Water-treeing seen as an environmental stress cracking phenomenon of electric origin

C. T. Meyer and J. C. Filippini

CNRS, Laboratoire d'Electrostatique, 166X 38042 – Grenoble Cédex, France

(Received 7 July 1979)

Water-treeing is an ageing phenomenon observed in the polyethylene insulation of high voltage power cables when they are in contact with humidity[1]. Water-trees are constituted by microscopic channels which are filled with an aqueous solution. They generally appear after months or years and may lead to the failure of the cable. At present, there is no satisfactory explanation of the origin and growth of water trees. In this communication, we propose to consider water-treeing as a fracture phenomenon in presence of a liquid due to mechanical stresses of electrical origin. Water tree propagation will be studied as that of environmental stress cracks using fracture mechanics concepts.

Water treeing

Water trees are constituted of channels or microvoid rows, whose diameter is of the order of 1 μm. Their length may reach some hundreds of μm (*Figure 1*). They grow from defects such as microvoids, contaminants or surface flaws at the conductor–insulation interface. Their mean direction of propagation is parallel to the electric field. Their propagation rate is of the order of 1 μm h^{-1} at the beginning and decreases to some 10^{-1} μm h^{-1} after some months. Water trees have been observed under d.c.[2] and a.c.[3] voltage and as well in extruded cylindrical cables insulation as in moulded plane sheets.

Water treeing is generally assumed to take place in three steps: (1) absorption of water and accumulation of defects: (2) initiation – formation of a channel from this water pocket by an unknown mechanism; (3) propagation and ramification of such a channel. The propagation mechanisms proposed up to now may be classified[4] according to the primary effects of the electric field.

(i) Thermal action. Dielectric or Joule heating inducing thermal degradation or mechanical forces through local pressures. Critical examination of the order of magnitude shows that this effect is negligible[4].

(ii) Chemical action. Local partial discharges, local dielectric breakdown, chemical or electrochemical reactions inducing chemical degradation or mechanical forces through gas generation.

(iii) Mechanical action, directly through stresses of electrical origin (dielectrophoresis, electrophoresis, electrostriction, electro-osmosis, Maxwell stress) or indirectly through high pressure due to the thermal or chemical effect. Critical examination of the literature[4] shows that the proposed mechanisms are insufficient either because the electrical situation is not correctly described or because unrealistic mechanical parameters (such as viscosity) are invoked. Although other mechanisms may be superimposed, in particular chemical effects, we have restricted our work to the examination of the direct mechanical action of the electric field and to the analogy we have noticed between water-treeing and environmental stress cracking.

Propagation and fracture

A first way to study the propagation of a water tree channel is to use an energy criterion as for crack propagation; that is, to compare the critical energy release rate G_c, which is the energy necessary to fracture with the energy supplied by the electric field.

At the tip of the water-filled channel the electric field E_p is larger than its value E_0 in the bulk of the material. In the case of a conductive channel (which is the case for water at least at power frequency) assimilated to a cylinder (length l, radius r) the field-enhancement factor a, defined by $E_p = aE_0$, is approximately given by $a = l^2/2r^2$. The electrostatic pressure exerted upon the polymer is $\epsilon_0\epsilon_p E_p^2/2(\epsilon_p)$ is the permittivity of PE relative to that of a vacuum ϵ_0. If the cylinder increases its length by Δl the work done by this electrostatic force is $\Delta l \cdot \pi r^2 \epsilon_0 \epsilon_p E_p^2/2$. On the other hand, the energy required for creating this new surface by rupture is $\Delta l \cdot 2\pi r \cdot G_c$. The criterion for propagation is then $E_0 l^2 > 4r^{3/2}(G_c/\epsilon_0\epsilon_p)^{1/2}$.

There is no experimental data on the system polyethylene–water. From a study on LDPE in presence of methanol[5], it is possible to calculate, from the stress intensity factor K_c and Young modulus E, a G_c value of 64 J/m^2 at slow propagation rates. Thus, a value of G_c of the order of 100 J/m^2 seems plausible. With $r = 1$ μm and $l = 20$ μm the value of E_0 needed for propagation is then 24 V/μm, which corresponds to experimental values of the applied field in the d.c. case[2]. In the a.c. case water-treeing appears for electric field less that in d.c. voltages (a few V/μm). This is in agreement with the fact that, in case of fatigue, crack propagation occurs under loadings which would not induce static fracture (the energy supplied is for example some J/m^2 for PE in air and presumably less in presence of water[6]).

Consequently, it appears relevant to consider fracture as a plausible mechanism for water tree propagation.

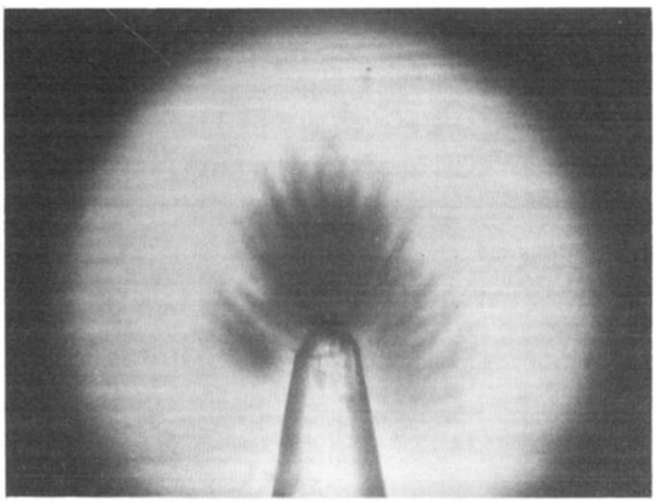

Figure 1 Photograph of a water-tree. This water-tree was grown at the tip of a water-filled conic cavity in PE. Other types of water-trees may appear: tree-like, bush-like, etc.

0032-3861/79/101186-02$02.00

Discussion

To make any progress in the interpretation of water-tree propagation in terms of stress cracking many difficulties must be overcome.

(1) *Mechanical problems.* From the experimental standpoint, the values of the parameters involved in the case of the system PE + water at very slow propagation rate are not available. From the theoretical standpoint, all mechanical data and concepts are related to a plane crack, whereas the electrical case corresponds to a cylindrical crack; the influence of this difference in geometry should be examined. On the other hand, due to the fact that the electric stress is localized at the channel tip, it would be interesting to discuss in terms of stresses and to use the second approach of fracture mechanics, that of a stress intensity factor.

(2) *Correlation between energy or stress intensity factor and propagation rate.* Up to now, only global water-tree growth rates have been measured, the local and instantaneous velocity of one channel is unknown. In fact, there is an apparent contradiction between the experimental decrease in propagation rate and the increase of the energy available due to the increasing length. This shows the importance of taking into account the ramification. The effective length to consider in the calculation of the electric energy at the tip is presumably that of the last right segment and it does not exceed about 100 μm. In fact, after each ramification a new growing phase is to be considered.

(3) *Other factors.* The following factors could play a part in the propagation mechanism: a possible decrease of the electric field at the tip of the channel due to a space charge created by migration of ions into the polymer under the electric field; an eventual limited supply of water leading to stress cracking in presence of air, which needs an increased energy compared with environmental stress cracking in water; an influence of the water resistivity on the field enhancement; an influence of the electric field on the rupture energy in so far as the environmental stress cracking could be associated with a surface energy and the electric field is known to modify the surface energy; a modification of the rupture energy due to chemical (oxidation) or electrochemical phenomena (polarity effects seem important in the d.c.[2,7]).

Conclusion

Water-treeing has been considered as a cracking phenomenon. The comparison of the available electrical energy required for rupture has shown that water tree propagation is possible by this mechanism. To go further, precise experimental data must be obtained for the mechanical parameters involved in environmental stress cracking of the PE–water system. Moreover, further theoretical treatment should take into account the difference in geometry between a plane crack and a cylindrical channel and involve the stress intensity factor approach.

References

1 Eichhorn, R. M. *IEEE Trans E. I.* 1977, **12** (1), 2
2 Franke, E. A., Stauffer, J. R. and Czekaj, E. *IEEE Trans. E. I.* 1977, **12** (3), 218
3 Ashcraft, A. C. *World Electrotechnical Congress. Moscow,* 1977
4 Meyer, C. T., Filippini, J. C. and Felici, N. *Conf. Elect. Insul. Dielect. Phenom.*, 1978
5 Marshall, G. P., Culver, L. E. and Williams, J. G. *Plast. Polym.* 1970, p 95
6 Andrews, E. H. and Walker, B. J. *Proc. Roy. Soc. (A)* 1971, **325**, 57
7 Fournie, R., Perret, J., Recoupe, P., Le Gall, Y. *IEEE Conf.* 1978