WATER TREEING

Water treeing is an electrical prebreakdown phenomenon and a mechanism of damage to electrical insulation that occurs under wet conditions. The term treeing is applied to the type of damage that progresses through a dielectric section under electric stress, so that its path generally resembles the form of a tree. In the early days of observation and investigation into treeing, three terms were used to describe it, namely electrical treeing, water treeing, and electrochemical treeing. In fact, water treeing included electrochemical treeing, which originally meant trees stained during growth by chemicals drawn from the surroundings or shields. An analysis of the proper uses of the names by vanRoggen in 1980 resulted in simplification of the two names currently used; electrical treeing and water treeing. In this article water trees are sometimes simply called trees, whereas electrical trees are always designated as such.

Although electrical treeing occurs in inorganic dielectrics, such as ceramic insulators, and moisture intrudes into cracks in them, such damage is not considered water treeing. Water trees have not been found in inorganic materials. The treatment in this article is based on knowledge of water treeing only in organic dielectrics. Treeing has been observed in slightly different forms in solid polymeric dielectrics and in paper/oil insulation systems. Polymeric dielectrics include polyethylene (PE), crosslinked polyethylene (XLPE), polypropylene, ethylene propylene rubber (EPR), ethylene propylene diene terpolymer (EPDM), butyl rubber, silicone rubber, polystyrene, polycarbonate, polyester, and polyvinyl chloride (PVC). Water trees are usually found in electrical insulation that supports at least moderate alternating current (ac) electric stress for extended periods of time in damp or wet locations and at changing, often cyclic, temperatures. These conditions almost completely describe the service conditions for underground, medium-voltage, power distribution cables. In fact, the problem of water treeing occurs not exclusively but commonly in these cables and in their connectors, joints, and terminations. Although electrical trees had been known and studied for many years, it was around 1967 that water trees were first observed by Miyashita and Inoue (1) in electrical insulations operating under water. When these observations were reported by Miyashita (2) and Lawson and Vahlstrom (3) in the early 1970s, a high level of largely commercially supported investigation commenced and has abated only slightly since then. Even though the great majority of the direct buried underground cable failures, over 90%, result from mechanical or connector faults, and electrical failures are more common in connectors and terminations than in cables themselves, water treeing is still believed to be the most relevant deteriorative mechanism for the electrical failure of medium-voltage underground power cables. Electrical trees found in electrically failed cables can grow together with, from, or within water trees, but after initiation usually grow rapidly and result in prompt failure. Water trees alone may, but often do not, result in electrical failure.

The main objectives of current investigations into water treeing are twofold. First, it is scientifically desirable to understand the mechanisms involved in the initiation and growth of trees. This understanding should facilitate the development of tree resistant dielectrics. To this end, experiments are done to investigate the effects of electrical stress, frequency of the applied voltage, mechanical stress, conductivity of the surrounding electrolyte (usually water), temperature, and so on. Understanding these results should reveal whether the mechanism is physical and/or chemical, mechanical fatigue, chemical potential, or oxidation-induced, and therefore the appropriate approach to overcome it. The second goal is to develop an insulation which is inherently as resistant as possible to the formation of water trees. This might be accomplished by analogy, without understanding, by evaluating molecular structures or additive systems, copolymers or blends which might be expected, based on the evidence already in hand, to resist treeing. This approach has already been extensively explored, and some workers have reported some success with this common empirical approach.

After electric treeing initiates at a point of high and divergent electric stress, electrical trees can grow by periodic partial discharge, decomposing material and forming permanent hollow channels, generally parallel to the electric field and with a wide range of sizes from a few micrometers to a tenth of a millimeter in diameter. Electrical tree channels are easily visible because of the difference in refractive index between the solid insulation and the gas that fills the channels and because the inner walls of the channels are often carbonized and darkened.

This is not true of water trees. Water trees do not consist of permanent carbonized channels but have microvoids connected with tracks in the range of 10 nm to 100 nm. Partial discharges have not been positively identified during initiation or growth despite many attempts, and the process is more complicated than electrical treeing. With no discharge or carbonization, water trees are often invisible or barely visible until chemically stained, except in the case of electrochemical trees which are stained during growth. Upon removal of the electric stress and source of moisture, water trees dry out and visually disappear. Upon reimmersing the "treed" section in warm water even without electric stress, water trees reappear in their original morphology. To render the trees permanently visible, they are chemically stained with one of several formulations described in the literature. The first was by Matsubara and Yamanouchi (4). Water-tree shapes and growth are usually measured by destructive optical methods. Nondestructive methods for measuring water treeing include dielec-

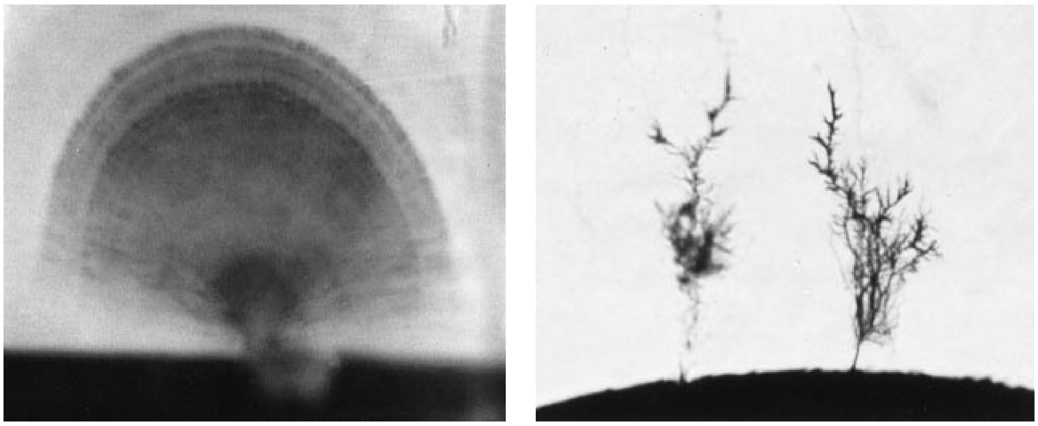

Figure 1. (left) Vented water tree. (right) Vented electrical tree.

tric properties, space charge, and current waveform measurements.

Water trees are not sharply defined but are diffuse and look more like a bush, a fan, or a cloud. The great variety in appearance of the patterns of stems, branches, and tiny cavities which comprise trees, plus the circumstances of their initiation, have led to the many descriptive names applied to them. Their shapes have been sketched by Bahder and Katz (5). Two subcategories of water trees based on their origins are vented and bow-tie trees. Vented trees are initiated at points of electric stress concentration at the surface of the insulation and grow into it. Vented trees are called plumes, streamers, deltas, or broccoli. Bow-tie trees are distinguishable from vented trees. Bow ties are initiated from heterogeneities with stress concentrations within the dielectric, such as small voids or cavities in which the stress is greater than in the surroundings, contaminants with sharp edges or points, or hydrophilic contaminating agglomerates. Bow ties can be symmetrical or asymmetrical. They typically grow symmetrically outward in opposite directions, parallel to the electric stress within the insulation. Single-winged, bow-tie trees have been grown in the laboratory and observed in more than 10-year-old field-aged 20 kV XLPE cables. Figure 1 shows vented water and electrical trees that grew from the surface into the insulation layer of a power cable, and those in Fig. 2 are bow-tie trees. Figure 3 shows electrical trees grown within water trees.

Water trees initiate and grow in the presence of divergent ac electric stress and moisture. Thus the connection of the tree to its source of moisture, which is needed for growth, is explicitly indicated. Water trees have been grown in liquids other than water, but the initiating step is always the formation of finite liquid-filled submicro or micro cavities or filamentary channels. These tiny voids or tracks in the solid-state morphology are formed during manufacturing or by aging. Moisture moves into these voids or channels by diffusion, Maxwell stress, or dielectrophoresis. Condensation of moisture to liquid water under electric stress was proposed in 1974, and current theory states that the chemical potential of water is lower in the condensed state than when dissolved in

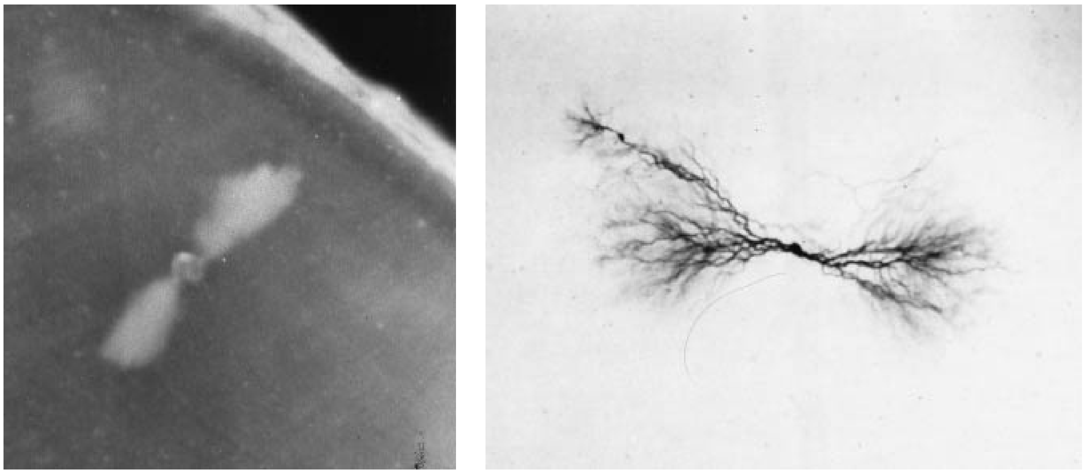

Figure 2. (left) Bow-tie water tree. (right) Bow-tie electrical tree.

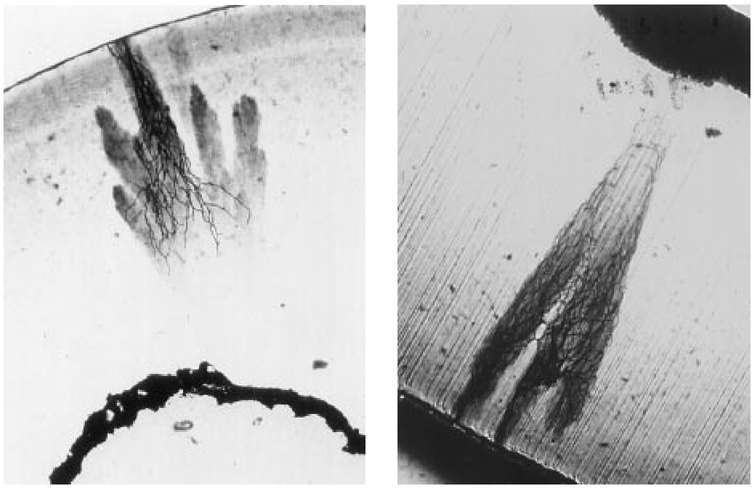

Figure 3. Electrical tree growing within a water tree. Original photomicrographs courtesy of Dr. A. Bulinski, National Research Council Canada.

molecular form. Thus moisture condenses in the electric field and fills existing micro or submicro cavities or tracks. Even though a dielectric may be dry at the start of its life, moisture intrudes by diffusion and moves to the region of maximum electric stress by dielectrophoresis, as suggested by Pohl (6) and Tanaka et al. (7). With sufficient electric energy, the inner surfaces of these water-filled voids or tracks are chemically degraded and become hydrophilic, therefore wettable. The vented trees, which often have an unlimited supply of moisture, can grow continuously with time. The bow tie, on the other hand, lacks an unlimited supply of water and as a result bow ties are limited and very rarely grow to dangerous sizes.

Although electrical trees can grow rapidly after initiation or even as the result of an impulse voltage or lightning strike, water trees grow quite slowly and at lower stresses. Bulinski et al. (8) estimated that electrical trees grow about 1000 times as fast as water trees. It has not yet been possible experimentally to detect critical or threshold levels of stress or energy required to initiate water treeing. Water treeing may or may not be followed by complete electric breakdown of the dielectric section in which it occurs, but in solid extruded insulations it is the most likely mechanism of electric failures that do not occur promptly but rather result from an aging process in a wet location. Usually, failure following the growth of a long water tree occurs after an electrical tree is induced from the water tree tip or opposite electrode to bridge the gap as the result of an impulse or lightning transient. Figure 4 shows an electric tree initiated from the tip of a water tree or induced from the opposite electrode near a water tree.

ELECTRIC DEGRADATION AND FAILURE DUE TO WATER TREEING

Water treeing is a highly localized electrical degradation process. Because the trees contain water which is somewhat conductive relative to the electrical insulating material in which they grow and has much higher permittivity, it is reasonable to expect the electrical properties in the region of water trees to be modified. An obvious problem is that if trees are localized in a small fraction of the length of a cable under test, they may be difficult to detect. Measurements of the conductivity or dielectric loss of samples containing water trees have

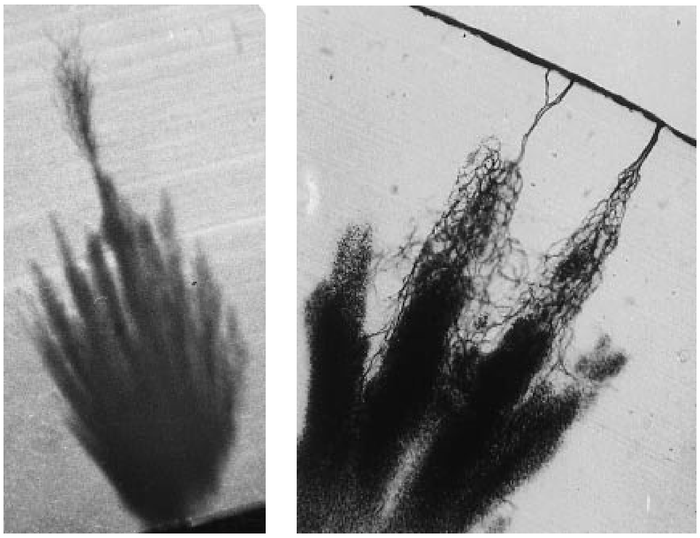

Figure 4. (left) Electrical tree induced from a water-tree tip. Original photomicrograph courtesy of Dr. R. J. Densley, Ontario Hydro Technology. (right) Electrical tree induced from the opposite electrode. Original micrograph courtesy of Dr. A. Bulinski, National Research Council Canada.

produced varying results, and sometimes the conductivity or loss does not increase measurably as trees grow. Some workers claim more success than others. Bahder et al. (9) reported the use of electrical measurements to detect the presence of trees and Radu et al. (10) observed increasing permittivity as trees grow longer under accelerated, uniform, field conditions. Some have attempted to study individual trees and Stucki and Schonenberger (11) reported an asymmetrical permittivity ratio of at least 1.3, measured parallel and perpendicular to the tree growth direction of single trees.

The presence of small water trees may not cause any significant reduction in breakdown voltage or increase in conductivity or loss as trees grow. It has been observed that vented trees grown beyond 50% of the insulation thickness result in a high failure rate, but power factor or electric breakdown strength are not changed until trees have grown through more than 10% of the insulation thickness. Both dielectric breakdown strength and loss are influenced by the extent of insulation degradation and the water content.

Most workers observe that the decrease in residual ac breakdown strength is influenced more by the length of the longest vented trees than the density of trees. This is true for both laboratory and field-aged cable specimens. Other workers report that the presence of vented water trees reduces impulse strength and dc breakdown voltage and increases tan delta. However, there are differences of opinion about the effect of bow-tie trees. Although it seems unlikely, some workers find that bow ties do not affect breakdown or impulse strength whereas others report that they do and that the effect increases with tree density and length, as expected.

The reduction in breakdown strength is generally determined by the longest length of vented trees rather than their densities or populations. Impulse, ac, and dc dielectric breakdown strengths are reduced when trees grow to a certain length. If bow-tie tree density becomes so great that it becomes correlated in position, breakdown has also been known to go from one bow tie to another and result in failure at a lower level of breakdown strength. Of course, not every tree, even at the same length, represents the same damage. That depends on its degradation level (channel conductivity in the tree channel), tree morphology (particularly tree-front asperity and shape), and the electrical characteristics of its tree root and untreed surroundings.

Many of the speculations about water-tree growth assume that the trees act like conductive intrusions in the field and increase the electric stress on the remaining thickness of insulation. However, water trees sometimes grow completely through an insulation without electrical failure. Pelissou and Noirhomme (12) showed that water trees in field-aged XLPE behave as dielectrics. In many cases, water treeing leads to dielectric failure by way of electrical tree formation and bridging. The growth rate of an electrical tree exceeds that of a water tree by several orders of magnitude. Bulinski et al. (8) found that the conversion of a water tree to an electrical tree under ac stress usually occurs when the tree grows to within about 0.2 mm of the ground surface for both field-aged 5 kV XLPE cables and molded samples. The severely treed cable maintained its life under normal operating stress at 60 Hz unless the ac stress was raised to 5 to 6 kV/mm. They also reported that a short duration lightning impulse (1.2/50 ms) requires higher overvoltages than switching surges (250/2500 ms) to induce breakdown and that higher temperature shortens the conversion time. Their findings suggest that the breakdowns induced by water trees require overvoltages from lightning or switching surges.

Power company records also reveal that water-treed cables often fail after electric storms, and this type of failure is most common in areas of high lightning frequency. Hence it is generally assumed that insulation containing water trees is sensitive to electrical surges and lightning strikes and that these are the mechanisms of failure. Recent investigation of the effects of dc impulse testing (thumping) of aged underground cables insulated with XLPE and containing water trees concluded that cable life is generally shortened, which supports the hypothesis. Although others found no detrimental effect from direct current (dc) testing, it is expected that such tests will be used with more caution.

SOLUTIONS TO INHIBIT WATER TREEING AND RESTORE ITS DAMAGE

It is known that if the intrusion of moisture from outside can be avoided, dielectrics do not suffer significant water treeing. One approach to preventing moisture intrusion is the use of a moisture-impermeable sheath around the cable, such as a continuous metallic outer sheath. This is very costly and not economical for medium-voltage power cables although it is used for high-voltage cables. For medium-voltage power cables, the most practical, economic, and effective approach, which resists the growth of water trees, is to use an insulating material which retards or resists tree growth. Additional steps for further enhancing resistance to treeing are improving the surface smoothness between insulation and semiconductive shields so no surface protrusions remain to provide stress concentrations, minimizing or eliminating impurities or contaminants by using cleaner insulating and semiconductive shield materials, and filling the interstices between the strands of stranded conductors to prevent collection of water.

The use of tree retardant insulation, such as TR-XLPE used in medium-voltage power cables, effectively extends cable life in wet environments as demonstrated by accelerated cable tests and field aging cable tests. It is economically practical and widely used. Significant increases in lifetimes determined by accelerated cable tests have also been achieved by improvements in the purity and cleanliness of both insulation and semiconductive shields used in cables. An outer jacket made of polyethylene, which has extremely low moisture vapor permeability, has also produced very good results in increasing the actual service life of underground, medium-voltage power cables.

The deterioration of electrical properties caused by water treeing is substantially reversed by drying a cable with a continuous stream of dry nitrogen gas, sometimes even by dry air, applied through the strand. Further improvement is achieved by forcefully impregnating certain silanes or silicones into the insulation. However the treatments must be continued to maintain the effect. The technique and treatment are commercially available and used. The results, reported by Faremo and Ildstad (13) and Arias (14) for 15 and 25 kV PE and XLPE URD cables laid in the 1960s and 1970s, show that treatment by silicone almost completely restores the ac and impulse breakdown strengths.

FACTORS AFFECTING WATER TREEING

The factors affecting water treeing can be classified as electrical, environmental, manufacturing, mechanical, and thermal. Electrical factors include ac and dc voltage and frequency. Environmental factors include intrusion of conductive liquids (such as water) or other species (ions, electrolytes), polar liquids, gases (air, oxygen), and other chemicals. Manufacturing factors include contaminants introduced during the manufacturing and transportation processes, voids, defects, protrusions, and morphological changes due to sample preparation. Mechanical factors include bending, tension, compression, torsion, and vibration. Thermal factors include temperature, temperature gradient, and cycling due to current loading. The purpose of considering these factors is to determine, if possible, the mechanism which leads to initiation and growth of water trees. Among these aging parameters other than manufacturing factors, Steenis concluded, based on phenomenological evidence, that solutes in water and frequency of applied voltage are the parameters most effective in accelerating water-tree growth.

Electrical Stress

Effect of ac Voltage. The first controllable, variable, driving force for electrical aging usually considered is voltage or electric stress. Most workers have found that increasing the electric stress on polyethylene increases the water-tree growth rate. However, no threshold or critical voltage that initiates water treeing has been detected at the low end of the voltage range. Ashcraft (15) used his multiple point-to-plane water-treeing test geometry to study the effect of field strength and verify this conclusion. He found that the growth rate is linearly proportional to the square of electric stress. Several publications report that water-tree growth increases with applied voltage, but a few refute that, and one even reports a maximum in growth rate versus electric stress response.

At the high end of the test voltage range, Eichhorn (16) observed that electrical trees grow in very wet conditions at rates slower than in dry conditions but faster than water treeing. A concern about using higher electric stress as the primary accelerating factor is the possibility of initiating and propagating a water tree at a typical electrically heterogeneous site which would not grow a tree under normal service stress. In general, deviations from simple ohmic charge conduction occur at fields beyond 10 kV/mm for most polymers.

Effect of dc Voltage. It has been believed that water trees cannot grow in a dc field, but Franke et al. (17) reported bushy and vented water trees grown under a constant dc stress in HMW LDPE (high molecular weight, low density polyethylene). He measured growth rates of 0.04 and 0.2 mm/h, respectively, for these two tree forms, under an average stress of 22 kV/mm in 70°C artificial sea water. Noto (18) also reported water trees grown in epoxy resins under dc stress. The former may result from the extremely high dc field strength which has sufficient electric energy for chain scission at a low rate, and the latter from chemical reaction between water and epoxy. Czaszejko (19) observed an increase in the average water-tree length in samples subjected to dc voltage of 4 U_0 for 15 min before and during ac aging compared with those under ac electrical stress only and not exposed to dc voltage. This result suggests that dc stress accelerates the growth rate.

Effect of Frequency. It has been shown that test voltage frequency affects accelerated test programs. As the frequency increases, the time for initiation decreases, and the rate of growth increases. The relationship, which has been generally accepted, is given approximately by Bahder et al. (20) as

$$\alpha = \left(\frac{f_t}{f_o}\right)^k \tag{1}$$

where α is the acceleration factor, f_t is the test frequency, f_o is the operating power frequency, and k is the acceleration factor given as 0.45 to 0.7. Some have reported the acceleration factor as 0.4 to 0.6 and others observed from 0.1 to 0.45 for frequencies up to 1 kHz. The frequency adopted for most small specimen accelerated testing is 1 kHz, and it is recommended that investigations be made to assure that the mechanism does not change with frequency before accepting test results.

Suzuki et al. (21) reported that water-tree growth increases with increasing number of zero crossings of the applied voltage. Crine et al. (22) analyzed existing experimental results and made the significant demonstration that the number of ac field cycles is a much better normalizing parameter of electrical aging than time and that water-tree length and density increase logarithmically with the number of ac field cycles, relatively independent of the test frequency.

Environmental

Environmental factors include intrusion of conductive liquids, such as water with and without conductive species (ions and electrolytes), polar liquids, and gases (such as oxygen). Water trees have been grown in liquids other than water. Conductivity is a key factor affecting water-tree growth. However, it is not positively known whether nonconductive liquids that have high dielectric constants can grow water trees.

Environmental effects observed involve the conductivity of surrounding water, contaminated semicons, and ions in solution. The effects of sulfur and silver and how they color trees during growth have been reported. Blue and brown trees contain iron. Results suggest that almost any ions accelerate the growth rate and some are more effective than others. For example the same concentration of NaOH is more effective than NaCl. Ashcraft (23) found that the water-tree growth rate is directly proportional to the square root of the ionic strength of whatever electrolyte is present and is enhanced in high pH electrolytes. Filippini et al. (24) reported that water-tree growth correlates with the absolute hydration entropy of ions. In particular, the lowest propagative rates are obtained with high valence ions, for example, Fe^{3+} and Al^{3+}. It is generally agreed that increasing the water conductivity increases the rate of initiation and growth of water trees. This is one of the few positives which can be stated. However it has not been possible to completely prevent water treeing by using commercially deionized or distilled water. An external supply of ions is not required, because water has sufficient conductivity to initiate water treeing under moderate electric stress.

Miyashita et al. (25) grew vented trees in XLPE using aprotic, polar organic liquids, such as acetonitrile or propylene carbonate, instead of water. It is claimed that electrolytes, such as lithium perchlorate and even trace amounts of ethylene glycol antifreeze, increase treeing. Fournie et al. (26) reported that water treeing is promoted by the gaseous products resulting from water decomposition at a metal electrode, and Koo et al. (27) suggests that the gas in contact with the material does not influence the initiating stage but increases the propagation rate, especially when nitrogen is used.

Manufacturing

Voids or Contaminants for Bow-Tie Trees. The effects of applied voltage, frequency, contamination, and void size on the occurrence of bow-tie water trees in steam-cured polyethylene has been studied, and the conclusion is that the contamination and void size are most important. Tree density increases with the contamination level, and the tree lengths are roughly proportional to the size of the voids that initiate them.

Defects or Protrusions at the Interface for Vented Trees. It was assumed for some time that a sharp, physical, conductive protrusion at the interface between electrode and insulation was required to initiate the growth of a vented water tree. Certainly most of the trees examined in early power cables were initiated by sharp protrusions like the carbon loaded fibers comprising semiconductive tapes. With the advent of smoother, extruded, semiconductive shields, trees usually grew from rough spots on the surface, like carbon black agglomerates or grit. Subsequently many water trees have been observed and studied without discovering such an initiating point.

The initiation site can be a physical (visible) or chemical (invisible) stress enhancement. Because water trees have been observed and studied without discovering any initiating point, the initiating site might be the free volume voids or tracks between polymeric molecules in the amorphous regions. Of course, if a visible sharp physical defect is present, tree initiation and growth is usually favored at the defect because electrical stress is highly enhanced near the tip. Using point-to-plane test geometries, many workers have observed that increasing the tip radius decreases the water-tree growth. The maximum stress $E_{\max}$, at a sharp conductive electrode of hyperbolic shape can be calculated theoretically by the following point-to-plane equation derived by Mason (28) or one of several others summarized by Eichhorn (29):

$$E_{\max} = \frac{2d}{r \ln\left(1 + 4\dfrac{d}{r}\right)} E_{\text{avg}} \tag{2}$$

where E_{avg} is the average electric field. The field enhancement factor is 200, 250, or 360 at a tip of radius $r = 4$, 3, or 2 μm that has a point-to-plane distance $d = 3.175$ mm. The enhancement factor at the same tip radius of 3 μm decreases from 430 to 250 if the point-to-plane distance decreases from 5.750 to 3.175 mm. This suggests that water trees grow in a decelerating manner toward the adjacent ground surface because of the decreasing field enhancement. Of course, after a water tree is initiated from this well-defined tip, this equation is no longer valid because the shape and conductivity of each tree front vary. Growth is driven by its own tree morphology and conductivity within a given insulating material.

Morphological Effects. It is believed that water trees grow in semicrystalline polymers through the amorphous regions between spherulites and possibly between the lamellae within spherulites. Water trees are more easily initiated and grown in amorphous regions between rather than in spherulites, and some spherulites are partially destroyed in the tree regions. Fan and Yoshimura (30) observed that water trees grow more slowly in LDPE samples with fewer and smaller spherulites, whereas Raharimalala et al. (31) showed a water tree growing through a spherulite but failed to reveal any effect of crystallinity, even a difference between quenched and annealed polybutene samples.

Mechanical

Experiments have been done to determine the effects of mechanical stresses on water-tree growth in dielectrics under simultaneous electric stress. The form of the specimen is important because of the stresses which can be applied, so both cables and molded plaques have been used. Moderate uniaxial stress, as tension, and the resulting molecular orientation affect vented trees, and the resistance is weaker in the direction of orientation. No effect on bow ties was noted. However contrary results have also been reported with the caveat that they may result from stress-induced microcracking. Vibrational stresses, within the range tested, have shown no effects. Summaries have been presented on this subject by Noto (18) and Shaw and Shaw.

Thermal

Temperature is the most controversial parameter involved in water treeing. It would seem that there should be a fairly strong temperature effect in water treeing. However, as temperature increases, the densities of polymeric materials generally decrease with expansion: crystallinity and modulus for semicrystalline polymers decrease, moisture vapor permeability increases, chemical reaction or degradative rates increase, and the mobility of free charges increases. Because water treeing is a complicated process and is related to many factors at the same time, the effect of temperature is quite dependent on material types and test conditions. Some materials show slight increases and others show no change or even decreases in water-tree growth with temperature. In fact there is such a divergence in test results that the test methods themselves are suspect in the eyes of some. The reason for the serious differences may be that all the investigators have not yet concentrated on performing the same test under exactly the same conditions and using exactly the same specimen materials prepared in the same way. Until this situation obtains, there will continue to be major disagreements.

WATER-TREE TESTS

Because of the commercial importance of water treeing and the interest in preventing it, many laboratory investigations have been carried out and many accelerated test methods developed. Basically they can be divided into two classes: first, those designed to compare materials for their sensitivity or resistance to water tree growth. These tests use compression molded plaques, pads, or cups as specimens; secondly, those which compare finished articles or systems, like power distribution cables, to determine their resistance to tree growth by their retention of dielectric breakdown strength or expected service lifetimes.

Miniature cables have been used to fill the gap between materials tests and full-size cable tests to study the effect of various insulating materials and semiconductive shields under accelerated testing conditions. For several years simple insulated wires, extruded insulation on a copper conductor, were mistakenly represented as miniature cables. With the development of more sophisticated extruders and extrusion dies, now it is possible to make small cables which consist of appropriate layers and materials to serve as insulation and semicon shields. The first well established miniature cable test, reported by Land and Schadlich (32) at Kabelmetal Electro, operates at 9 kV (9 kV/mm maximum stress), 50 Hz, 30° or 70°C in tap water bath, and 45° or 85°C conductor heating for 1000 h. The electric breakdown strength is determined before and after aging. The results among different miniature cable tests vary and do not always correlate well with either materials or full-size cable tests.

As with any nationally or internationally supported consensus standard, the problem of designing tests to give comparable results is difficult, and the major difficulty is in the details. The problems involve at least the form of the specimen and its preparation, specimen conditioning or preconditioning, test temperature, electric stress, frequency, nature of the electrodes, electrolyte and container, specification of the end point (initiation, growth rate or time to failure), number of replicates and statistical treatment of results, the form of the report, and a statement of significance. Possibly the most difficult point is the use of preconditioning. Some consider the fair test is to start with materials as delivered and fabricated into finished items of trade. Another view is that some careful preconditioning eliminates fugitive agents, such as acetophenone, which is a tree retardant yet has high vapor pressure and escapes with time even without use. The result of this approach is a more sensitive test that emphasizes differences among materials and distinguishes among them in shorter times. Diagnostic tests after accelerated wet aging can be water-tree analysis, retention of electric breakdown strength, and time to failure. Breakdown strength can be determined by various test methods; dc, impulse, ac step, or ac short time breakdown tests. The 5 min step test is commonly used. Of course, not all diagnostic test results have the same resolution to differentiate water-treeing degradation among various insulating materials.

Materials Test

The first electrical treeing test devised to compare materials used a single, sharpened steel sewing needle slowly inserted into a heated specimen and point-to-plane geometry at 60 Hz under a dry environment. It was improved and published by Kitchin and Pratt of Simplex Wire and Cable Company in 1958. In 1964 McMahon and Perkins of DuPont modified this test to be a double-needle test. The tests determine the "characteristic voltage" or threshold voltage required to initiate an electrical tree, with a precision of ±1 kV at controlled temperature. This test has been extended to determine a Weibull characteristic time to failure from 10 specimens tested under controlled temperature and applied voltage. The double-needle test provides more consistent and less scattered data than the single-needle test and with further modifications has been established as an American Society for Testing and Materials (ASTM) Standard Test Method, D-3756, since 1979.

Small scale materials tests for water treeing initially took the same approach using sharpened steel needles to generate sharp pointed conical depressions in molded plaques which cause stress enhancements and subsequently filling the points with water. However, no test has been developed to assess the initiation of water treeing because no threshold voltage has been found experimentally. The earliest and simplest material test to determine the resistance to vented water-tree growth using a standard defect was proposed by Nitta (33) in 1974, then modified by Ashcraft (15) in 1979. Since then, many materials tests have been developed and used. They fall into two general types: (1) tests with artificial defects at the interface with water which have well-controlled shapes, like the sharp pointed conical cavity filled with water used in ASTM and Conference Internationale des Grands Electriques à Haute Tension (CIGRE) needle tests, sand-blasted surfaces used in the National Research Council Canada (NRCC) test, and a molded-in conductive film with a sharp point; and (2) tests with a smooth interface which places the insulation material between and in contact with molded semiconductive shields used in CIGRE cup and University of Connecticut (UCONN) Rogowski tests or with salt water on both sides used in a U-tube test, described by Eichhorn. The former has a divergent field because defects are present and it uses salt water as the conductive medium, whereas the latter has a uniform field like a cylindrical conductor (wire) or Rogowski electrode. Water trees are smaller when they grow from the interface of semiconductive shields than from salt water under the same aging conditions. Some of these material tests are made at frequencies of 1 kHz to minimize the time required for tree initiation, growth, and failure. In addition to frequency, sharp electrodes, and conductive electrolytes, accelerating factors include overvoltage and elevated temperatures.

Tests with defects usually determine vented water-tree lengths and by calculation the growth rates. Tests without defects can determine vented and bow-tie tree length, density, aged electric breakdown strength. Test specimens can be compression molded plaques or slabs, extruded films or thin insulations on wire, injection molded cups or containers, and sections cut from finished full-size cables. In most of these material tests, the specimens are usually immersed in an electrolyte of 0.01 or 0.1 M NaCl rather than tap or distilled water or commercially deionized water. It is considered that the standard solution prepared with distilled water is more uniform than the alternatives, provides a reasonable standard for reference, and is not inconvenient in the small volumes required for these tests. Most of the water-tree materials tests are fixed-time tests. Real-time tests are not common but have been reported.

For several years there has been interest in establishing a standard water-treeing test for materials. This interest has been addressed in the United States by the ASTM and in Europe by CIGRE for the International Electrotechnical Commission (IEC). After several years of consideration and development, the ASTM adopted a water needle point-to-plane test based on Ashcraft's test as ASTM Standard Test Method D-6097-97. The test sample geometry, shown in Fig. 5, is a compression molded disk 6.4 mm thick and 25.4 mm in diameter

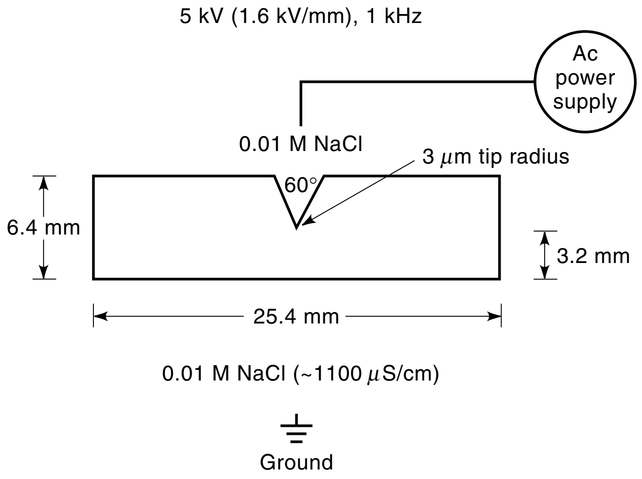

Figure 5. Schematic diagram of the ASTM D6097-97 test setup.

with a conical defect of included angle 60° and a tip radius of 3 μm located at the center of each disk. All peroxide-cross-linked test specimens are preconditioned in a nitrogen-purged vacuum oven at 80°C for seven days to remove volatile components, like peroxide by-products, before electrical aging. A solution of 0.01 M NaCl in distilled water is used as the controlled conductive medium on both sides of the specimen. The point-to-plane distance (from the high-voltage defect point to the ground) is 3.2 mm. The test runs under an applied voltage of 5 kV ($\sim$1.6 kV/mm) at room temperature and is accelerated by frequency at 1 kHz for selected aging times, typically 30 days. A vented water tree is initiated from the water needle tip and grows into the insulation. Ten specimens per material are electrically aged. The maximum tree length parallel to the electric field and point-to-plane distance are determined optically after electrically aged samples are stained and sliced. The precision of tree length measurement is usually about 0.01 mm. Typical standard deviations in tree length measurements among the replicates of a given material sample vary from 0.02 to 0.10 mm. A longer tree has a larger standard deviation. In 1997 the CIGRE task force TF 15-06-05 also proposed a test draft to IEC sub-committee SC 15B. The CIGRE proposal includes three test methods: (1) method IA for plaque specimens with water needles in a divergent ac field, similar to ASTM D6097, developed by AEG; (2) method IB for plaque specimens under a uniform ac electric stress, developed by Siemens, and (3) method II for cup-shaped specimens sandwiched between two layers of semiconductive shields under a uniform ac field, based on the Norwegian Electric Power Research Institute (EFI) cup test method. Other water-treeing materials tests have been used and reported in the literature.

Full-Size, Finished Cable Tests

To minimize reservations as much as possible about accelerated materials testing, while still accomplishing comparisons in reasonable time, real full-size finished cables have been used as specimens. The test conditions have been modified from those of practical commercial service to accomplish acceleration. These tests offer the advantage of a large database of available test results for comparison with new materials, constructions, extrusion conditions, and so on.

Retention of Dielectric Strength Tests. The most popular and well-established cable test is the Accelerated Water Treeing Test (AWTT), written by the Association of Edison Illuminating Companies (AEIC) and included in their specifications AEIC CS5 for XLPE and AEIC CS6 for EPR. This test is run using 15 kV rated cables with insulation thickness 4.39 mm (175 mils), 1/0 AWG compressed Class B aluminum or copper conductor filled with water, unjacketed, with a concentric wire neutral. The specimens have a shielded length of at least 4.6 m (15 ft) inside a 76.2 mm (3 in.) inside diameter plastic (PE or PVC) conduit filled with tap water plus enough cable to provide sufficient test terminations. Cables are preconditioned before aging by 14 thermal load cycles without voltage applied. Each load cycle is accomplished by conductor heating 8 h on and 16 h off to achieve 130°C in the conduit during the last 4 h of the current on period.

Cables are electrically aged at three times rated voltage to ground, about 6 kV/mm (150 V/mil), and 49 to 61 Hz for 120, 180, and 360 days. Conductor current for specimen heating is induced with toroidal transformers for 8 h on (about 75°C) and 16 h off for five consecutive days per week. The current magnitude is sufficient to achieve an in-water insulation shield temperature of 45° ± 3°C by the end of current on period and an in-air conductor temperature of 90°C by the end of the current on period on a dummy cable sample. At the end of each aging period, at least three cables are removed and subjected to a voltage breakdown test while still wet. The ac breakdown is determined with a five min step test using 1.4 kV/mm (40 V/mil or 7 kV steps at 175 mils). This qualification test is widely used in North America and requires a minimum electric strength of 10.4 kV/mm (260 V/mil) after 120 days of aging. A revised version of the test method which will include both XLPE and EPR will be approved by Insulated Cable Engineers Association (ICEA) and by AEIC. Other accelerated cable tests, similar to the AEIC AWTT test, are used in Europe and Japan. The 2-year International Union of Producers of Electric Energy (UNIPEDE) and DIN VDE 0273 tests are widely used in Europe.

Another wet aging test for full-size cables that is carried out at water temperature of 30° ± 5°C and includes surges to simulate switching effects in underground cables has been developed by Katz et al. (34) for Electric Power Research Institute (EPRI). Cables used are 15 kV- and 28 kV-rated 1/0 AWG power cables with 4.4 and 7.2 mm (175 and 280 mil) insulation wall thickness, respectively, on compressed aluminum conductor. Cables are not preconditioned before aging, and the conductor interstrand spaces are filled with water. Ten coils 73 m (220 ft) long are immersed in a water tank and electrically aged under 1, 2, and 2.5 times rated voltage to ground, 1.7, 3.5, and 4.4 kV/mm (43, 87, and 109 V/mil), for as long as 48 months. Three transient 120 kV stresses in the 1.5 x 40 μs impulse standard waveform are applied within a time interval of 3 min at a rate of 3 times per week during aging. No current load is applied during aging. At the end of the predetermined aging period, one coil is taken out and cut into 6 lengths (11.7 m/piece) for the 5 min step test to breakdown using 4 kV/mm (100 V/mil) steps.

Lifetime Tests. The other category of full-size cable tests is a time to breakdown test which includes the Accelerated Cable Lifetime (ACLT) and National Electric Energy Testing, Research, and Applications Center (NEETRAC) cable design aging tests. The former was proposed and developed by Lyle (35,36), and the latter established by Hartlein et al. (37).

The NEETRAC cable design aging test, supported and used by some utilities and cable makers to establish the performance characteristics of different extruded dielectric cables, uses 25 kV- or 35 kV-rated 1/0 AWG power cables with 6.7 or 8.8 mm (260 or 345 mil) wall thickness, respectively, on aluminum conductor. Four 36.4 m (120 ft) coils per cable specimen are used. Cables are jacketed with 1.28 or 2.05 mm (50 or 80 mils) of low density or linear low density PE. Cables are thermally preconditioned in air for 200 h at a conductor temperature of 120° ± 5°C, then immersed in tanks filled with tap water. No water is used in the conductors. Cables are electrically aged at four times rated voltages about 8 kV/mm (200 V/mil average stress) at 52 and 69 kV for 25 kV and 35 kV rated cables, respectively. The load current is cycled 12 h on and 12 h off 5 days/week. The conductor current is maintained at 150 A for the first 3 h, and 225 A during the remaining 9 h. Water temperature in the test tank is raised to 50° to 55°C by conductor heating. The conductor temperature during the current load is expected to reach 80° to 90°C to simulate the 8 h peak usage in the field. When a failure occurs, the failure section (about 40 ft) is cut out. The coil is reterminated and returned to the test. The aging failure data and other diagnostic test results, including residual ac breakdown strength for cables without failures and water tree analysis, are reported.

The ACLT test offers the options of running the test at 1, 2, 3, or 4 times rated voltage to ground and controlling the maximum conductor temperature during thermal cycling to 45°, 60°, 75°, or 90°C. Groups of specimens are contained in large tanks. Deionized water is used in the tanks and to fill the interstices between the strands of the conductors. Cable specimens may be #2 or 1/0 AWG copper or aluminum. The lifetimes of replicates are analyzed by log normal or Weibull statistics. However, this test appears to be material-dependent, because the severity of test conditions appears to be different for XLPE and EPR. For EPR, electric failures occur more rapidly at cyclic temperatures with maxima of 45° and 60°C than at 75° or 90°C as reported by Walton et al. (38), whereas XLPE fails only at the higher temperatures. In 1981 Wilkens (39) also found more significant ac dielectric breakdown strength reduction and sample failures for EPR cables aged at 35°C than at 50°C under 4.5 times rated voltage in a wet environment up to 3 years. It has been suggested that because EPR does not fail during aging in accordance with an assumed higher temperature/voltage stress–shorter life relationship, a different failure mechanism is responsible for EPR. In the same experiments, carried out with water both inside and surrounding the full size cables under test, it was observed that removing the surrounding water from the test conditions decreases the life of the EPR cables but increases the life for XLPE cables. Because the most commonly used 4,4 ACLT test conditions are 90°C conductor cycling temperature and 4 times V_g, any imperfection or different residual mechanical stress built up from cable fabrication and sample preparation can be very critical. The ACLT test may not be appropriate for differentiating materials with significant differences in dielectric properties and mechanical modulus, such as lossy, flexible EPR versus low loss, rigid XLPE. However, this test has been used to demonstrate the improvements in the same class of insulating materials or semiconductive shields for uses, such as XLPE versus TR-XLPE or conventional versus supersmooth extra clean semiconductive shields. A test similar to this ACLT test is under development by a working group of the IEEE, Power Engineering Society, Insulated Conductors Committee, which may become a full-size cable life test standard.

Statistical Treatment of Test Results

Because tree related degradation is associated with localized imperfections or stress enhancements in the insulation, the values of water-tree length, population, electric strength, and failure times usually exhibit a large statistical variance. Therefore replication, a reasonable number of test specimens, and some form of statistical treatment must be used to assign values and significance to the results. No single datum point should be used to differentiate materials in these tests. As the level of sophistication in these tests has improved, the level of statistical interpretation of data to rank and differentiate materials and constructions has also improved. The arithmetic average with its standard deviation is often used for tree length and dielectric breakdown measurements. The Weibull, log normal, and other appropriate statistics have also been used, particularly for breakdown strength and time to failure data. Materials should be statistically differentiated by their test results with a confidence level of at least 90%.

Peaked distributions are usually observed in typical water-treeing tests and are close to log normal or Weibull distribution curves. A longer tree has a larger deviation. This implies that growth itself is probabilistic or stochastic through a random statistical process. Lifetime data in accelerated laboratory tests do not correlate well with field failure statistics, but retained breakdown strength data show similar trends in field-aged performance for cables insulated with the different dielectrics, XLPE, TR-XLPE, and EPR. Retained breakdown strength is determined by the longest length of vented or bow-tie trees rather than their population. Ildstad et al. (40) presented the physical justification for using extreme value statistics to treat the maximum tree length as a stochastic variable and estimate the most probable length of the longest tree in a given length of cable. He showed that when water tree penetration exceeds about 75% of the insulation wall, the limited Weibull type of distribution may give a better extrapolation than the unlimited first asymptotic distribution function.

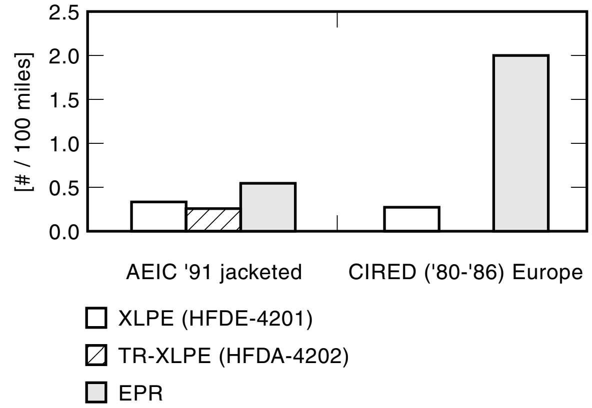

Figure 6. Field failure comparison of XLPE, TR-XLPE, and EPR cables.

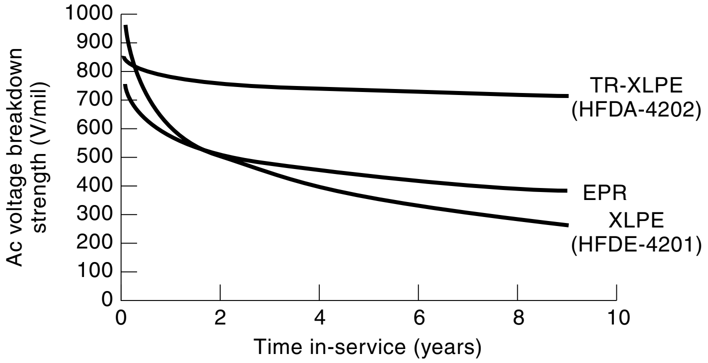

Figure 7. Comparison of ac breakdown strengths of field-aged 35 kV-rated XLPE, TR-XLPE, and EPR cables.

FIELD-AGED PERFORMANCE—UTILITY SERVICE RECORDS

There will always be problems with the acceptance of accelerated tests by some engineers, and the reasons are understandable. It can be argued that any acceleration factor introduces an unnatural variable into the evaluation which might change relative results. For this reason, records have been kept on failures and frequency of repair to utility-owned distribution cables in service. The first consolidated records from more than one company kept in the United States were put together by Thue (41) from 1972 until 1980. More complete records of a smaller database have been kept and analyzed by NELPA, AEIC and CIRED (42). Figure 6 shows field failure statistics for XLPE, TR-XLPE, and EPR cables. Figure 7 compares the retained ac breakdown strength of field-aged EPR, XLPE, and TR-XLPE cables as a function of time in service, based on data reported by Katz and Walker (43), and Xu and Gorton (44).

INSULATING MATERIALS USED IN UNDERGROUND POWER CABLES

Power cables are usually classified according to the type of insulation: gas, tape, oil, and extruded solid dielectrics. Gas insulation by compressed SF_6 gas is a costly system but provides excellent dielectric properties. It is only used for getaways from substations and line crossings and is not suitable for underground distribution cable applications. The principal tape insulation is oil-impregnated cellulose paper or paper polypropylene laminate which has been widely replaced by extruded dielectrics. The extruded solid dielectric insulations include thermoplastic polyethylene, cross-linked polyethylene, and crosslinked ethylenepropylene rubbers. The use of underground power cables has significantly increased for reasons of land cost, reliability, reduction in frequency of repair, safety, and beautification. Medium-voltage underground power cables are typically rated from 5 to 69 kV.

Low density polyethylene was introduced as an insulating material for power cables in the 1940s. When the thermoplastic, high molecular weight, low density polyethylene (HMW LDPE) replaced the standard paper/oil insulations and rubbers in medium voltage power cables, it was considered a tremendous improvement. PE has a lower dielectric constant, lower power factor, very low moisture permeability, higher breakdown strength, chemical stability, and purity than paper/oil, rubber, or PVC insulation. Therefore, it was surprising when service failures began to be noticed. From 1961 until 1980, Thue of Florida Power and Light Company (41) kept annual cable failure records for the utility industry which showed that failure rates increased steadily for HMW LDPE cables. Closer examination showed that certain construction features, like the tape strand shield, and some manufacturers and production periods were associated with high failure rates. Improvements in materials, design, and construction have all followed. Extruded semiconductive shields were developed and used to replace the tape strand shield. In fact, a switch from HMW PE to XLPE (cross-linked polyethylene) to meet the 90°C service temperature requirement, had already commenced in the 1960s and accelerated until the use of HMW PE essentially ceased in 1978. It was found that XLPE is less susceptible to treeing, and later studies showed that the chemical residues of the cross-linking reaction, including acetophenone, provide some retardation to initiation and growth of trees until lost because of their high vapor pressure and diffusion. Improvements were also made in cable manufacturing, such as triple extrusion and dry cure instead of steam cure. Cleanliness in insulation and semiconductive shields has also been significantly improved.

In 1978, tree retardant, thermoplastic polyethylenes were introduced by Union Carbide and E.I. DuPont to replace HMW LDPE. Trade names were UCAR TR 6202 and TREBAN 100, respectively. UCAR TR 6202 proved to have better long-term effectiveness in tree retardance and was used increasingly until 1982 when a crosslinked version (HFDA-4202) was substituted by Union Carbide. This material is called by the acronym TR-XLPE (tree-retardant crosslinked polyethylene). It has become the insulation of choice for medium-voltage cables in North America and has had excellent field performance to date for underground medium-voltage power cables as shown in Fig. 7. The well-established accelerated water treeing tests, such as ASTM D6097-97 and AEIC AWTT tests, shown in Figs. 8 and 9, also differentiate the performance differences in water-tree retardance between TR-XLPE and conventional XLPE materials.

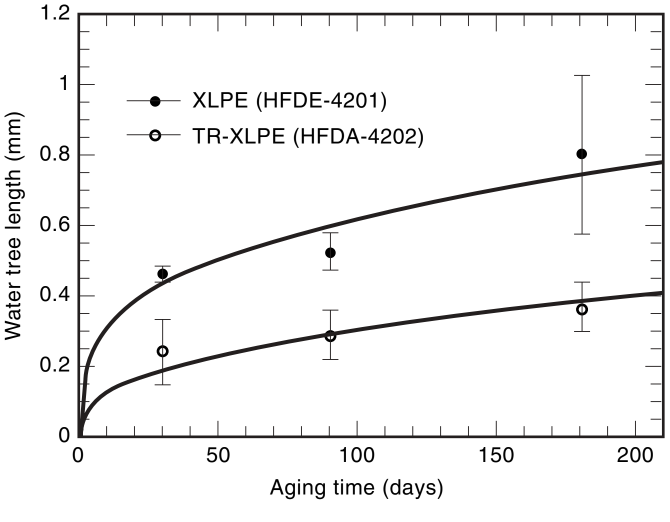

Figure 8. Water-tree growth comparison of XLPE and TR-XLPE materials in the ASTM D-6097-97 test at room temperature.

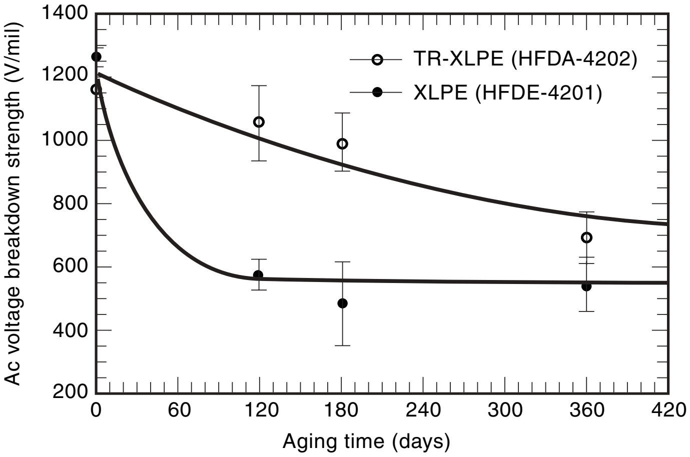

Figure 9. Comparison of ac breakdown strengths of 15 kV-rated XLPE and TR-XLPE cables in the AEIC AWTT test.

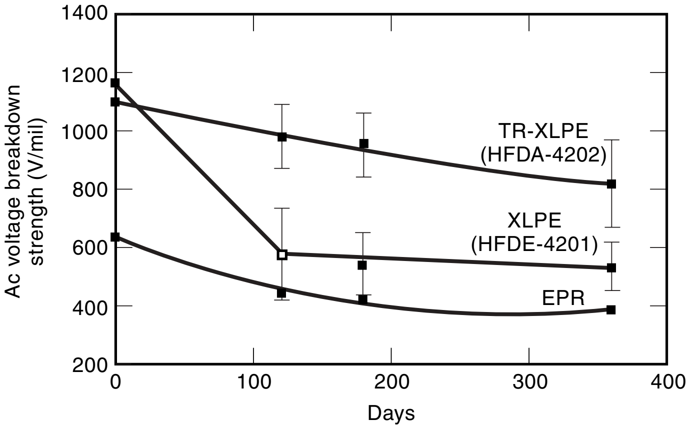

Figure 11. Comparison of ac breakdown strengths of 15 kV-rated XLPE, TR-XLPE, and EPR cables in the AEIC AWTT test.

In the 1990s, several tree-retardant XLPEs were also introduced by British Petroleum (BP) (BP-118 and 119Y), Borealis (LE-4210), AT Plastics (AT 320TR), and Pirelli. However, not all of them have the same performance in well-established accelerated water treeing tests; such as ASTM D6097 and AEIC AWTT. Obviously, the definition of tree-retardant XLPE is ambiguous. It is a commercial and a technical issue. Today, the performance of conventional cross-linked polyethylene insulated cable has improved because of better cleanliness and the use of true triple-head extrusion. Of course, TR-XLPE with better tree retardance and electrical performance is very desirable and commercially important. A working group in the IEEE, PES, ICC was launched in 1997 to define the meaning of TR-XLPE and differentiate it from conventional XLPE from the user's rather than the material supplier's point of view.

Other materials used for insulating underground power cables are primarily EPR and EPDM, a copolymer and terpolymer, respectively, of ethylene and propylene, plus a diene in the terpolymer. These materials have some advantages and some disadvantages compared with polyethylene. They are relatively soft, flexible and resistant to corona discharge. They are also physically weak and are highly filled with other materials and chemically cross-linked to achieve some strength and processability. The composite is electrically more lossy than XLPE. Many publications have shown that EPR grows water trees (43–45). Figure 10 shows a photomicrograph of a water tree grown in a 15 kV underground EPR cable after 6 month service (43). Although water trees grow in all three of these materials, and in other solid organic polymeric dielectrics, there is disagreement about whether the mechanisms are the same or not. They are based on observed differences in the conditions which accelerate electric degradation. The retained ac breakdown strengths of full-size EPR, XLPE, and TR-XLPE cables in the AWTT test up to 360 days are compared and shown in Fig. 11.

TREE MORPHOLOGY

Treeing has been studied most extensively in extruded electrical insulation. In translucent polymeric insulation, such as polyethylene, visual observation of treeing is relatively easy and therefore it is often studied by optical methods. Various tree structures have been observed, ranging from those composed of a small number of coarse radiating units, through a

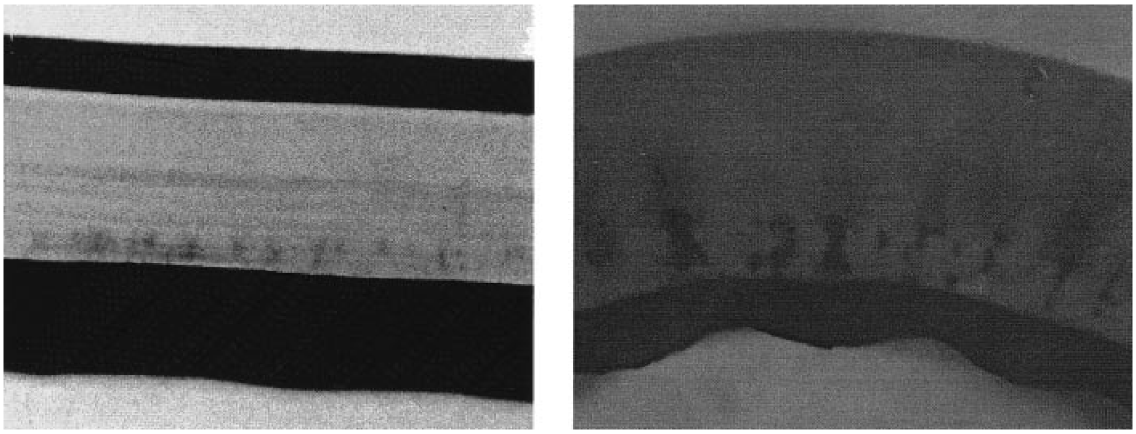

Figure 10. Photos of water trees in EPR cables.

congested array of channels, to those where the envelope of the tree appeared to be filled with small voids. Optical microscopy after chemical infiltration (permanganic etching), scanning electron microscopy (SEM), and transmission electron microscopy (TEM) imaging techniques have been used for many years. More recently fluorescence microscopy and confocal laser scanning microscopy in 3-D views have been added. The microscopic examination of tree structure is typically carried out with thin sections to reveal details. Therefore, channels normal to the direction of sectioning appear as circles or ellipses in two dimensions and look like continuous channels only if they lie within the section for some finite length. Moreau et al. (46) showed that water trees consist of microcavities connected by electro-oxidized tracks. Three dimensional views by confocal laser scanning microscopy reveal the tree structure as a network of continuous submicroscopic branched and zigzag channels measuring in the range of a tenth of a micrometer.

Water trees consist at least of tiny moisture-filled regions. Microscopic observations and moisture analyses verify that. When the source of moisture is removed, the trees visually disappear, unless they have been chemically stained during formation (electrochemical trees) like sulfur trees, silver trees, or trees colored blue or brown by iron salts. That indicates that the cavities collapse and do not have permanent hollow shapes. If the cavities were permanent and did not collapse, they would become more visible after drying than before because the difference in refractive index between polyethylene (1.5) and air (1.00) is greater than the difference between polyethylene and water (1.33). Adding to this idea, laboratory experiments have been performed to grow water trees in a thin section of translucent material like polyethylene, watch the trees disappear with drying, and then reappear with exactly the same morphology when rewetted. Virgin polyethylene is highly hydrophobic, and degradation renders it hydrophilic. The inside surfaces of the water tree channels are hydrophilic, and therefore are easily wetted. Thermal Brownian motions or secondary bond attraction may collapse these tiny channels when moisture is removed. The moisture refills and expands the structure by wicking, a well known effect of surface tension in capillaries.

PROPOSED THEORIES AND MECHANISMS OF WATER TREEING

Water trees cannot be initiated from a perfectly smooth, homogeneous, featureless interface nor within a continuous, uniform, isotropic medium. The first step in tree initiation and growth requires localized electric stress concentration of some kind: physical or chemical, visible or invisible. It could be a sharp point, a foreign impurity or contaminant, tiny cavities and tracks which might or might not initially be moisture filled, a surface crack and field-assisted diffusion, or even an ionic concentration near the smooth surface of the semiconductive layer of a power cable which may alter the local chemical potential. Many, but not all, of the mechanisms considered today involve a cracking, splitting, or forced intrusion type of failure where flexible molecular chains are pushed aside in low-density amorphous regions. Therefore water treeing might sometimes be called an electromechanical prebreakdown phenomenon. Other possible mechanisms proposed are chemical, mostly oxidative, in nature.

Another generalization is that oxidation of the walls of cavities and channels occurs either as a prerequisite to or during water-tree extension. It is a bit easier to accept the latter because evidence of oxidation by spectroscopy and the iodostarch reaction is limited to treed regions and not the surroundings. The presence of solvated ions in the moisture supply accelerates the rate of penetration into dielectrics under electrical stress. The presence of certain ions under moderate electrical stress over extended periods of time might cause some oxidation of the channels. It is claimed by some that oxidation is necessary for water trees to grow, but results are not unequivocal. Including high concentrations of antioxidants and antiozonants as tree retardants has not prevented water trees, and oxidation in advance of tree growth has not been proven. Steennis suggests that electrochemical degradation is the cause of vented tree growth because the effects of electrochemical degradation are consistent with the phenomenological observations.

Water trees form when moisture penetrates into a dielectric and condenses in an electric field. If there is a single mechanism which explains this, as some workers claim, it has not yet been agreed upon. Excellent reviews on water-treeing mechanisms have been published and are listed as recommended additional reading. Among proposed explanations are (1) electroosmosis; (2) electrostriction due to penetration under Maxwell force into surface cracks; (3) dielectrophoresis which drives a polarizable particle toward the strongest point in a divergent field; (4) electrothermal heating to enhance thermal degradation and increase permeability and diffusion at elevated local temperature caused by dielectric or joule heating; (5) partial discharge; (6) electron bombardment; (7) electromechanical fatigue which accompanies the periodic deformation of cavities that contain moisture by electrostatic effects; (8) electrochemical degradation or oxidation; and (9) chemical potential.

Electro-Osmosis. A very interesting speculation was presented by Mole (47) using an equation by Helmholz published in about 1879. Water moves through pores by electro-osmosis or electroendosmosis under the action of an electric field. This is caused by the presence of an electric double layer in which ions of one sign are attached to the pore walls and ions of the other sign are carried by the water. These layers are assumed to be only about 50 pm (~0.5 Å) thick. In pores open at one end and closed with a sharp point at the other and assuming values for ξ, the zeta or electrokinetic potential, ϵ, the relative permittivity of the liquid, d, the pore diameter, and V, the applied voltage, the pressure at the end of the pore, p in newtons per square meter can be calculated by the following equation:

$$p = \frac{\xi \cdot \epsilon_r \cdot V}{4.5 \cdot \pi \cdot d^2 \cdot 10^9} \tag{3}$$

The pressure at the end of the pore calculated by Mole is 2.23 MPa (22 atm) for a pore diameter of 1 μm and 223 MPa (2200 atm) for a diameter of 100 nm with $\xi = 10$ mV, $\epsilon_r = 78$, and $V = 10$ kV. For very fine channels the pressures can be enormous. This electro-osmotic pressure is higher than the typical elastic limit for polyethylene (about 20 MPa). When the polarity of the applied voltage reverses, the water pulls back from the end of the channel. In a dc field, this electro-osmotic pressure will not vanish, and trees could be initiated and grow by this mechanism. However, the effect of hammering due to frequency can occur at the end of the channel, a tree front. Water-tree growth is expected to increase with increasing applied voltage, frequency, and temperature if the mechanical yield stress decreases with temperature.

Electrostriction

Electrostriction describes the variation in the dimension of a dielectric in an electric field. The following equation modified by surface tension describes the electrostrictive force on a water-filled void in polyethylene:

$$p \approx \frac{3}{2}\epsilon_0[3\epsilon_1 + (\epsilon_2 - 1)(\epsilon_2 + 2)]E^2 - \frac{0.06}{r} \tag{4}$$

The pressure parallel to the direction of the electric field is p. The average electric stress is E. The radius and permittivity of water-filled cavities are r and ϵ_2. The mechanical stress outward from a water-filled microvoid is estimated on the order of 20 MPa, beyond the elastic limit of PE. Fine channels from the water-filled microvoid are created.

Dielectrophoresis

Dielectrophoresis considers the movement of uncharged but polarizable particles in a divergent field by induction. The force on such a particle in cylindrical geometry is given by Pohl as follows:

$$\boldsymbol{F}_e = -4\pi r_0^3\epsilon_0\epsilon_{r1} \cdot \frac{\epsilon_{r2} - \epsilon_{r1}}{\epsilon_{r2} + 2\epsilon_{r1}} \cdot \frac{V^2}{r^3\left[\ln\left(\frac{r_1}{r_2}\right)\right]^2} \cdot \boldsymbol{r} \tag{5}$$

where the radius of the particle is r_0, ϵ_0 is the permittivity of free space, ϵ_{r1} and ϵ_{r2} are the relative permittivities of the medium and the particle, respectively, V is the potential on the inner electrode, the outer electrode is grounded, r_1 and r_2 are the radii of the inner and outer electrodes, respectively, r is the distance of the particle from the axis of the inner electrode, and $\mathbf{r}$ is the unit radius vector. The direction of motion depends on the dielectric constant of the polarized particle. The negative sign indicates that the force is directed radially inward when ϵ_{r2} exceeds ϵ_{r1}. Water is most influenced by dielectrophoretic force because of its high permittivity of about 78 when compared with other impurities or additives. Calculations indicate that clusters of water with a radius of 500 Å (0.05 mm) would be drawn into regions of high electrical field. The effect would not work with molecular water because the distance of charge separation is too small. Recently, Patsch (48) reported that a stable water cluster of five molecules, about 0.32 nm (3.2 Å), could lead to the high dielectrophoretic forces that produce the liquid precipitates found in water trees.

Dielectrophoresis explains how water moves from its source toward the maximum stress site where a tree is growing but not how the tree grows because these two effects occur in opposite directions. It also explains how mobile polar additives act as voltage stabilizers or tree retardants to reduce the maximum local stress.

Electrothermal

Joule or dielectric heating of water increases its volume more than that of the surroundings and might cause cracking or splitting. However, the moisture vapor permeability of the medium also increases with temperature and would diminish the effect. Localized joule heating becomes important when conductivity or dielectric loss is increased by water, ions, and polar groups. A temperature rise from joule heating changes the local electrical properties. Of course, conductivity and dissipation losses also depend on temperature and electrical stress. The electric energy dissipated in the region that contains water could be much higher than in the dry regions. Degradation may be accelerated in these water-filled regions.

Partial Discharge

Partial discharge at very low levels is an attractive idea which could also explain the oxidation observed. However, the level possible, using the equation of Bahder et al. (9), is very low:

$$Q = \epsilon_r\epsilon_0 A\left(\frac{E_{\max}}{E_{\text{avg}}}\right)\frac{\Delta V}{d} \tag{6}$$

Assuming that ϵ_r is the relative permittivity of polyethylene at 2.1, ϵ_0 is the permittivity of free space, A is the discharge area, a circle with a point radius of 1 to 10 μm, $E_{\max}/E_{\text{avg}}$ is the stress enhancement due to a nonuniform electrical field (assume between 10 and 100), ΔV is the local potential in voltage associated with the discharge (about 345 V which is the Paschen minimum in air), the partial discharge level, Q, would be between 0.00002 and 0.02 pC. No equipment available responds to such low discharge levels, so the effect cannot be verified.

In 1974 Nitta (33) observed light emission from the sites of water-tree growth. The observation was made by using photographic film in contact with a transparent ground plane in a multiple point-to-plane test geometry. The light first suggested partial discharge, but attempts to detect discharges were unsuccessful and calculations of the probable discharge magnitude suggest they would be undetectably small. Subsequently, attention focused on mechanisms of luminescence, electroluminescence, chemiluminescence, and oxiluminescence. Results are not unequivocal, but oxyluminescence is a reasonable explanation for the observation because oxidation accompanies water treeing and has been observed independently by other techniques.

Electron Bombardment

Yamanouchi et al. (49) developed a theoretical equation assessing the durability of XLPE, from water-tree growth, assuming that the tree channel is highly conductive. Growth is assumed to be the result of C–C bond scission due to bombardment by accelerated electrons in microvoids. The decrease in electric breakdown strength is proportional to the decrease in the remaining insulation thickness as the longest water tree approaches the counter electrode. Their calculated durability data agreed well with the durability of both XLPE and EPR cables obtained from electron microscopic data. Assuming that the number of accelerated electrons is proportional to the electrical stress and that the probability that electrons have an energy greater than the C–C chemical bond energy G_0 ($\sim$3.6 eV) is given by an exponential distribution function, a water tree length l is described as follows:

$$l = kE \exp\left(\frac{-G_0}{qd^*E}\right) t \qquad (7)$$

where q is the charge on an electron, d^* is the mean free path of an electron in a void, k is the rate constant, E is the electric stress, and t is time.

In 1992 Patsch (56) also proposed bond scission as the decisive point in both electrical and water-treeing deterioration mechanisms. In electrical treeing very strong electric fields create hot electrons and/or high energy photons that cleave molecular bonds and produce radicals. Then, small dry voids and tree channels are formed in which gas discharges and carbonization occurs. In water treeing, the precipitation of water clusters driven by dielectrophoresis induces a local mechanical or electrical overstressing of the neighboring polymer chains and leads to a slow rate of localized chain scission under a moderate ac field.

Electromechanical Fatigue

One assumption which is verified by experimental results is that the growth of water trees and their damage is cumulative with the number of voltage cycles which have occurred within a certain range of frequency. Some experiments in which the frequency of the test voltage is varied show that the growth increases with cycles accumulated instead of frequency, and some workers have reported a maximum. This observation supports the idea of fatigue damage due to mechanical flexing within the dielectric as the water-filled regions change shape, an apparently reasonable assumption.

Electrochemical Degradation or Oxidation

A contrary idea is that water treeing follows pathways generated by oxidation which renders them hydrophilic in a hydrophobic matrix and thus provides the pathway for water to intrude. Electrochemical processes generate oxidizing species which in turn lead to partial oxidation of the material and cavities. Therefore, they become hydrophilic. This explains the condensation of water from a generally hydrophobic material into hydrophilic regions. Further, microscopic channels that connect clusters are not channels in the geometric sense (hollow tubes) but pathways of enhanced permeation. This mechanism does not involve mechanical damage, cracking, splitting, or deformation. Rather water treeing represents a localized chemical effect. Oxidation occurs which changes the chemical structure of the material in pathways by providing for the ingress of moisture and the further development of water trees.

From an analysis by Boggs, a water tree can range from a nearly electromechanical to an electrochemical tree, depending on the degree of oxidation and test conditions. The material can yield mechanically to extend the tree. Evidence of such yielding from the work of Dorris et al. (50), who measured electric signals from growing water trees, suggests that the water tree extends between 10 and 100 nm per step. When water trees are grown from water needles in very short periods in very strong fields, very little evidence of electro-oxidation is found in the dielectric based on FT-IR measurement of carboxylates (51,52). In this case, the electro-mechanical forces are so high that there is relatively little electro-oxidative degradation to be detectable by FT-IR but sufficient for chemical staining. On the other hand, when water trees grow in installed cables at low stresses for years, the dielectric is heavily electro-oxidized because much greater damage must occur before the dielectric is weakened to the point that it yields electromechanically to the very low forces at normal operating stress. In this view, water-tree growth is not that different from electrical tree growth, except for the mechanism by which the dielectric is damaged to the point that it yields electromechanically.

The following statements, among others, have been published by experienced investigators about the effects of oxidation in the growth of water trees:

1. In regions degraded by the growth of electrical trees, the dominant polar group found by FTIR is carbonyl.
2. Similar studies in regions degraded by water trees show carboxylates.
3. Ketones (carbonyl) from thermal oxidation and carboxylates from electro-oxidation are observed.
4. Carboxylates are found more often in field-aged cables than in laboratory test specimens by some and by others in all water trees where their concentration depends on the type of polyethylene.
5. Oxidation is catalyzed by some ions (such as transition-metal, sulfate, and carboxylate ions). These ions (Cu^+/Cu^{2+}, Fe^{2+}/Fe^{3+}, and Al^{2+}/Al^{3+}) can be recycled by electrochemical reactions.
6. Semiconductive shield materials are a reservoir of metal ions for water treeing. Ionic species (such as K^+, Na^+, Ca^{2+}, Al^{3+}, Mg^{2+}, Fe^{2+}, Fe^{3+}, Cu^+, Cu^{2+}, Zn^{2+}, Si^{4+}, S^{4+}, and S^{6+}) have been found in treed regions. It is believed that ionic impurities in semiconductive materials or from ground water diffuse into the cable insulation and promote water treeing.
7. Neither enhanced tree growth nor significant oxidation was found in LDPE aged in strong oxidizing solutions of $FeCl_3$ or $KMnO_4$, which suggests that oxidation is not responsible for tree growth.
8. The oxidation level of water-treed regions may be higher than that in the surroundings, but oxidation in regions under N_2 atmosphere is greater than that produced under O_2 atmosphere.
9. Moderate oxidation levels present before electrical aging do not affect initiation and growth of vented water trees. Preoxidized specimens grow fewer and shorter bow-tie trees than nonpreoxidized ones. Treed insulation may be less oxidized than untreed insulation. There is no definite evidence that oxidation affects water-tree initiation in field-aged XLPE insulated cables.

Thus it appears that a conclusion regarding oxidative effects must be postponed because the published results and opinions are contradictory.

Chemical Potential

A chemical potential, defined as the derivative of the field-dependent Gibbs free energy with respect to solvated ions, was proposed by Zeller (53) in 1991 as the driving force for water treeing. Zeller showed that this chemical potential can be many electron volts, sufficient to cause electrooxidation. Analytic formulas of electrochemical potential for an ellipsoid with aspect ratio A and the long axis parallel to the field are presented following:

$$\mu_1 = \frac{-E^2\sigma\epsilon_1}{\epsilon_0\omega^2}\left\{\frac{1}{B_1^2 + K^2\dfrac{\sigma^2}{\omega^2\epsilon_0^2}} - \frac{K\left[(\epsilon_2 - \epsilon_1)B_1 + K\dfrac{\sigma^2}{\omega^2\epsilon_0^2}\right]}{\left(B_1^2 + K^2\dfrac{\sigma^2}{\omega^2\epsilon_0^2}\right)^2}\right\}\left(\frac{1}{n_\mathrm{w}}\frac{\partial\sigma}{\partial c_1}\right) \tag{8}$$

where $B_1 = \epsilon_1 + (\epsilon_2 - \epsilon_1)K$ and the symbols have their accepted meanings. Subscripts o, l, w, 1, and 2 indicate free space, liquid, water, liquid, and polymer, respectively and

$$K = \frac{1}{2\left[\sqrt{\left(1 - \dfrac{1}{A^2}\right)}\right]^3}\left[\log\frac{1 + \sqrt{\left(1 - \dfrac{1}{A^2}\right)}}{1 - \sqrt{\left(1 - \dfrac{1}{A^2}\right)}} - 2\sqrt{\left(1 - \dfrac{1}{A^2}\right)}\right] \tag{9}$$

For a sphere, $K = 1/3$.

If $E = E_0 \sin \omega t$, the previous chemical potential has a dc and an ac component whose frequency is 2ω, as shown following. It depends on E_0 and also on changes in E_0.

$$\mu_l = \frac{-E_0^2\sigma\epsilon_1}{\epsilon_0\omega^2}\left\{\frac{1}{B_1^2 + K^2\dfrac{\sigma^2}{\omega^2\epsilon_0^2}} - \frac{K\left[(\epsilon_2' - \epsilon_1)B_1 + K\dfrac{\sigma^2}{\omega^2\epsilon_0^2}\right]}{\left(B_1^2 + K^2\dfrac{\sigma^2}{\omega^2\epsilon_0^2}\right)^2}\right\}\left(\frac{1}{n_\mathrm{w}}\frac{\partial\sigma}{\partial c_1}\right)\left(\frac{1 - \cos 2\omega t}{2}\right) \tag{10}$$

Zeller showed that chemical potential versus water conductivity has a peak. As expected, chemical potential is proportional to the square of the applied stress or voltage. However, his calculated peak chemical potential (up to 1,000 eV) is too high for chain scission in a low water conductivity range (10^{-9} to 10^{-6} S/m), even for theoretically pure water (5.5×10^{-6} S/m).

COMPUTER SIMULATION OF WATER TREEING

The increasing power and availability of computers has introduced new approaches into investigation of treeing, its initiation, growth, and failure mechanisms and the behavior of materials under the conditions which favor water treeing. The growth of trees in two and three dimensions has been simulated by random walk statistics and fractals. Finite-element and field-mapping methods are used to model protrusions and calculate stress enhancements more accurately. Czaszejko (54) presented computer simulation of a 3-D growth pattern generated by a random walk to resemble a water tree grown from a needle electrode. The pattern was embedded in a 3-D impedance network in which appropriate electrical properties were allocated to the regions occupied by the water tree (filled with water or void channels) and the surrounding dielectric (polyethylene). His simulated results suggest that water-tree channels cannot be connected if water within them has conductivity higher than 10^{-6} S/m. They could be interconnected and completely filled with water only if the conductivity of the water was not over 10^{-6} S/m. Such low conductivity seems unlikely in practice (0.0041 S/m for distilled water). Because all polymeric insulating materials are heterogeneous in the micrometer range, Jow et al. (55) stochastically simulated water-tree growth by using a field-enhancement equation and studied the effects of electrically heterogeneous inclusions at various concentrations and sizes on tree shapes and growth time.

CONCLUSION

Water treeing is an interfacial phenomenon. Trees grow from an electrically heterogeneous site within an insulation (bow-tie trees) or from an interface of an insulation (vented trees). The vented trees, often with an unlimited supply of moisture, grow continuously with time and cause electrical deterioration, but bow-tie trees very rarely grow to dangerous sizes because they lack an unlimited supply of water. The length distribution of vented trees usually has a peaked shape close to either a log normal or Weibull distribution because of its stochastic characteristics. Dielectric breakdown strength or failure is determined by the longest length of vented tree rather than tree densities or average length. Trees of the same length have different effects on breakdown strength reduction or the conversion to an electrical tree for final breakdown because of differences in the degradation level (conductivity) in the tree channel, tree morphology (particularly tree-front asperity and shape), and the electrical characteristics of its tree root and surroundings.

Water treeing is a highly localized degradation. It may well be inevitable for currently available polymeric dielectrics used under moderate electrical stress in a wet environment. A visible defect is not necessarily required to initiate or grow a water tree. However, the presence of a sharp physical defect significantly enhances the local field and accelerates water-tree initiation. The initiation site might be an invisible stress enhancement in the nanometer range, such as free volume voids or tracks between molecules in the amorphous region of a semicrystalline polymer. These tiny voids or tracks are usually formed during manufacturing by heating and cooling cycles or result from aging.

Moisture or mobile polar liquids move into these voids or tracks by nonfield or field-assisted diffusion and condense to fill them. To this point the process is diffusion limited and reversible. Assuming the chemical hypothesis of water treeing, if sufficient electric energy exists at the liquid–solid interface, chain scission might be induced, most likely at the end or side groups of molecules residing in these free volume routes. Such damage is irreversible and to a certain extent, where the inner surfaces of these water-filled regions are chemically degraded, they become hydrophilic, therefore more easily wetted. Further degradation increases the dimension of the voids or tracks from the nano into the micro and millimeter range, which is then macroscopically recognized as water treeing.

From the viewpoint of chemical bond energy, water treeing is an energy-driven, slow degradative process rather than a stress-driven fracture process. Theoretically, water treeing can occur in a dc field, and indeed it has been observed and reported, but it requires a higher applied voltage level to overcome the thermodynamic activation energy of chain scission. The growth rate is expected and observed to be slower in a dc than in an ac field. It is likely that higher frequency accelerates tree growth by fatigue. Ions, particularly cations, usually accelerate the growth by increasing local conductivity and chemical potential to promote chemical degradation. Higher temperature alters the morphological and thermodynamic state and the materials' electrical properties, all critical to treeing. Higher stress or voltage magnifies the significance of some electrically heterogeneous sites where local degradation would not occur under normal service conditions. Therefore, temperature and stress may not be the best choices as the primary acceleration factors in accelerated water-treeing tests. Frequency and conductivity may be preferable.

Water treeing has three distinct phases: initiation, growth, and conversion to an electrical tree which results in failure. An electrical tree grows from, toward, or within a water tree. The main differences between water trees and electrical trees are that water trees (1) grow at lower voltage or stress in an ac field; (2) grow only in organic materials, (3) require the presence of water or a polar liquid, (4) have a lower growth rate; (5) form water-filled microvoids during growth; (6) grow without detectable partial discharge; and (7) grow strongly dependent on the frequency of the voltage applied.

Treeing is one of many electrical degradation processes. Not all are as optically visible as treeing. In some cases depending on conductivity in its pathway, a water tree can penetrate the entire insulation thickness without causing electrical failure. In other cases, insulations are degraded to failure without water treeing. Therefore, formulating a general electrical degradative and failure mechanism, including treeing, from thermodynamic and kinetic aspects with a stochastic nature is the first step in assessing and predicting the service life of electrical insulating systems used in dry and wet environments. Of course, understanding the effect of a material's morphology and molecular structure on tree-related degradation is important for developing and using new tree-retardant materials.

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JINDER JOW
ROBERT M. EICHHORN
Union Carbide Corporation

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