WATER TREEING IN EXTRUDED CABLE INSULATION AS REHBINDER ELECTRICAL EFFECT

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Abstract: The paper contains systematic comparison of signs and properties of the water treeing phenomenon (the basic mechanism of degradation of medium voltage electric cable extrudered insulation which develops under combined action of electric stress and water) and Rehbinder Effect – the reduction of mechanical strength of solids due to physical and chemical action of liquid medium.

The analysis of the published data permits to distinguish 13 indications of the Rehbinder Effect. The authors show successively the direct analogy of the water treeing and the Rehbinder Effect using the above mentioned indications, including decrease of work of the development of new surfaces in the course of destruction, chemical specificity, role of material defects, two-stage destruction nature, etc. The analogy obtained is accepted as a working hypothesis which permits to bring certain order into theoretical and experimental studies of the water treeing.

Key words: water treeing, Rehbinder Effect, destruction, medium, defects.

Today XLPE cables are the basic types of 10-500 kV AC power cables. These cables are used for feeding cities and energy-intensive manufacturing facilities, as well as for carrying energy from electric power stations. Polymer cable insulation operates under the exposure to high electric stresses; therefore polyethylene insulation of medium and high-voltage cable has to meet strict electric strength and reliability requirements over the operation period of several decades.

However if there are cavities and microimpurities in the polymer insulation, then in the course of operation degradation known as treeing begin to develop within the insulation material. Treeing may be caused both by contaminants in the original polyethylene and imperfection of cable manufacturing process.

In the long run treeing leads to cable failure in operation. Therefore the investigation of tree initiation and development is of paramount importance. The main form of electrical insulation breakdown is associated with dendric tree-like growth known as electrical trees (ET). The main factors of ET growth are electric stress and temperature. Ageing known as water treeing [3, 8, 7] occur in the insulation under the simultaneous exposure to electric field and water diffusion into the insulation from the environment.

Electrical and water trees (WTs) tend to grow from the defects of the cable insulating system. ETs initiate slowly but grow quickly. On the contrary, WTs initiate quickly but grow relatively slowly. In medium voltage cables WTs form the basic mechanism of degradation of extruded insulation.

Despite the dramatic progress achieved over the recent 20-30 years in the field of development of more reliable dielectric materials and their processing into high-performance products, WTs still remain the main concern of major companies producing both insulating and semiconducting materials and cables, as well as of cable operating companies.

This concern is dictated by the desire to create more durable materials and cable constructions, as well as to develop more reliable and valid methods for the assessment of WT resistance of the electrical insulation system and its service life forecast.

The WT problem continues to be of critical importance due to both the complexity of physical and chemical nature of ageing and complexity of the above mentioned goals. For deeper understanding and more effective study of the WT development mechanisms a "system working hypothesis" is offered in order to bring a certain order into the experimental investigation and mathematical modeling of the process (both are necessary for the successive solution of the above mentioned problems).

A statement about the analogy between the WT development in the insulation and the Rehbinder effect is accepted as this "system hypothesis".

As is well known [13], the Rehbinder effect (RE) is the drop in mechanical strength of solids through the reversible physicochemical action of a particular medium associated with the increase of specific free energy and as a result – with the decrease of work of the development of new surfaces in the course of destruction.

The analysis of typical indications of the RE which are known from scientific publications shows that XLPE cable insulation ageing due to combined action of electrical field and water resulting in the decrease of dielectric strength and WT development has similar features, i.e. it can be considered as a certain electrochemical demonstration of the RE. This can be seen from the Table below where both processes are compared.

No.	Indications of RE	Corresponding features of electrochemical ageing of polymer cable insulation in the presence of moisture
1	Exposure to external destructive force – mechanical stresses.	Exposure to external destructive force – electric field.
2	Facilitation of destruction under combined impact of external forces and liquid medium [12].	Significant decrease in dielectric strength under combined action of electric field and water.
3	RE is related to decrease of work of the development of new surfaces in the course of destruction [13].	In this case new surfaces are surfaces of microcavities comprising WTs. In the absence of the medium the work of development of new surfaces raises dramatically, which is manifested in a considerable increase of "destructive" electric stresses when wet ageing transforms into dry ageing.
4	Reversibility: the strength recovers after the removal of the medium [13, 9] and the load [9]. As regards the thermodynamics, RE represents weakly non-equilibrium processes [12].	When water is removed from the insulation the electric strength recovers and WTs dry up.[1] After the electric field is switched off and the cable is conditioned in water the electric strength recovers [6], at least partially.
5	RE may subside with the rise in the temperature due to dissipation of deformative microinhomogeneities and healing of microcracks, diffusion dispersal of the medium, reduction of active component adsorption [9].	Ageing under operation conditions or in tests at elevated temperature (for example, 90^0C) is expressed much less than at low temperatures (20÷40^0C). WTs develop in a less intensive way, the dielectric strength decreases to a smaller extent.
6	Contact with the medium has to be relatively long [13].	WTs grow over a prolonged period – from several weeks/months (accelerated laboratory tests) to years and decades (commercial operation).
7	Chemical specificity with regard to the nature of the material, medium and additives [9].	WT growth dynamics and their subtle properties (for example, spectral properties) depend strongly on the composition of the insulation system under destruction, the electrolyte composition and the chemical nature of the defects at which WTs initiate.
8	Essential role of the structure defects [13, 9].	WTs always initiate at the defects, and not only technological defects, like foreign inclusions or cavities, but also "molecular" polymer defects are essential for their development.
9	Specific role of the solid grain boundaries: destruction develops at the grain boundaries [9].	WTs develop in the amorphous phase of cross-linked polyethylene, i.e. at the crystallite boundaries.
10	The medium should be related to the material under destruction [9].	Hear the medium is water. As shown in [10], WTs in cross-linked polyethylene are hydrophilic.
11	Destruction proceeds in two stages[2]: 1) gradual initiation and development of equilibrium microcracks; 2) fast propagation of non-equilibrium crack over the entire body cross-section [9].	Destruction also has two stages: 1) gradual initiation and development of WTs; 2) fast propagation of ET (initiated at WT as at "secondary" defect) over the entire insulation thickness.
12	Surface diffusion along the crack walls.	Surface diffusion along the cavity walls (and, perhaps, submicroscopic channels, presumably connecting these cavities).
13	Time (t) dependence of the crack length (l_c) is approximated by the power function [11]: $l_c \sim t^{0.31}$	Experimentally obtained time dependence of WT length (l_{wt}) is approximated by the power function [4]: $l_{wt} \sim t^{\beta}$, $\beta \approx 0{,}2 \div 0{,}4$

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[1] The idea of reversibility as applied to WT should be treated with some care. It seems reasonable to speak about partial physical-chemical reversibility.

[2] This is characteristic of other types of destruction.

Below we deal with a variety of experimental data which illustrate the typical features of the RE in respect to the electrochemical ageing of extruded cross-linked polyethylene cable insulation with reference to the processes described in the Table.

Dielectric strength reduction due to ageing (item 2).

Accelerated ageing tests of full-scale specimens of medium-voltage cable are being conducted in VNIIKP at present; the tests comply with the norms of CENELEC (HD 605, HD 620). The electric strength data obtained by now and averaged over some manufacturing plants are given in Fig. 1 versus test duration.

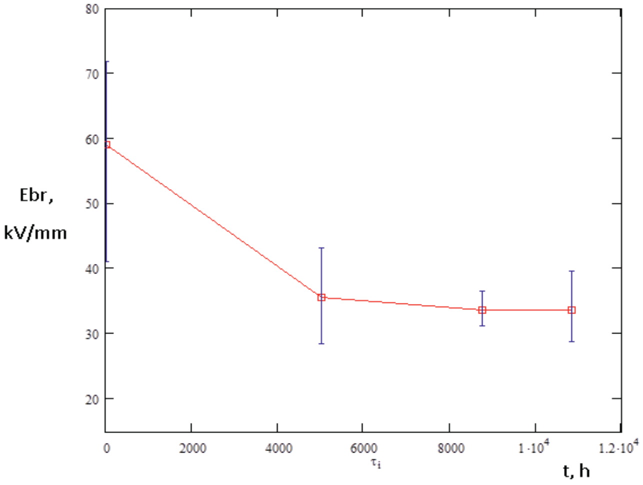

Figure 1. Dependence of dielectric strength (E_{br}) of full-scale 10 kV cable specimens on time (t) of accelerated electrochemical ageing tests carried out in accordance with CENELEC norms

Significant increase in the work of development of new surfaces in the absence of active medium which is represented by a sharp increase of destructive electric stresses (item 3).

WTs initiate even at electric stresses (E) equal to 2-3 kV/mm and probably at lower stresses. At the same time the electrical ageing at moderate temperatures in the absence of moisture in the insulation is registered only at E values within tens of kV/mm. This is confirmed by the experimental data given in [14].

Specimens of 1 mm thickness cut out of 110 kV cable insulation were aged at a temperature of 40^0C and E=23 kV/mm. Examination of the specimens after 5000 hours of ageing revealed no signs of ageing.

In addition test of a full-scale specimen of a 110 kV cable as carried out at continuously applied voltage, with E=13 kV/mm at the inner screen and constant heating, the conductor temperature was 130^0C. The breakdown occurred after 23800 hours of testing, whereupon the insulation was examined using the FTIR spectrophotometry, thermal analysis, video microscopy and other techniques which revealed some signs of thermal ageing and no signs of electrical ageing.

If exposure to water had been "included" into the performed tests one could have with certainty expected mass initiation of WTs and most likely early failures of the test specimens.

Reversibility (item 4) – this property requires additional analysis.

Weakening of the RE with the rise of temperature (item 5) is illustrated by two length histograms of WTs revealed in two different parts of the same cable after 12 years of operation (Fig. 2 a, b). The difference between the parts lies in the following: due to the outer source of heat one part of the cable was heated to a higher temperature which prevented WT growth. As a result the mean sizes of the trees exhibit two-fold difference.

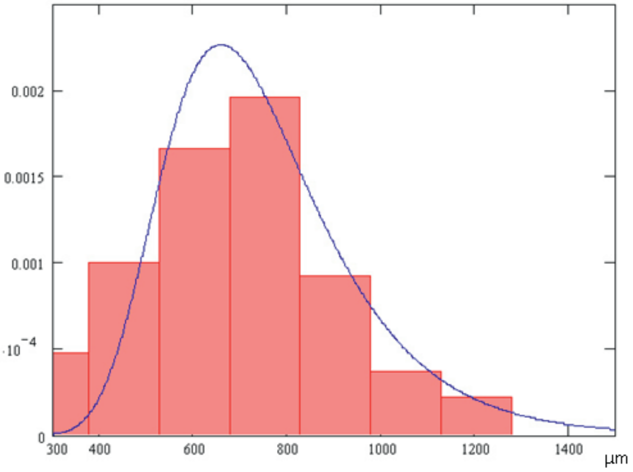

Figure 2a. Histogram of "bow-tie" water tree lengths and approximating density of type 1 maximum value distribution (detailed description of this distribution is given, e.g., in [5]). The trees were revealed in the cable specimen after 12 years of operation at moderate temperature

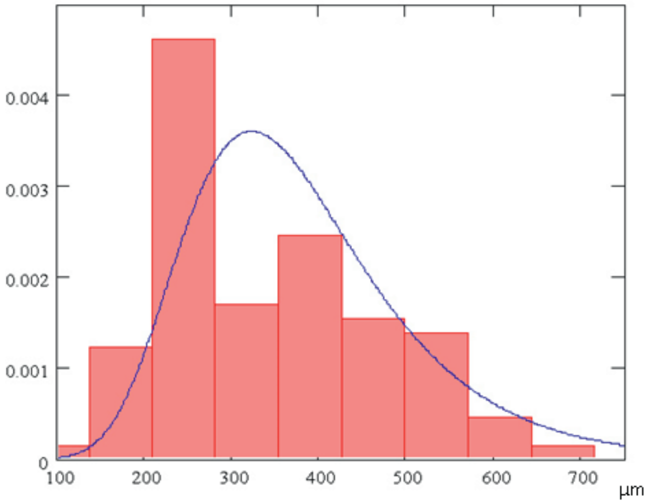

Figure 2b. Histogram of bow-tie water tree lengths and approximating probability density. The trees were found in another specimen of the same cable: the specimen was taken from a cable line section that was in operation at elevated temperature

This phenomenon also requires additional consideration.

Chemical specificity (item 7). There are many scientific papers which show the dependence of the WT growth rate on the chemical composition of insulating and semiconducting compounds, for example, [3, 8], and electrolyte composition [2]. Consideration must be given to the differences in the chemical nature of WT which are resulting from the differences in the composition of the defects that give rise to treeing.

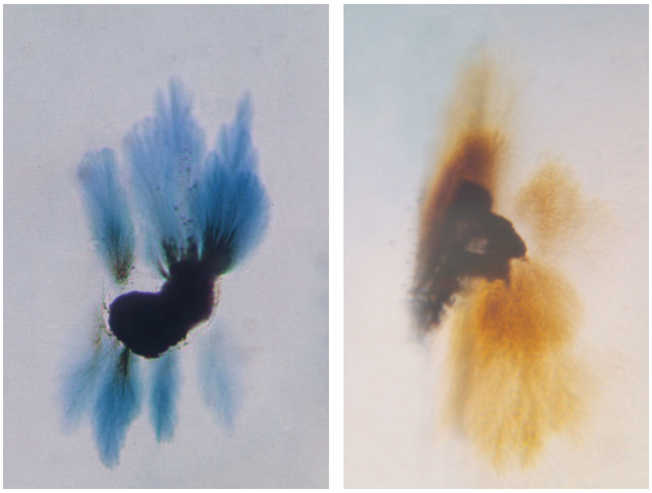

Figure 3. Bow-tie water trees possessing intrinsic optical absorption in different spectral regions. The distinctions are caused by the difference in the chemical nature of the defects at which the trees grew.

Such chemical "individuality" of some WTs is demonstrated in Fig. 3. Optical contrast of the trees against the surrounding dielectric is resulting from the primary absorption.

Role of defects (item 8). On the whole it is safe to say that there is a positive correlation between the sizes of defects and trees; large WTs growing at large defects are shown in Fig. 4 a, b, c. However this correlation is not strict: while examining cables that failed in operation one could sometimes come across large trees growing from small inclusions. The WT growth rate seems to be dependent on a variety of defect characteristics: its form and dielectric constant (and hence local increase of electric stress), hydrophilic property and water solubility of substances comprising the defect, their chemical activity, compatibility of the defect and the surrounding polymer. A large WT growing from a small-size defect is shown in Fig. 4 d.

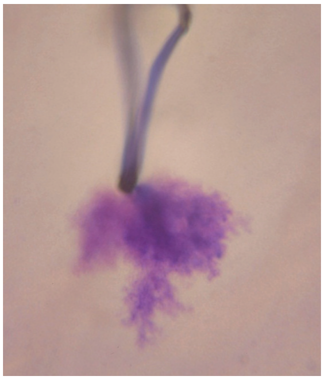

Figure 4a. Water tree growing from the hydrophilic cellulose material fiber.
Stained with methylene blue.

Figure 4b. Vented water tree growing from the semicon screen protrusion.
Stained with methylene blue.

Figure 4c. Bow-tie water tree growing from a foreign inclusion in the insulation bulk. Stained with methylene blue.

Figure 4d. Bow-tie water tree of 1.5 mm length growing from a small inclusion. In this case the image contrast is provided with the help of the so-called Reihnberg illumination (color variant of the dark field microscopic method) – "optical staining" based on the use of light filters instead of staining the insulation slices containing water trees (see photo in **Fig. 4a**-c and **Fig. 6**) with a special staining agent.

WT development in the amorphous phase of the material (item 9). Comparative investigation with the aid of a polarizing and a phase-contrast microscope shows that WTs, as well as other types of degradation of amorphous-crystalline polymers, develop practically in the amorphous phase of the material.

Indeed, as may be seen in Fig. 5 a, b, birefringence, determined by the dielectric crystalline phase organization, undergoes no changes inside the WT as compared with the intact insulation, and as a result the WT is practically invisible in the polarization contrast and at the same time it is perfectly visible in the phase contrast. It means that the crystalline phase of the polyethylene inside the WT remains intact. It is fair to say that this simple proof of the crystalline phase intactness is effective only for “young” and relatively small WTs. Large WTs often scatter light in such a way that they introduce an amplitude contrast into the optical image which does not disappear when the polarizer and the analyzer are in a crossed position. Nevertheless this difficulty may be overcome by using the special technique of video-enhanced polarization microscopy [1].

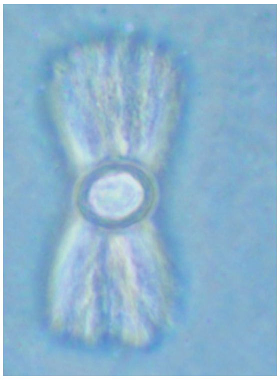

Figure 5a. Bow-tie water tree. The photomicrograph was obtained with the use of the phase contrast method.

Fig. 5b. The same as in **Fig. 5a** but polarization contrast is used instead of phase contrast. The water tree is practically invisible.

Two-stage cable destruction (item 11). In case of the electrochemical ageing of the extruded power cable insulation the failure condition is achieved in the following way. At first WTs are developing over a long period of time; then as their dimensions and the extent of polymer degradation within the WT reach some critical level (enter a certain critical region), electrical trees originate at the water trees as secondary defects and rather quickly they grow through the entire insulating layer causing a breakdown. Photos of WTs at which electrical trees began to grow are shown in Fig. 6.

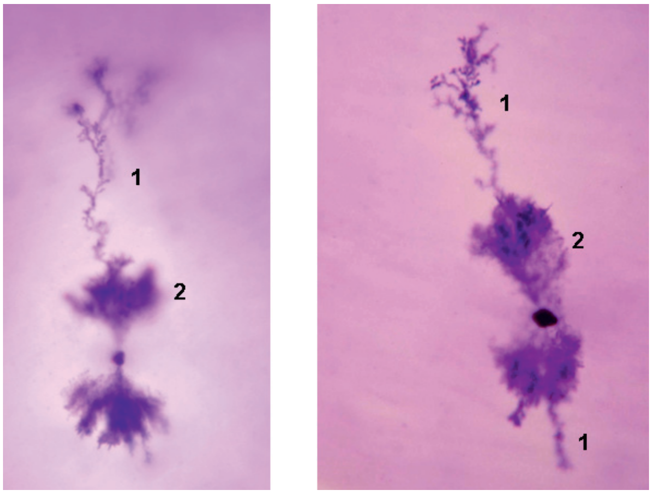

Fig. 6. Electrical trees (1) growing from water trees (2), stained with methylene blue

Therefore on the basis of both our own and foreign test data we may say that there is a rather close analogy between the Rehbinder effect and the WT development. However this analogy cannot be absolutely full for variety of reasons, including the following:

- RE in its traditional meaning refers to mechanical destruction phenomena while WT growth is an electrochemical process;
- RE covers a wide spectrum of phenomena [12] and thus it cannot be determined comprehensively;
- RE suggests that no chemical reactions [11] occur in the degredated material or a “moderate” chemical interaction takes place [12]. At the same time it is known [10] that the WT development is accompanied by local oxidation of the dielectric. Therefore the electrochemical ageing of the extruded power cable insulation should be viewed as only partly reversible process (in the sense that was mentioned earlier – after the moisture is removed the WTs dry up and the cable dielectric strength recovers). With respect to thermodynamics it is proper to regard the WT growth as a relatively weakly non-equilibrium process [14].

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