Analysis of Water Trees in Power Cable Polymeric Insulation

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ABSTRACT: This article deals with the basic mechanism of aging, that is water treeing (WT), that takes place in polymer-insulated power cables. WT was studied by means of computer-aided video-enhanced microscopy, microspectrophotometry, and micromanipulation. The microdiagnostics procedure was used for cables operating in a wet environment. A phenomenological WT model aimed at estimating the residual lifetime, which considers WT as a diffusion-with-reaction process, was developed. The theoretical calculations were in reasonable agreement with the experimental data. © 2003 Wiley Periodicals, Inc. J Appl Polym Sci 88: 1543–1549, 2003

INTRODUCTION

Nowadays, the majority of power cables are insulated with polymeric materials; the leading position is occupied by crosslinked low-density polyethylene (XLPE) applied by extrusion. A specific kind of aging is typical for this insulation, called *water treeing* (WT); see, for instance, refs. 1 and 2. This phenomenon has been known for more than 30 years; however, in many respects, it is still not adequately understood.

Russian experience with the commercial operation of XLPE-insulated power cables is rather limited at present, but extensive growth of their production and application is expected in the near future. Our study simulated WT and was aimed at estimating degree of degradation and residual lifetime.

Water trees are insulation–deterioration structures that develop in response to the combined action of an electrical field and the migration of water into insulation from the environment. Technological defects, such as cavities, foreign particles, and semiconducting screen protrusions, typically contain water-soluble impurities and serve as initiating sites for water trees.

EXPERIMENTAL

The following experimental techniques were used in this study for WT analysis: computer-aided video-enhanced microscopy, microspectrophotometry in the visible and ultraviolet (UV) ranges, and micromanipulation.

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RESULTS AND DISCUSSION

According to generally accepted practice, water trees must be stained to provide visibility. Because we used light microscopy methods, which are sensitive to phase shift (e.g., asymmetric illumination contrast,[3] dark field); even the smallest trees could be seen without staining. An example of a water tree, accessible for observation with the help of anoptral contrast[4] is given in Figure 1. The sponge-like tree structure can be clearly seen; it consisted of water-filled microcavities. The dimensions of water trees ranged from some microns up to a few millimeters.

A comparison of video micrographs, obtained by means of phase contrast and polarization microscopy, showed that damage involved only the amorphous phase of the material (Fig. 2).

Generally, local XLPE oxidation is an integral part of WT.[5] Within the framework of this study, this was illustrated by the following: the treatment of insulation slices with dansyl hydrazine, which reacted with carbonyl groups, resulted in a bright fluorescence of the tree (Fig. 3).

In the early stage of growth, the water trees appeared to be phase objects (in an optical sense), and the previously mentioned methods were used for observation. However, in the process of development, the water trees not only increased in size but also acquired light absorbance and, in some cases, fluorescence. Examples of absorption spectra are depicted in Figure 4. The locations of absorbance bands were subjected to some scattering. This was an indication of some chemical specificity of the trees, obviously caused by the random chemical nature of the tree-initiating defects.

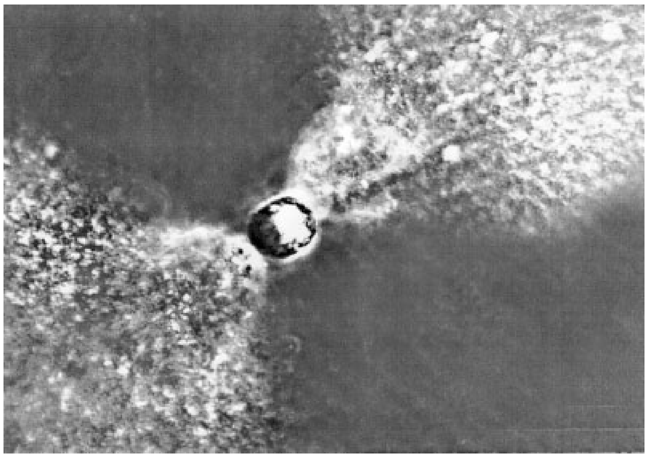


Figure 1 Anoptral video micrograph of a bow-tie water tree. The viewfield width is 1 mm.

We used a microdiagnostics procedure for cables operating in a wet environment. The procedure was based on a laboratory analysis of short cable samples by means of the previously mentioned methods. It involved the determination of relatively large water tree sizes and concentrations and the measurement of absorption spectra and local dielectric strength. The latter parameter was actually equivalent to the electrical treeing resistance.

A *microelectrode*, that is, a sharp metal needle, was inserted with the help of a micromanipulator inside the individual water tree region with the highest optical density (OD). The method of needle delivery to the place of interest provided high spatial accuracy and a minimum distortion of dielectric properties. High voltage was applied to the electrode and was increased up to the electrical tree inception. This event was registered either by means of video microscopy or, if the water tree transparency was insufficient, by means of an electrical scheme of partial discharge detection. An electrical tree initiated inside a water tree is shown in Figure 5. It was established in the course of this study that the electrical tree inception voltage decreased as a function of the water tree OD (Fig. 6). The latter characteristic was, therefore, the quantitative measure of material degradation.

The inception of an electrical tree in a water tree during cable operation actually implied the prebreakdown state of insulation. Tree-type recognition in the process of the cable sample analysis may have created some problem because sometimes electrical trees and water trees may have very similar morphologies (Fig. 7). It is possible to determine the type of a tree with the help of spectral characteristics of the trees. Electrical trees typically possess primary fluorescence, whereas water trees seldom exhibit this property, and the fluorescence spectra of both types of deterioration are different (Fig. 8).

To develop some kind of an approach to the problem of the residual lifetime estimation, we used a phenomenological WT model that treats the phenomenon as a result of some liquid substance diffusion and its bimolecular reaction with weak chemical bonds.[6] The primary model is presented with the following system of partial differential equations:

$$\begin{cases} \dfrac{\partial C}{\partial t} = D\dfrac{\partial^2 C}{\partial x^2} - KCn \\ \dfrac{dn}{dt} = -KCn \end{cases} \quad (1)$$

where C is the diffusant concentration, n is the weak bonds concentration, D is the diffusion coefficient, K is the rate constant, t is time, and x is a spatial coordinate.

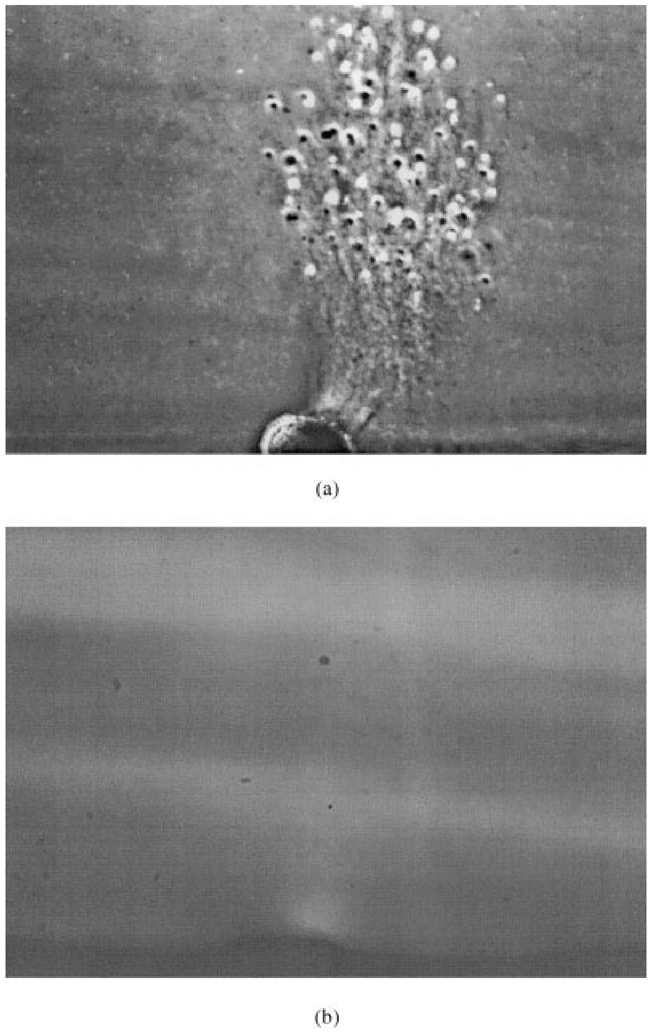


Figure 2 Comparison of water tree images obtained by (a) phase contrast and (b) polarized light microscopy. The crystalline phase remained intact, and hence, the tree is invisible in part (b).

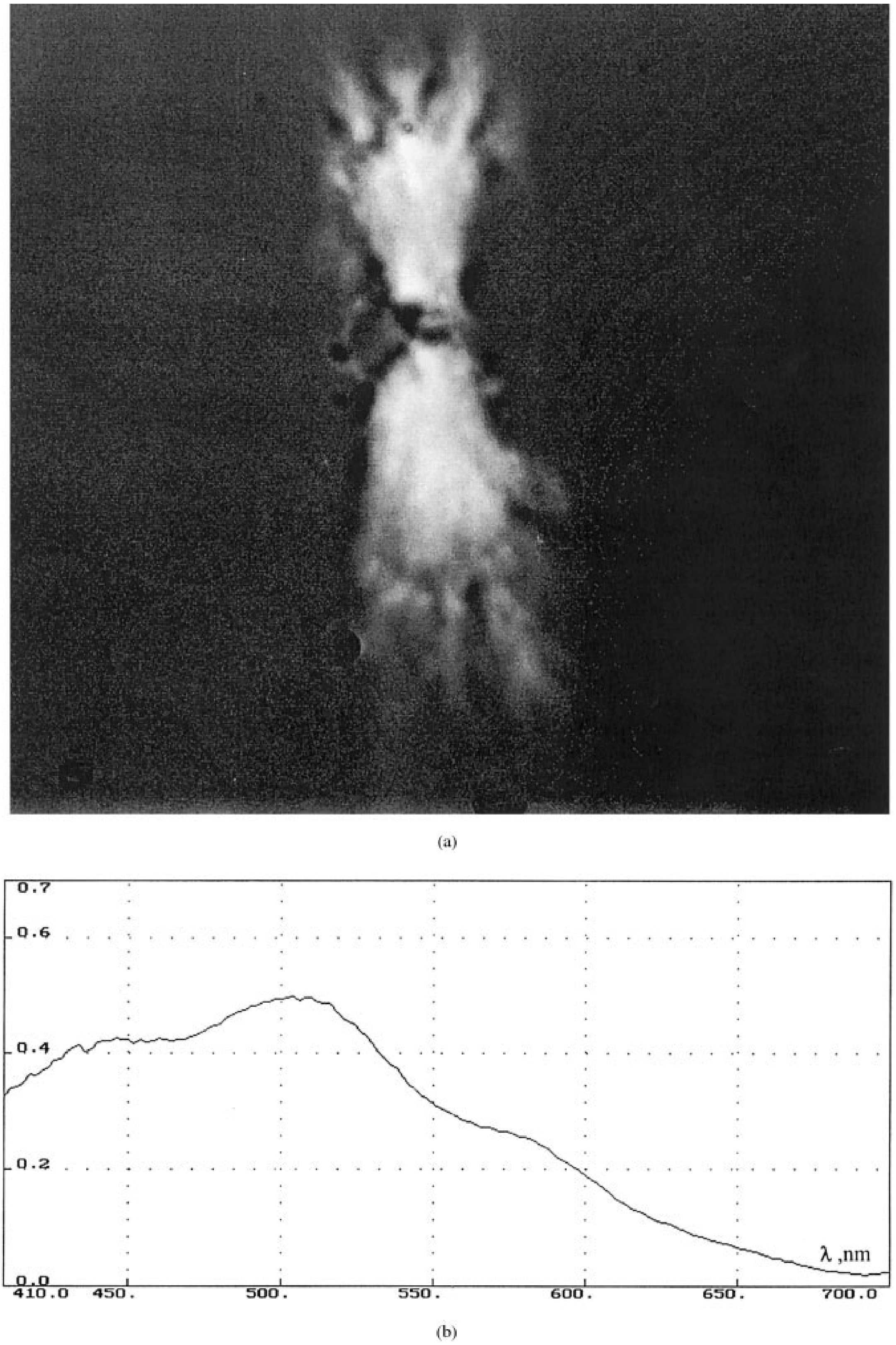


Figure 3 Water tree created by dansyl hydrazine: (a) secondary fluorescence and (b) corrected fluorescence spectrum of part (a).

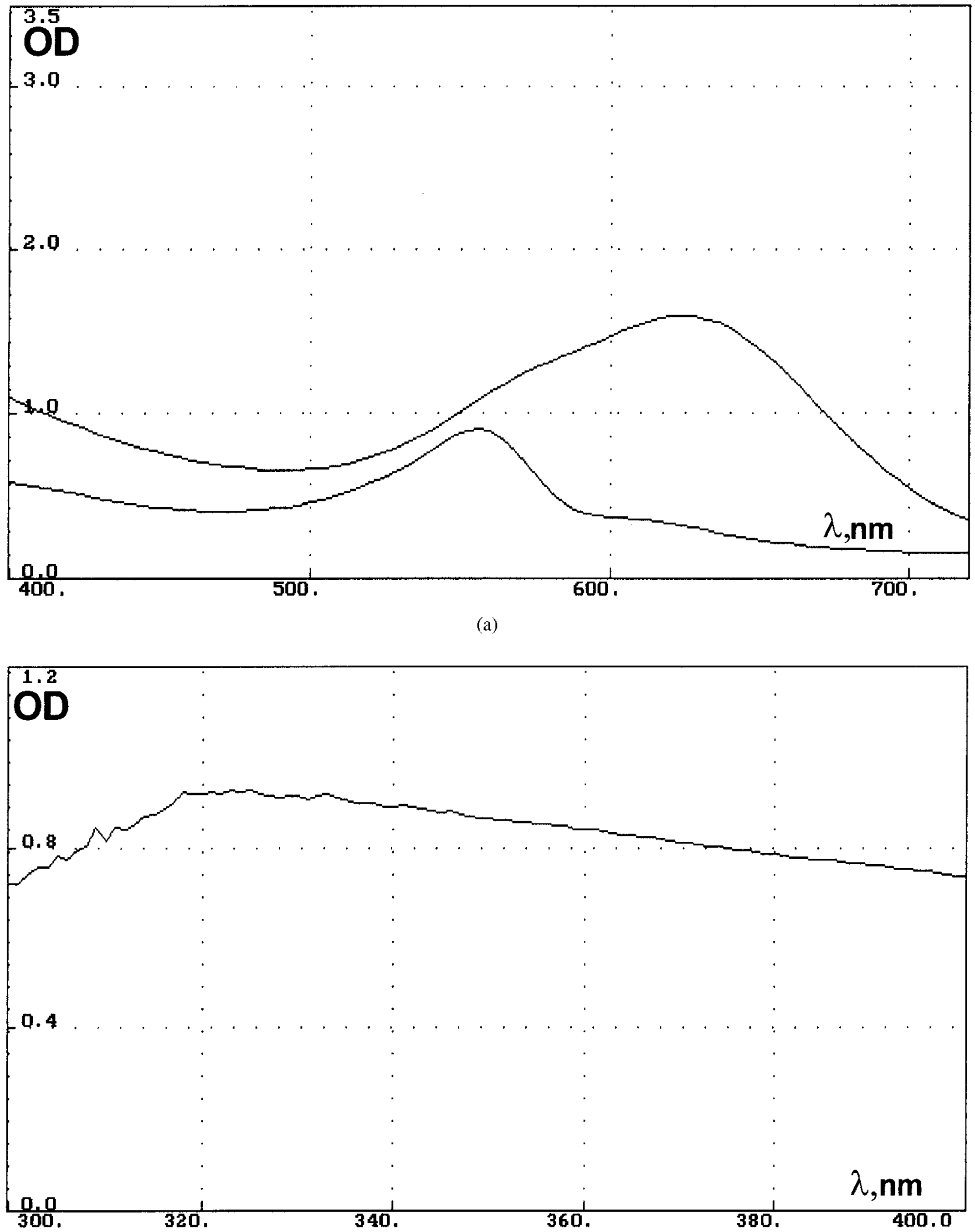


Figure 4 Examples of water tree absorption spectra in (a) the visible range and (b) in the UV range.

This approach to the destruction of polymeric materials under exposure to an aggressive medium is presented in ref. 7.

The boundary and initial conditions for eq. (1) are as follows:

$$\begin{cases} x = 0 & c = c_0 = \text{constant} \\ x = l(t) & c = 0 \\ t = 0 & n = n_0 \end{cases} \qquad (2)$$

where C_0 is the boundary value of C, l is the water tree length, and n_0 is the initial value of n.

Equation (2) is valid for a vented tree growing from a insulation–semiconducting screen interface (Fig. 9). The majority of authors agree that this type of water tree is more dangerous than bow-tie tree, which grows from the imperfections in the insulation bulk (Fig. 1).

We decided to reduce the primary model in eq. (1) so that it contained variables that may be directly

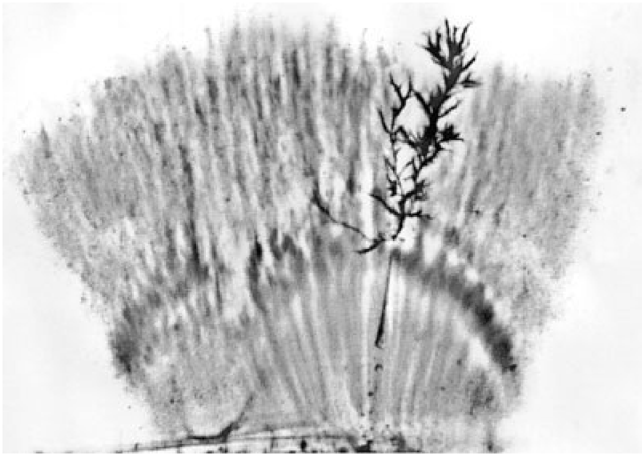


Figure 5 Electrical tree grown inside a water tree in laboratory conditions.

measured. Such a reduction was carried out with the help of the theory of averaging.[8] The following additional assumptions were used: (1) the local rate of material degradation inside the tree is limited by the rate of microcavity accumulation and is described by OD, and (2) the solution may be presented in approximate self-similar form.

As a result of the previously mentioned formalism, the model was transformed to the following system of ordinary differential equations:

$$\begin{cases} \dfrac{d\phi}{dt} = k\dfrac{1}{\phi} - \mu_1\kappa\phi + \mu_1\kappa\chi H\phi \\ \dfrac{d(H\phi)}{dt} = \dfrac{k\mu_2\phi}{\chi} - \kappa\mu_2 H\phi \end{cases} \tag{3}$$

where H is the optical density; ϕ is the relative tree length, that is, the ratio of tree length to insulation thickness; and κ, μ_1, μ_2, and χ are parameters.

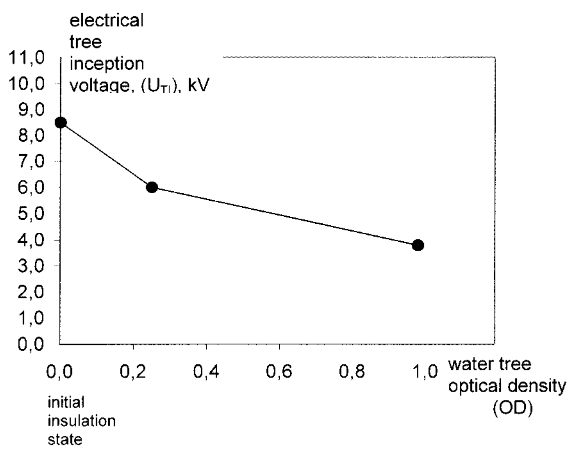


Figure 6 Influence of water tree OD on electrical treeing resistance.

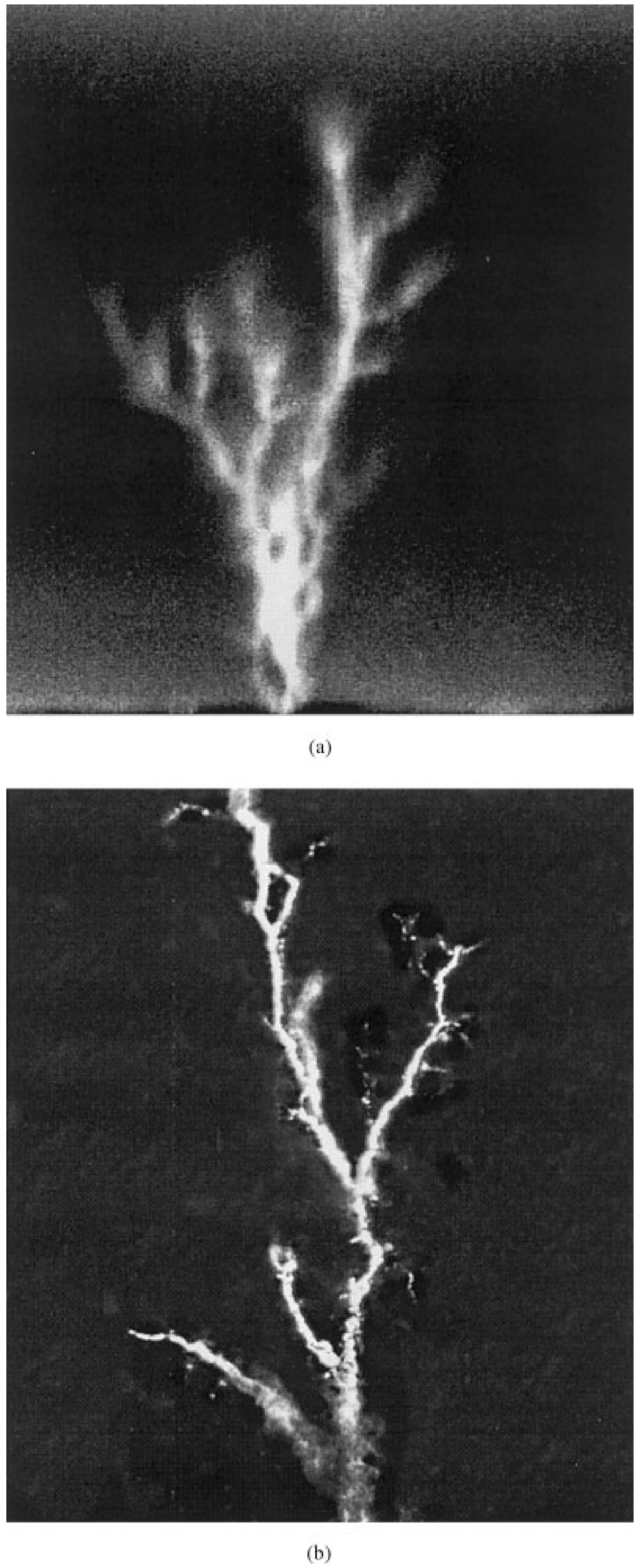


Figure 7 (a) Water tree with dendrite morphology (primary fluorescence). (b) Typical morphology of an electrical tree.

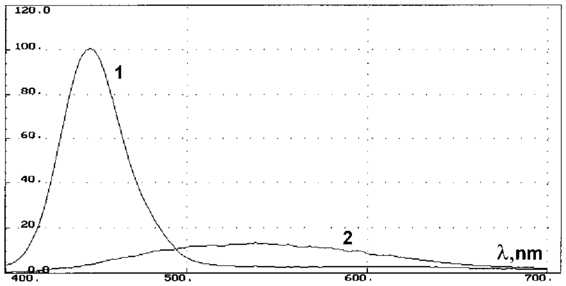


Figure 8 Fluorescence spectra of (1) a water tree and (2) an electrical tree.

Calculations showed that water tree length as a function of time is well approximated by simple power dependency. This often takes place for self-similar solutions and, at the same time, was supported

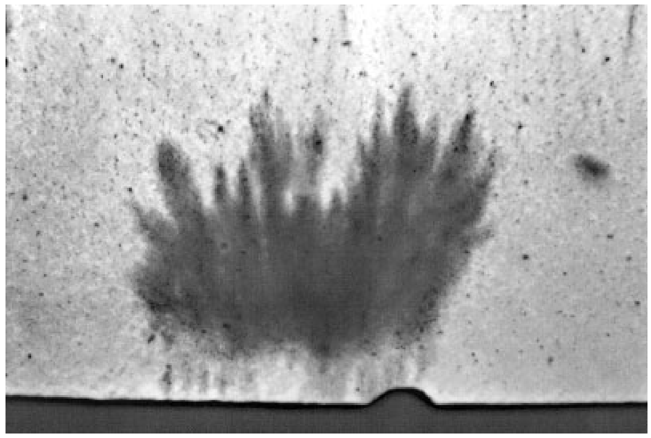
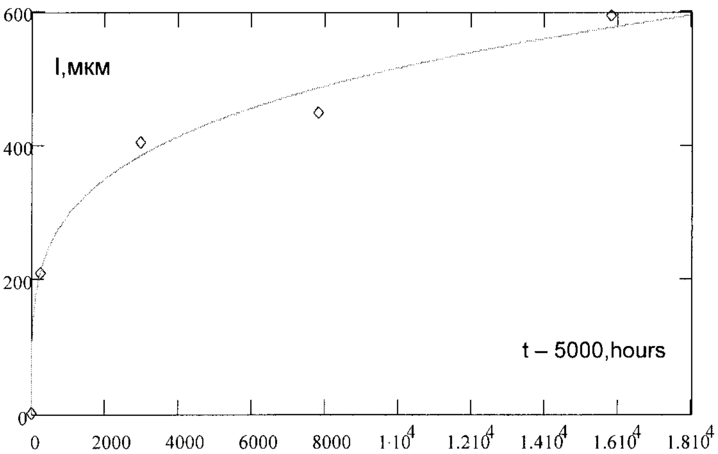
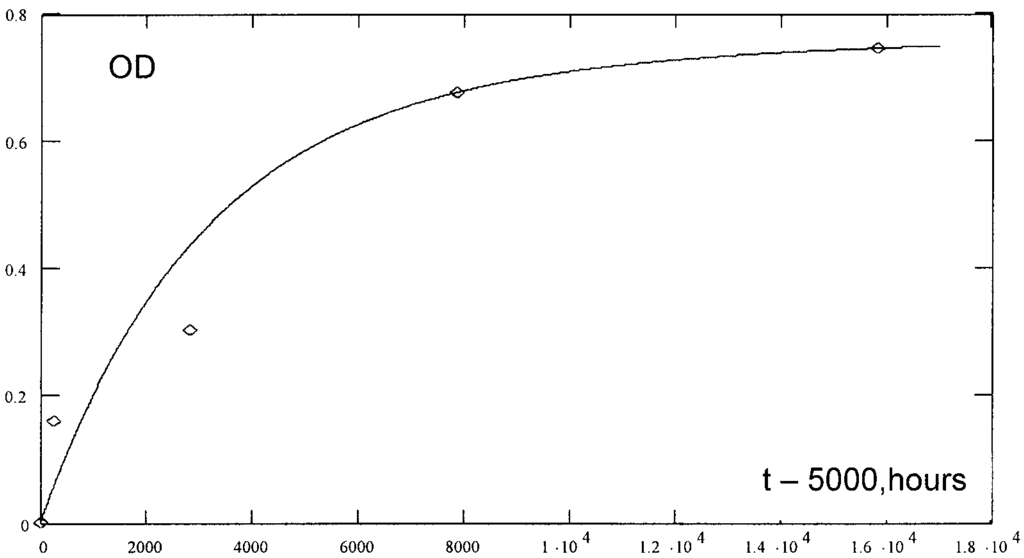


Figure 9 Example of a vented water tree (700 μm long) growing from a semiconducting screen/insulation interface.



(a)



(b)

Figure 10 (a) Water tree length versus time dependency: (◇) experimental values and (—) calculations according to eq. (4). (b) Water tree optical density versus time dependency: (◇) experimental values and (—) calculations according to eq. (5).

by a lot of experimental data obtained in different laboratories, including ours. This permitted us to derive the solution of eq. (3) in the approximate analytical form:

$$\phi(t) \approx a(t - t_0)^b \tag{4}$$

$$H(t) \approx \eta_2 \exp[-\eta_1(t - t_0)] \sum_{i=0}^{i=p} \frac{\eta_1^i (t - t_0)^{i+1}}{i!\, i + 1 + b} \tag{5}$$

where a and b are coefficients, $\eta_1 = \kappa\mu_2\eta_2 = \kappa\mu_2/\chi$, t_0 is the time of water tree initiation, and $p \approx 50$–150.

The verification of this model was carried out by way of long-term testing of insulation samples having the shape of plane sheets cut out from commercially manufactured cables. The results obtained up until now show satisfactory agreement between the theoretical and experimental data (Fig. 10).

The final aim of the WT mathematical simulation was the forecasting of the remaining cable life span. To estimate the ability of this model to solve this problem, three samples of cables were analyzed: two of them after 10 and 13 years of commercial operation and the third after 4.5 years of testing in the authors' organization. The data of this analysis were treated by means of eqs. (4) and (5) and are presented in Figure 11.

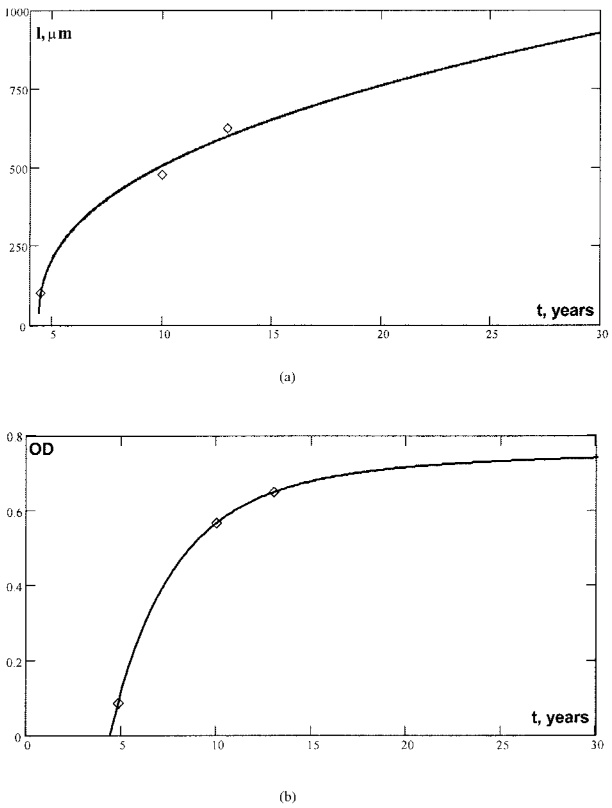


Figure 11 Example of a water tree model application [(◇) experimental data and (—) calculations according to eqs. (4) and (5)]: (a) length and (b) optical density.

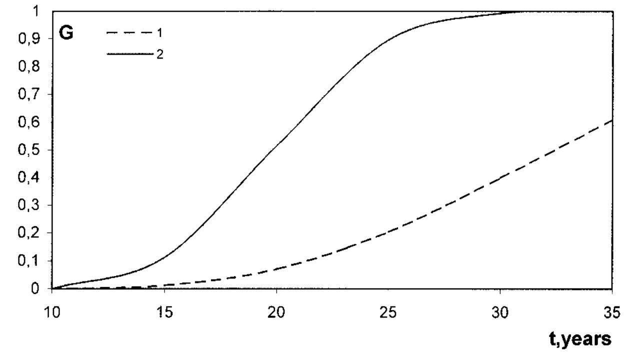


Figure 12 Probability versus time dependence for tree lengths reaching specified values; inspected cable lengths were (1) 0.15 and (2) 1.5 m.

It was established by our Norwegian colleagues that the maximum lengths of water trees in XLPE insulation slices obey the asymptotic distribution of the largest values.[9] The statistical forecast based on this distribution and on the previously mentioned data is depicted in Figure 12. Here, the probability is given for a tree length reaching the specified (maximum permissible) value as a function of time.

CONCLUSIONS

Our results are obviously intermediate. Future work will focus on further development of the WT mathematical model and on a more precise experimental definition of the essential parameters, such as the maximum permissible OD of the water tree.

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