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ABSTRACT

The paper reports on an investigation of the fatigue failure of tree retardant cross-linked polyethylene (TR-XLPE) that is relevant to water tree development in underground cable insulation. Finite element calculations were used to estimate the stresses developed in cable insulation by di-electrophoretic forces; these stresses are in the low megaPascal range around inclusions (or water tree branches) that are long and thin. They are insufficient to bring about instantaneous failure of the insulation. However, these stresses might be sufficient to cause cyclic fatigue failure of the insulation, and, accordingly, fatigue measurements were carried out on samples from a commercial cable. The resulting fatigue failures, that occurred at cycle numbers achievable in practical work, suggest that fatigue might be an explanation for slow development of water trees over years of service in the ground. Cycle numbers at failure were found to be lower at higher mechanical stresses, at higher temperatures and in the presence of water.

Index Terms - Water tree, TR-XLPE, fatigue, polyethylene

1 INTRODUCTION AND PREVIOUS INVESTIGATIONS

THE literature on water trees is vast and no attempt will be made to review it here. However, even a cursory inspection indicates two main schools of thought about the formation and growth of water trees. One school suggests that water trees arise from mechanical phenomena, notably various mechanical stresses that arise in the cable, and that these stresses are capable of propagating a water tree once it is nucleated (e.g., at a defect in the insulation). Exemplary of this first school is the work of Yoshimura et al [1]. They found, in laboratory experiments, that the rate of growth of water trees in insulation subjected to an AC field was increased by increasing the frequency of the AC and argued that this was due to the insulation being mechanically stressed on each cycle. The other school of thought holds that the development of water trees is a largely chemical phenomenon with mechanical stresses insufficient, alone, to cause water tree formation and propagation. The insulation, being exposed to water and dissolved species within the ground or damp conduits, is chemically attacked within the water trees which are thereby extended. Exemplary of this second school is the work of Zeller [2, 3]. He examined the various mechanical and electromechanical phenomena suggested for water-tree development and concluded that none provided a satisfactory explanation of the experimental data. In particular he concluded that the field necessary to produce mechanical stresses leading to failure of polyethylene insulation (of the order of 8-18MPa for TR-XLPE – see below) is not reached before the field exceeds that necessary to generate an electrical tree. Zeller went on to study the thermodynamics of water treeing and concluded that the strong electric field within the insulation could raise chemical potentials, thereby promoting chemical reaction, which breaks bonds, weakens the material, and results in mechanical failure.

One possibility that appears to have been neglected so far is the cyclic fatigue failure of the insulation. Typically materials fail in fatigue at stresses much less than those necessary for failure in a simple monotonic loading test. Polymeric materials are no exception [4]. Furthermore, fatigue is invariably affected by the environment to which the material is exposed; for example, Weaver and Beatty [5] report that the number of fatigue cycles to failure of polystyrene diminishes with increasing temperature.

2 MODELING OF FIELDS AND STRESSES IN PE INSULATION

One type of stress that will certainly occur in all cable that is in service is the stress that arises from dielectrophoretic forces. These forces, acting on any material that has a permittivity different from vacuum, are given by:

$$F = (\varepsilon_0 / 2) \nabla (\varepsilon_r - 1) E^2 \tag{1}$$

where \mathcal{E}_0 is the permittivity of vacuum, \mathcal{E}_r is the relative permittivity of the dielectric and E is the electric field.

This body force, F, acting everywhere on the dielectric (and its surroundings), is readily calculated throughout the material in question from the properties and electric field. The electric field is obtained by a solution (analytical or numerical) of the equation giving the electric potential within the dielectric; the electric field is then simply the gradient of the potential:

$$\nabla \cdot \mathcal{E}_r \mathcal{E}_0 \nabla \phi = 0 \tag{2}$$

where ϕ is the potential.

Once the dielectric force distribution is known, the mechanical stresses within the body are given by the equation of mechanical equilibrium:

$$\sigma_{ji,j} + F_j = 0 \tag{3}$$

where $\sigma_{ji,j}$ is the divergence of stress tensor σ_{ji} , (the indices indicating each of the three orthogonal co-ordinates) and F_{ji} is the body force per unit volume.

Figure 1 below shows a cut-away view of PE cable insulation with a small region of the PE where the above analysis was carried out.

The present investigation was intended to address the question of whether fatigue is a plausible mechanism for water tree growth in tree retardant polyethylene (TR-XLPE). First an estimate was made, using finite-element analysis, of the electro-mechanical stresses that can arise in the insulation. Then the mechanical behavior of polyethylene (PE) was examined experimentally, including measurements of the cycle life of TR-XLPE samples taken from commercial cable, as a function of stresses in the range estimated from the FE calculations. The investigation also entailed preliminary experiments on the effect of water and two chemical species on fatigue life of TR-XLPE.



Figure 1. Region of the PE being modeled. A small spheroid with different electrical properties is introduced.

A small region was selected so that an even smaller defect, with different properties than the surrounding PE could be examined; in this case a spheroidal defect was chosen. A defect could be a tiny water-filled void or a region of PE that is occupied with water-filled microcracks and microcavities sufficient to change its properties, e.g., water trees. Figure 2 below shows the computed potential and electric field in and around a prolate spheroid with an aspect ratio of 2.5. Because of axial symmetry, only one half of the computed results are presented in the figure. The average electric field in the PE is set to 2 megavolts/meter. As the calculations are quasi-steady ones, this field may be the peak or rms field with equal validity. As seen in the figure, the spheroid substantially distorts the potential (indicated by the color and the contour lines). This is because the relative permittivity in the spheroid is set to 5 compared to 2.3 in the PE as argued by Koo et al [6]. These and other computed results were obtained using the finite element software COMSOL Multiphysics. Analytical and approximate equations are also available for the potential and field distribution in this geometry (e.g., Boggs [7]) Here a numerical analysis of mechanical stress distribution is conducted based on the same FEM model by coupling between the electric field and stress.



Figure 2. Computed potential and electric field in and around a spheroidal defect. The aspect ratio of the spheroid is 2.5. The conductivity and relative permittivity within the spheroid are respectively 5×10^{-2} S/m and 5 while outside they are 1×10^{-15} S/m and 2.3. The background electric field is set to be 2 megavolts/meter oriented from bottom to top of the figure.

The computed electric field (red arrows) in Figure 2 shows a low and fairly uniform value and orientation (upwards in the figure) until the spheroid is approached. As it distorts the potential distribution, the spheroid also distorts and enhances the electric field, particularly in the vicinity of the poles of the spheroid where the field becomes huge and bent from an axial direction. Note that there is negligible phase shift in the electrical variables at 60 Hz, so the electrical field peaks coincide with peaks in the applied voltage.

In Figure 3, the calculated mechanical stress distribution caused by the dielectrophoretic forces is presented. These stresses reach a maximum at the poles of the spheroid. For the geometry presented and applied electric field, the stresses are a little more than 3.6 kiloPascals. As will be seen below, such stresses are small compared to those necessary to inflict immediate damage on the PE. However, these stresses increase as the aspect ratio (height to diameter ratio) of the spheroid increases. Figure 4 illustrates this increase together with the electric field and it is seen that, when the defect becomes long and thin, stresses of a few megaPascals at the ends of the defect can result. These COMSOL calculations of the electric field were compared with the approximate analytical solution of Boggs [7]. They were found to be in close agreement up to a height to diameter ratio of 25. In this figure the results of



Figure 3. Stress distribution due to dielectrophoretic forces acting on the PE. Amplification of stress is greatest at the poles of the spheroid.



Figure 4. Increase in stress and electric field at poles of a prolate spheroidal defect as ratio of height to diameter increases. Though the combination of dielectrophoretic and coulombic stresses at the most extreme aspect ratio studied are likely unrealistic, as the field required to generate these stresses exceeds the dielectric strength of the material, stresses on the order of a few megaPascals are possible before breakdown occurs.

calculations where a second stress ("coulombic stress") arises have also been included; this stress results from the development of a surface charge at the interface between the PE matrix material and the spheroid ("void"). A theoretical analysis of the space charge accumulation has been conducted by McAllister et al [8]. Based on their analysis, the surface charge establishment in the water tree is frequency dependent for AC conditions. Significant decreases in total charge density in insulation with increases in frequency have also been observed [9], so a correct value probably lies between the red (purely dielectrophoretic stress) and blue (dielectrophoretic and coulombic stresses) curves.

The point to recognize from the model calculations is that stresses of a few megaPascals should occur within the PE at the ends of long, thin defects. It remains to be determined whether stresses of this magnitude can damage the PE.

3 THE MECHANICAL BEHAVIOR OF PE

The mechanical properties of various samples of PE insulation were studied using a servo-hydraulic mechanical testing apparatus (Instron mechanical test system Model 1350). Compression samples were placed between two flat platens and loaded at a displacement rate of 6.858 µm/s. Loading and unloading tests were run by controlling the displacement of the loading platens while recording the load and displacement. Strain was measured by calculating the ratio of elongation or compression to original sample length, with the assumption that all displacement of the platens was accommodated by deformation of the PE. The inelastic behavior of TR-XLPE can be seen in Figure 5 where samples have been unloaded once the strain reaches a predetermined level (0.02, 0.04, and 0.06). The upper curve of each loop shows behavior during loading (platens increasingly squeezing the sample) and the lower curve the behavior during unloading (platens moved apart). The samples are deformed permanently. For example, if the sample is unloaded at a strain of 0.04 (about 7 MPa), it is approximately 1% shorter after test than before.

This inelastic behavior of the PE was found in both used and new samples of PE as shown in Figure 6 (dates indicate year of manufacture); it starts at around 3 or 4 MPa. The results of this compression testing suggest that the PE ought to withstand the dielectrophoretic stresses (a few MPa) that should be encountered in service, albeit with some deformation resulting from the stresses. However, the inelastic behavior suggests a different mechanism for mechanical failure, namely fatigue. Fatigue can occur when stresses are applied, then relieved, repeatedly, either in compression or in tension. A related example is found in the paper by Pruitt and co-workers [10] on fatigue failure of ultra-high density polyethylene. These workers studied crack propagation in far-field compression at up to 2.5 million cycles. Fatigue testing was carried out on TR-XLPE samples from a new cable sample provided by a commercial manufacturer. The fatigue testing had to be carried out under conditions different from those anticipated in service:

- 1. Testing was carried out at 5 Hz, rather than the 120 Hz of the dielectrophoretic stresses because the displacements required to achieve the stress amplitudes of interest in TR-XLPE cannot be applied at 120 Hz by any mechanical testing apparatus.
- 2. Testing was performed in tension as the compliance of TR-XLPE allowed the sample to flex in bending without significant stresses being developed. Rigidly fixing both ends of the sample to the machine allowed for high stress to develop without the sample bouncing in the machine. Reid et al [11] investigated the fatigue mechanism in compression and stated that fatigue crack growth in compression results from

residual tensile stresses that arise near a stress concentrator, such as a notch or void. Crack growth in such a situation occurs on the unloading portion of each cycle, in contrast to tensile fatigue where crack growth occurs on loading.

3. Experiments were necessarily shorter than the years or decades of service in the field.



Figure 5. Inelastic behavior of PE under loading and unloading to various compressive strain levels: respectively 0.02, 0.04 and 0.06.

Further mechanical tests, including fatigue tests, were performed using the geometry prescribed in "ASTM D638 -08 Standard Test Method for Tensile Properties of Plastics" (Figure 7a) [12]. Illustrative examples of samples before/after testing are shown in Figure 7b. In most cases, the samples fractured during testing (as intended), but in some cases, the samples stretched to the limit of the machine's extension. These samples, which strained to more than 250% their original length, were said to have failed, as deformation to this magnitude would render insulation ineffective.

In order to compare with the results for subsequent fatigue testing, samples were first loaded to failure in monotonic tension. From these data, ultimate tensile strengths were obtained. The ultimate tensile strength is the maximum stress achieved in the material before local plastic instabilities cause a localization in deformation. Beyond this point, the engineering stress obtained will apparently



Figure 6. Inelastic behavior shown by six cable samples of various ages and chemical compositions under loading and unloading to various compressive strain levels.



Figure 7. (a) Schematic of standard TR-XLPE specimen for testing: where W is the width of sample narrow section (3.18 mm), L is length of narrow section (9.53 mm), WO is width overall (9.53 mm), LO is length overall (63.5 mm), G is gauge length (7.62 mm), D is distance between grips (25.4 mm), R is radius of fillet (12.7 mm); (b) one untested sample (#15) and seven samples after failure.

fall, although this is only an artifact of the equation used to define stress (load/original area). Results are seen in Figure 8, where the peak of each stress-strain curve represents the ultimate tensile strength of that material. The difference in ultimate tensile strengths of XLPE and TR-XLPE is small, but high density PE (a much stiffer and harder form of PE) exhibits a much higher ultimate tensile strength. The ultimate tensile strength is then used to choose the stress amplitudes (maximum stress minus mean stress) for fatigue testing. As



Figure 8. Results of monotonic tensile testing of three types of PE. The mechanical response of XLPE and TR-XLPE are very similar, while HDPE, a much stiffer and harder material, can withstand higher stress levels but at the expensive of ductility. XLPE and TR-XLPE can elongate by more than 150% before failure, while HDPE fractures after an elongation of only 75%.

will be discussed below, the maximum stresses applied during the fatigue experiments did not exceed the ultimate tensile strength of the material until the sample was very near to the end of life. As a result, deformation occurred throughout the entire sample. All tests were performed at a load ratio (minimum load/maximum load) of 0.1.

Stress amplitudes varying from 3-4 MPa (i.e., well within the range of stresses predicted by numerical analysis of dielectrophoretic forces) were applied to the sample using a 5 Hz sinusoidal waveform. Failure of the sample was defined as either when the sample fractured into two pieces or elongations greater than ~150% were achieved. Figure 9 illustrates the elongation of four samples, at four different stress amplitudes, as a function of the number of tensile stress cycles applied. At all four stress amplitudes the samples fail. At the highest stress amplitudes, the samples fracture almost immediately. For these stress amplitudes, sample elongation and crack growth occur quite readily. At the lowest stress amplitude, very little elongation occurs initially. Crack growth during each cycle is minimal. After approximately 70,000 cycles, a small, localized region of deformation begins to form at a local incongruity within the material. From this point forward, the elongation occurs rapidly, as this local deformation spreads throughout the entire sample in a process known as necking. This behavior is common for fatiguing materials. The presence of fatigue deformation is readily apparent in micrographs of fracture surfaces, such as those shown in Figure 10. The origin of the fracture is near the bottom left hand corner of the low and medium magnification micrographs (Figures 10a and 10b). The crack propagated towards the upper right of these two micrographs. The wave-like features of the surface are known as fatigue striations and are the usually observed patterns for fatigue. Each striation represents the local advancement of the crack during one cycle. Note that the "crests" of the waves are initially close but their separation subsequently increases, implying greater crack growth with each cycle, consistent with Figure 9.



Figure 9. Elongation of TR-XLPE samples during cyclic loading. For large stress amplitudes, failure occurs very quickly. At the lowest stress amplitude, the majority of life is spent nucleating the flaw which will lead to failure. After ~70,000 cycles, the deformation begins to localize, and elongation occurs rapidly to failure.

These striations can also be seen in the highest magnification micrographs that were taken from near the fracture origin (Figure 10c and 10d). In fatigue studies, a common way of expressing results is with a "Stress-Life plot", also known as a Wöhler or S-N curve. The number of cycles to failure is plotted on the horizontal axis versus the stress amplitude on the vertical axis. Figure 11 is the measured S-N curve for TR-XLPE samples tested at 5 Hz, in air, with the anticipated result that the fatigue life is significantly diminished at higher stress amplitudes. It is emphasized that these measurements are necessarily short-term compared to the lifetimes of cables. For example 180,000 cycles is 10 h at 5 Hz. At the 120 Hz of the dielectrophoretic forces, these cycle numbers are even briefer; for example 300,000 cycles is reached at 40 minutes. Nevertheless a large extrapolation from the results of this plot to the lifetimes of a cable yields the following. At 120 Hz, 10^{10} cycles = 2.6 years and extrapolation suggests that this lifetime would be reached at 1.7 MPa. The stress amplitude required to cause failure after 26 years is, by this extreme extrapolation, 1.6 MPa (0.15 to 3.25 MPa). These are stresses comparable to those predicted by the mathematical model (e.g., Figure 4), which implies that fatigue might well be a mechanism for long-term failure of cable insulation. Also Sauer et al [13] concluded that for polymeric material fatigue where hysteresis losses are significant, an increase of frequency will cause greater energy dissipation. The significant temperature rise may then ensue and deleteriously affect the fatigue lifetime. So for fatigue at higher frequencies, shorter lifetimes are expected for PE.



Figure 10. Scanning electron microscopy (SEM) micrographs of the fatigue fracture surface with four magnifications. Stress amplitude = 3.25 MPa. Failure originated in the lower left corner of Figures 10a & b and propagated towards the upper right hand corner. Each striation represents the amount of crack growth in one cycle. Note that as the striations proceed from left to right the separation between each striation increases, indicating greater crack growth per cycle as the crack extends.

The results of Figure 11 were obtained in fatigue experiments at "room temperature", i.e., no attempts were made to control the temperature of the samples during testing. It was anticipated that some temperature increase could occur by frictional heating as polymer chains slide past each other (the hysteresis of the loops of Figure 5) but that the temperature increase would be small. For example Sauer et al [13] report temperature increases of a degree or

two at the stress levels in question for PE. However, to test the TR-XLPE for susceptibility to failure at higher temperatures that might be encountered in service (e.g., from Joule heating in the central conductor or concentric neutrals), samples were enclosed in a heated chamber and further tests run. Figure 12 shows that the cycle life of the TR-XLPE is diminished significantly by a temperature increase of only 10-15 °C. The effect of temperature reinforces the supposition that fatigue is a credible failure mechanism for cable insulation materials.



Figure 11. S-N curve for TR-XLPE in air at 5 Hz with a load ratio (minimum stress/maximum stress) of 0.1. The lifetime of TR-XLPE increases dramatically with a small decrease in stress amplitude.



Figure 12. TR-XLPE samples tested at higher temperature shows diminished cycle life (Weibull Characteristic Life) at a stress amplitude of 3 MPa. An increase in temperature of only 10-15 °C shortens the fatigue lifetime of TR-XLPE by more than two orders of magnitude. The maximum and minimum observed life cycles among the six tested samples for each testing condition are shown using the error bars. This is true for Figures 16, 17 and 18.

The temperature rise in a sample caused by frictional heating during tests performed in air was measured using an infrared surface temperature measurement device: model OS36 IRt/c from OMEGA. Figure 13 shows the results of sample surface temperature measurements during fatiguing of TR-XLPE samples in room temperature air. The anticipation of a small temperature increase was borne out at low stress amplitude but not correct for higher stresses. The results are consistent with the temperature increase being due to the mechanical energy input as the sample is taken through the hysteresis loops similar to those seen in Figure 5. The area of the hysteresis loop is the work done on the sample and this area will be larger for higher stress amplitudes because both the stress and strain are larger. Consequently heat generation within the sample and its temperature are larger at higher stresses.



Figure 13. Measured surface temperature increases during TR-XLPE fatigue testing at various stress amplitudes in room temperature air.

The temperature increase in the sample can be estimated using the following algorithm. In Figure 5, or a corresponding one for a cycle in tension, it is possible to calculate the net work done on the sample from the area between each loading curve and its corresponding unloading branch. This can then be expressed as a percentage (about 30%) of the work done during loading. If it is assumed that this percentage remains the same during all the fatigue cycles, then the work done on the sample can be calculated for each cycle from the measured extension on that cycle and the imposed stress. This work increases with increasing cycle number as the extension per cycle increases. The calculated results were input into a finite element, steady state, heat transfer calculation with a convective heat transfer coefficient at the sample/air interface. The algorithm assumes that 50% of the hysteresis energy is converted into heat whereas the other 50% is converted into the breaking of chemical bonds resulting in internal structure change [14]. The results of calculations for one stress level appear in Figure 14. We conclude that on experimental as well as theoretical grounds, the temperature increases due to cycling at the stress amplitudes of interest here are small.



Figure 14. Comparison of measured surface temperature rise and simulation result at a stress amplitude of 3.25 MPa. Power Dissipation in simulation is shown in the right axis. A heat transfer coefficient of 10 $W/(m^2 \cdot K)$ at the interface of PE and air was used for the COMSOL Multiphysics simulation.

In the field, the insulation might experience much more than elevated temperatures. For example groundwater or water in conduits/ducts can reach the insulation and common constituents of such water (e.g., road salt or compounds common in the lithosphere) might also be present. Nikolajevic and Drca [15] have determined that water reduces the breakdown stress of cable insulation, although these authors are referring to the electrical field at which the insulation fails, rather than the mechanical stress of interest in the present investigation. Fatigue experiments were therefore conducted with a constant stream of water (delivered from a reservoir to jets impinging on the sample by a pump) flowing over the surface of the sample as shown in Figure 15. This was done for samples not previously exposed to water and for samples that had been kept in water for three months ("soaked samples"). The temperature of the water was controlled at the sample to 7-8 C above room temperature (room temperatures were 22-23 C), in order to minimize any cooling offered by the water. The results are given in Figure 16, which shows fatigue lives of both fresh and soaked samples tested in this water environment. Both soaked samples and samples freshly exposed to water showed enhanced cycle life, even though the temperature was above that of samples tested in air. A hypothesis explaining this unexpected result is that the advancement of a fracture crack through a material is promoted if the newly formed surface reacts chemically with the environment. When fracturing PE in air, the broken bonds will react with oxygen or other corrosive species. If the sample is immersed in water, access of oxygen to the fracture surface is limited and propagation of the fracture slowed. Water may be absorbed at the crack tip causing swelling of the polymer and crack blunting effects similar to what Samat et al [16] found with polyvinyl chloride (PVC) in aqueous environments. Further study is necessary to determine the origin of this behavior, although the testing performed here demonstrates that fatigue is still mechanism of failure in service-like a possible environments.



Figure 15. Schematic of testing setup for fatiguing samples under flowing water or solutions. The temperature of the flowing solutions was regulated to minimize any cooling effects.



Figure 16. Fatigue behavior of TR-XLPE samples in heated water environment after being just wetted and soaked in water for three months at a stress amplitude of 3.25 MPa.

Figure 17 shows the results of fatigue measurements in room temperature air, where a sample of TR-XLPE was first exposed to the sodium salt of humic acid or to acidified ferric chloride solution. Humic acid is a product of the decay of vegetation; the salt was used at a concentration of 1 g/L and the samples have been immersed for both three and six months before testing. Although concentration of humic acid used here is higher than that in most groundwater [17], a high concentration of humic acid was chosen to highlight any deleterious effects and simulate the cumulative effects of prolonged exposure in service. Iron is the fourth most abundant element in the lithosphere [18], and near the Earth's surface, oxidizing conditions result in much of that iron being present as ferric ions. Also common in the lithosphere are chloride ions. For this reason, fatigue experiments were performed on samples soaked for three months in ferric chloride solution at a concentration of 1 mol/L, also containing 1 mol/L sulfuric acid. Results of these experiments are seen in Figure 17. Both solutions have decreased significantly the fatigue resistance of TR-XLPE after being immersed. The results of fatiguing samples in flowing, heated humic acid salt solution are displayed in Figure 18 along with the results for humic acid soaked samples tested in air (Figure 17) for comparison. The flowing solution enhances the cyclic life of TR-XLPE, perhaps by inhibiting oxidation of the forming

fracture surface as hypothesized in the previous paragraph. The flow was kept at a constant elevated temperature to mitigate any potential cooling caused by the testing environment.



Figure 17. Fatigue behavior (in air) of TR-XLPE after humic acid salt and ferric chloride exposures at a stress amplitude of 3.25 MPa.

The micrograph of the fracture surface of a sample that had been soaked in the humic acid salt for three months prior to fatigue in flowing humic acid salt solution is seen, at high magnification, in Figure 19a. Compared to the fracture surface to that shown in Figure 10d, which is reproduced as Figure 19b for convenience, the sample immersed in humic acid appears to have a much more pitted surface than the one fractured in air, perhaps indicating a greater degree of reaction with the environment in the former case and explaining the results of Figure 18. Also note the flatter surface topography of the fracture surface, indicating a much more brittle fracture for the sample exposed to humic acid.



Figure 18. Environmental effects on fatigue life of TR-XLPE at a stress amplitude of 3.25 MPa. Samples were exposed to 1g/L humic acid salt solutions for various lengths of time. Exposed samples tested in air showed dramatic reductions in fatigue life after only three months of immersion.

CONCLUSIONS

The results of this investigation are suggestive, rather than compelling. The application of cyclic mechanical stress is different, in the present investigation, from the stresses likely experienced by the PE surrounding a water tree in the field. However the reader will recognize that, in both cases, behavior is determined by material properties, notably the response of the PE to cyclic stress and the environment. The results of the investigation are therefore relevant to propagation of water trees. The conclusions from this investigation are that fatigue of polyethylene insulation, due to cyclic dielectrophoretic stresses around defects such as voids or inclusions, is a possible mechanism for the development of water trees. Dielectrophoretic stresses can be on the order of a few megaPascals and fatigue experiments in the laboratory suggest



Figure 19. Fracture surfaces of samples tested after 3 month immersion in 1g/L humic acid salt solution (a) and in air (b). Fracture propagated from left to right in each micrograph. Note the significant increase in damage and pitting in the humic acid sample (a) when compared to the air sample (b). The fatigue life of a sample immersed in a humic acid salt solution is dramatically reduced compared to samples tested in air. Samples were tested at a stress amplitude of 3.25 MPa.

that these stresses are sufficient to damage TR-XLPE insulation in the long-term. The suggestion is made more credible by experimental results showing that TR-XLPE is less robust at the higher temperatures likely in the field. However, there are significant environmental effects. The fatigue life of TR-XLPE appears to be enhanced in the presence of water but to be significantly reduced when TR-XLPE is exposed to chemical species likely encountered in service.

This investigation has been a combination of mathematical modeling (for estimating the stresses within the PE) and experimentation (for determining the mechanical behavior of PE and the effect of various environments on that behavior). The results do not rule against the "chemical school" (e.g., Zeller [2] and [3]) in favor of the "electro-mechanical school". Indeed, the work presented here indicates that they are both correct; both chemical reaction and mechanical forces, working in concert, are likely culprits in the development of water trees.

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Z. Wang et al.: Mechanical Fatigue as a Mechanism of Water Tree Propagation in TR-XLPE



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