre-stressed under electrical stress only. The endurance tests conducted at an electrical stress of 70 kV/mm (rms) caused failure, but there was no discernible evidence for lifetime differences due to the different pre-stressing electrical fields in the range up to 28 kV/mm (rms). Furthermore the pre-stressing at 363 K caused a reduction in endurance capability but pre-stressing at 293 K and 19.5 kV/mm showed no evidence for such a reduction. These findings raise two questions:

- Is there a threshold electrical stress for ageing?
- Is there a threshold thermal stress for ageing?

and suggest that the answer is yes to both but further work is required in order to identify an accurate threshold for ageing.

5 CONCLUSIONS

This paper has reported on the effect of long-time electrical and thermal cable stresses upon the endurance capability of XLPE. This was investigated by subjecting a number of cable peelings with different stressing pre-histories to two endurance test conditions. The endurance tests were carried out at an ac electric field of 70 and 55 kV/mm (rms) both at 363 K. The endurance data acquired was analyzed by Weibull statistics and suggests that the cable stressing during the ARTEMIS programme did degrade the insulation matrix as the inherent endurance capability of the peeling has been reduced. Different stressing pre-histories showed variations in the failure times. These are:

- for the first 5000 h of electrical and electro-thermal stressing only cables that experienced a thermal component (363 K) showed evidence of significant ageing as expressed through a reduction in endurance life at 70 kV/mm and 363 K;
- for the same period of cable stressing there was no significant difference in endurance between samples from cables with different applied electrical fields, in the range from zero up to the maximum of 28 kV/mm. This was found to be the case for both cables stressed at 293 and 363 K.

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