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REVIEW

WATER TREEING IN POLYETHYLENE - A REVIEW OF MECHANISMS

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ABSTRACT

A literature survey on the mechanisms of water-treeing in electrical cables is presented. The survey provides an introduction, some background, and examples of current research on water-treeing mechanisms. The mechanisms of water-treeing have been broken into three categories: chemical, electrical, and mechanical.

Along with discussion on the types of mechanisms, methods are discussed for reducing tree growth by fillers, additives, or structural changes in polyethylene. Some interesting new theories have been proposed which may help to explain the appearance and growth of water trees in electric cables.

1. INTRODUCTION

Water treeing is a prebreakdown phenomenon associated with dielectric cable failure. It is currently suspected that buried cables throughout the country are laced with these defects which will inevitably produce an accelerating failure rate.

In general, a tree is the name given to the type of damage in dielectrics that, when made visible, assumes the shape of a tree. Unlike electrical trees (Fig. 1), which have distinct hollow channels, water trees are diffuse and indistinct, and seem to disappear upon drying (Fig. 2). This suggests that water trees consist of minute paths along which water penetrates under the influence of a voltage gradient. When the voltage and water are removed, the trees disappear. Upon re-immersion, the trees take on their original appearance [1-6] demonstrating that the damage to the insulation is indeed permanent. A dye is usually required to make water trees visible, whereas electrochemical trees are ones that are permanently stained by chemicals drawn from the insulation, the shield or the conductors, or ones that are introduced from the external environment during the growth process. There has been a controversy in the nomenclature between "electrochemical" and "water" trees [7]; van Roggen [87] has suggested the universal use of "water" rather than "electrical" trees. Because the mechanism need not involve any chemical reactions [9], and for historical reasons, we will employ the phrase "water tree" in this review.

Most workers agree that points of high electrical stress invariably facilitate the initiation of water trees. This stress can cause polymer degradation, fatigue or cracking, which in turn can initiate a water tree [8]. The stress could be caused by a void (Fig. 3), contaminant, or a protrusion in the insulation [9-11] usually at the insulation shield interface [6,12-15].

The mechanism of water tree growth is a very complex subject, and an appreciable number of mechanisms have been researched and proposed. Due to large scale differences in initiation vs. growth patterns, it has been suggested that there may be two mechanisms; one would govern initiation of water trees and the other, the growth of water trees [6,8,16,17]. Certainly it is possible, even likely, that several parallel effects are at work during the propagation of trees, the importance of each effect depending upon conditions and material.

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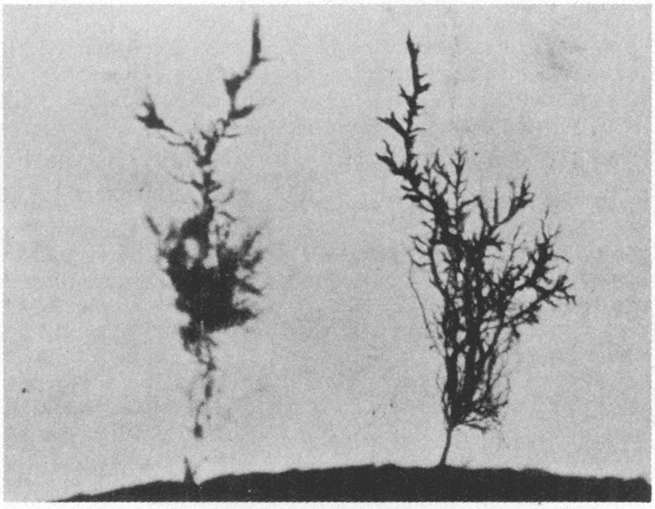


Fig. 1: Electrical Trees

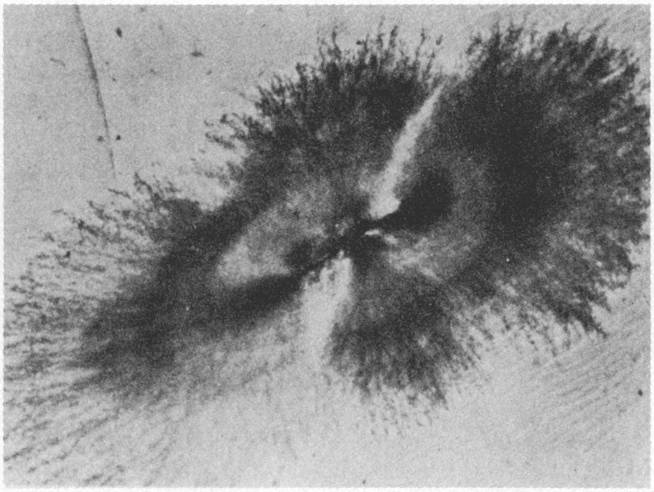


Fig. 2: Water Tree

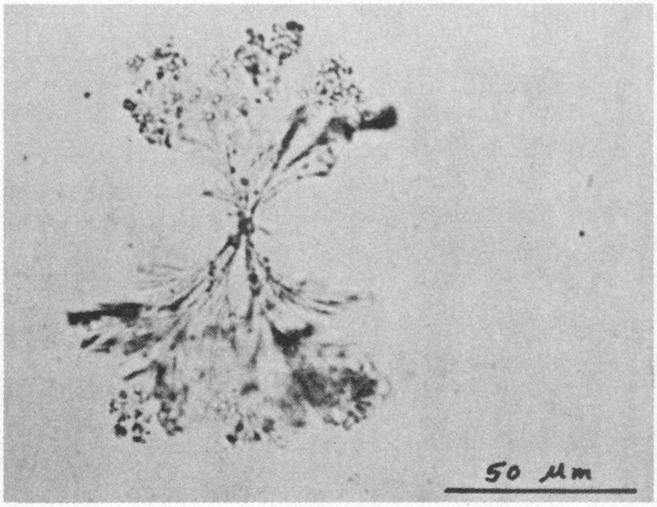


Fig. 3: Bow-tie tree from structural irregularity

The main concern about water trees is whether or not they will lead to failure of cables. Some authors have suggested that water trees will lead to failure if one tree bridges the insulation [1]. This implies that the maximum tree length is more important than the average length [18] or the number of trees in determining breakdown resistance [19,20]. Others suggest that water trees lead to electrical trees which in turn lead to breakdown [4,6,7]. Clearly the growth rate of water trees and the change of this rate with time are additional topics of importance, as well as the correlations between cable life (or failure frequency) and tree population and size distribution.

2. HISTORY

Treeing is not a new phenomenon, but has been known since about 1920 to occur in paper/oil cable insulation [1]. Since World War II, polyethylene has become a very popular insulant due to its favorable dielectric characteristics, longevity, and low cost. It was anticipated that polyethylene would last essentially indefinitely under most conditions.

In 1971, Vahlstrom and Lawson discovered that several buried cables, recovered after failure, contained tree-like damage [21,22]. Since then an all-out effort has been made to determine the cause of trees in polyethylene insulation.

Polyethylene has superior qualities as an insulator, yet even with its low moisture permeability, water has been found to permeate polyethylene cables [23]. The growth of water trees is very dependent upon the environment and voltage stress; however, the voltage stress required for inception of water trees is much less than that required for electrical trees [2,11,24]. Immersion of the cable in liquid water is not essential; a high humidity environment (65% R.H., 50°C) can also support water tree growth [25].

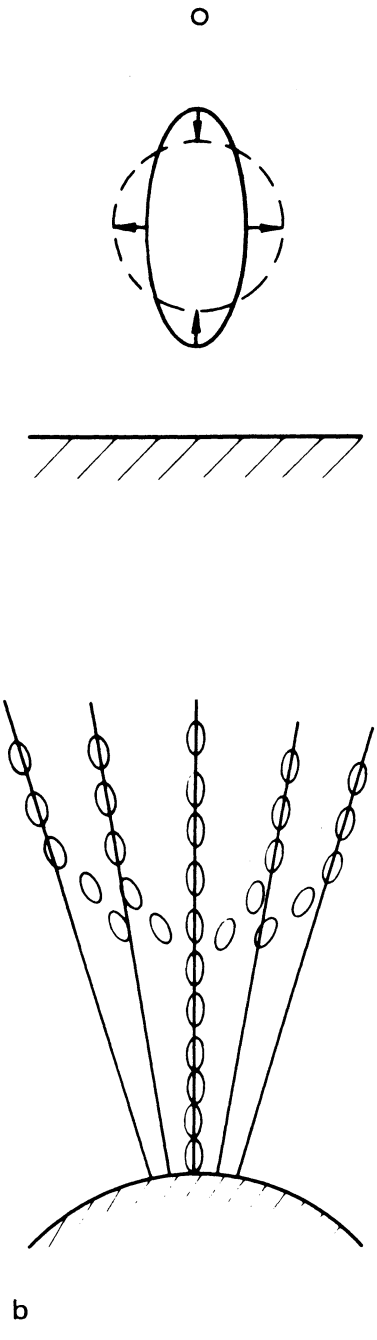


Fig. 4: Model for water tree growth from microvoids; a) Expansion of water causes void to form a sphere. Compression and tensile stresses occur in polyethylene in the short radius direction and large radius direction respectively. b) Region subjected to tensile stress forms another microvoid. Repeated contraction and expansion causes chains of voids to grow in line with original.

The high stress found at protrusions, contaminants and voids is enough to initiate the growth of water trees, but water or humidity must also be present [25,26]. Once initiated it is believed that another mechanism takes over and governs the growth of trees [6,8,16,17].

It has been stated that water trees are diffuse and will disappear and reappear under certain conditions. Using a powerful microscope, a fine pattern of the trees can often be observed in recovered cable insulation. Matsuba and Kawai claim that the trees are clusters of water-filled microvoids, a pearl bead-and-string structure [11]. Isshiki et al. describe the trees as clusters of microvoids with no ducts or passages [3], while Tanaka and Fukuda observed chain-link type microvoids [27] (Fig. 4). While the magnified shape of trees should provide clues to the mechanism [5] of tree growth, it is often difficult to draw conclusions from micrographs alone because the history of the objects observed is not always clear. The observation of water trees during growth might be worthwhile.

In the following sections we will review most of the proposed water-tree mechanisms, along with a summary of the supporting evidence for each.

3. MECHANISMS

A. *Chemical*

Treeing has been studied in several types of polymers, including ethylene-propylene rubber (EPR), polyethylene, chemically crosslinked polyethylene, and radiationally crosslinked polyethylene. Water trees were found to propagate faster in uncrosslinked polyethylene than in chemically crosslinked polyethylene, but approximately the same in uncrosslinked polyethylene vs. radiationally crosslinked polyethylene [18,28]. This phenomenon suggests that tree growth is a function of the crosslinking agent rather than the type of polyethylene utilized [29].

The most popular agent used for crosslinking polyethylene is dicumyl peroxide, which, upon decomposition, forms cumyl alcohol and acetophenone as its main by-products [30]. Of several tests performed on uncrosslinked polyethylene, the addition of acetophenone to the system produced a significant reduction in the number of water trees formed [2,29,31]. When this polyethylene/acetophenone system was heated, however, the acetophenone was lost and several trees were found. This suggests the possibility of trees being present the entire time, and of acetophenone somehow suppressing the trees. When Katz and Bernstein [10] removed the catalyst decomposition by-product from a chemically crosslinked polyethylene system, they found that treeing in the crosslinked polyethylene was about equal to the treeing in uncrosslinked polyethylene.

Bahder et al. [32] found that other chemicals such as water, copper sulfate, and ethylene glycol all promoted the creation of water trees, while liquid paraffin seemed to suppress treeing. Hayami and Yamada [33] found an increase in treeing inception voltage from the use of liquid paraffin, cable oil (silicone based), polybutene, and some polyvinylchloride plasticizers.

The salt content in water also seems to have an effect on tree growth and intensity. As previously mentioned, tree inception and propagation are affected by the electrical stress at imperfections and by the nature of the liquid present [20,34]. Fournié observed no breakdown in demineralized water, suggesting that salts or minerals in tap/ground water may accelerate cable failure [35]. The influence of ions on water absorption and tree propagation is also discussed by Tanaka [36] and Auckland, [37,38] who observed increased treeing when ions were present in water. Auckland's work [37,38] initially suggested that water absorption was also found to be voltage dependent. A later publication retracted this observation [70], citing electroosmosis as a possible factor in water absorption.

Another proposed mechanism for treeing involves the "internal discharge" theory. Tanaka et al. [39] and Nitta [40] observed white light being emitted from spots in polyethylene, suggesting either electroluminescence or discharge. On the basis of this observation, Nitta proposed an internal discharge mechanism, saying that water is decomposed into hydrogen and oxygen which give rise to high pressure in the polyethylene. High pressure (mechanical stress) from these gas discharges can cause deterioration of the polyethylene, giving paths for water trees [8,35,41, 42,43].

Matusba et al. [44] also support the theory of void propagation by high pressure, but explain it in terms of chemical potential. The water inside the microvoids is expected to have lower chemical potential than external water, due to the electric field within the microvoids. This difference in potential generates a gradient whereby external water enters the microvoids, generating pressure. This high pressure in turn causes polymer cracking and leads to treeing, but would not explain the ability of vented trees to propagate.

A newer theory suggests a free radical mechanism of chain scission, which in turn creates a path for water trees [13,23,45,46]. This is a mechanochemical reaction and will be discussed in detail in a later section of this report.

A popular theory, and one with much supporting evidence, deals with oxidation reactions in the polyethylene. It has been suggested that the polyethylene oxidizes and that the oxidation reaction induces tree growth. Blodgett [47] states that under the alkaline dye method used to make trees visible [48,49] it is necessary for the polyethylene to have oxidized in order that the basic (cationic) dye be permanently bound to the polyethylene. Upon treatment with alkali, a basic dye breaks down into a colored cation which attaches itself to the anionic portions of a molecule, rendering color. Upon ionization, weakly acidic groups such as carboxyl will attract the dye cation. Pure polyethylene itself has no affinity for methylene blue, but the presence of carboxylic groups, resulting from oxidation, will cause the polyethylene to absorb the dye [50].

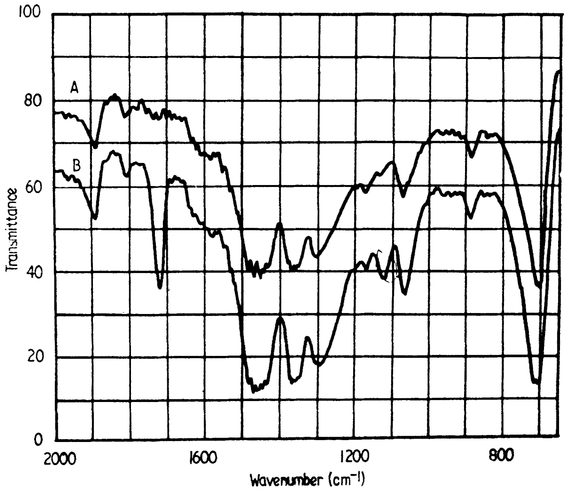


Fig. 5: Infrared absorption spectra of polyethylene after immersion for 80 days; a) in tap water at 60°C and b) in NaCl solution at 60°C. (Copyright, 1975, The Institute of Physics)

It has also been observed that polyethylene will color under an iodostarch test [40]. The iodostarch test indicates an oxidation reaction if iodine shows a positive reaction with starch (forming a blue color). The iodine is liberated from potassium iodide by an oxidizing agent such as O_2, O_3 or peroxide [51].

McKean [13] and Morita et al. [43] have observed peaks on an IR spectrum of insulation material corresponding to oxygen-containing structure. Rye [41] observed oxidation peaks on polyethylene suspended in NaCl solution at 60°C (Fig. 5). In eighty days the polyethylene had gained approximately 0.2% weight, due to the oxidation reaction. Auckland and Cooper [52] found similar weight gain when they tested polyethylene under an applied voltage, but the samples were not tested for oxidation by IR analysis. Rye found no weight gain and no IR peaks corresponding to oxidation when tap water was used in the previous experiments.

DeCoste (Fig. 6) [53] and Bebbington [54] found IR evidence for carbonyl groups in cables that had been soil-burial tested. Samples with no antioxidant had a very strong carbonyl band.

Fournié [35] studied the effect of types of electrodes (simulating a conductor) on the antioxidant and found that tree growth was reduced when iron or lead was used. The antioxidant seemed to promote trees when there was no reaction with the corrosion products from the electrode. For example, when platinum, copper, or aluminum were used (these metals are not easily corrodable), the presence of the antioxidant seemed to induce tree growth. Low conductivities in the salt solutions used, low temperature, and iron or lead electrodes all seemed to decrease tree growth.

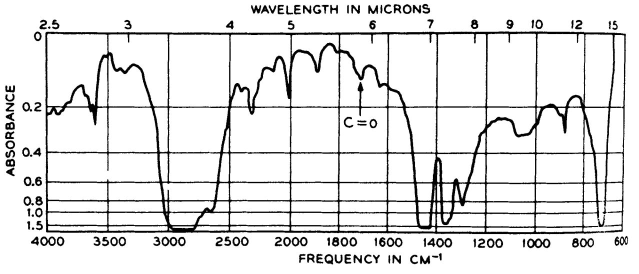


Fig. 6: Infrared absorption spectrum of LDPE showing carbonyl absorption after four years of burial.

B. Electrical/Thermal

A very controversial mechanism concerning treeing in electrical cables continues to be a subject of debate. The basis for this mechanism is the phenomenon of dielectrophoresis. Dielectrophoresis [55,56] arises from polarization of matter and the subsequent tendency of this matter to move into regions of higher field strengths. The direction of movement is independent of the sign of the electric field - either alternating or direct currents can be used. Dielectrophoresis requires a divergent field of high strength (about 10 V/mm or more) and there must be a sizeable difference in the relative dielectric constant of the particles as compared to the surrounding medium. This effect is easily observed with large particles in low viscosity fluids when the fields are high.

Auckland and Cooper [37] found that the flow of water in a stressed sample was proportional to the applied voltage E, and not to the square of the applied voltage as expected with dielectrophoresis. Auckland therefore proposed that dielectrophoresis may be an explanation for the mechanism of water absorption but not of water penetration. That is, if dielectrophoresis were the controlling mechanism, then penetration (tree growth) would occur only in the presence of a nonuniform field. Auckland and Cooper [38] have observed treeing in a uniform field, ruling out the tree-growth mechanism of dielectrophoresis.

Auckland and Cooper [37] observed that the tree-growth rate was dependent on the ion concentration in water, and not on dielectrophoretic effects, since as previously stated, water flow was found to be proportional to E and not E^2. Franke [57] also supports this theory since he found dc trees whose growth rate was slower than ac trees and whose growth was polarity dependent, in contradiction to that expected if dielectrophoresis were important.

Nitta [40], Miyashita [42], and Ashcraft [2] observed that water trees grow more easily the greater the conductivity of the water contacting the polyethylene. Also, by varying the solute and concentration, differences in tree growth rate were observed.

Dielectrophoresis is not claimed to be frequency dependent, yet Matsuba [11], Iwata [5], and Nitta [40] each found frequency acceleration in cables. Nitta found that the rate of propagation increased as the frequency of the applied voltage was increased; therefore, he suggested the possibility of another mechanism besides dielectrophoresis contributing to water treeing. In contrast to this frequency dependence, Densley [58] observed no frequency acceleration from 60 to 1000 Hz and Ashcraft [2] and Sletbak [34] found little frequency dependence of water trees from 6 to 10 kHz. It is possible that the dependence increases, then levels off, as frequency is increased to high levels.

Auckland [28] has suggested the possibility of electroosmosis as a mechanism for treeing. Electroosmosis is the transport of electrolyte due to the formation of an electrical double layer at the surface of pores (voids). The solid walls of the pores absorb ions of one charge and the counter-ions accumulate in the liquid close to the interface. Since the counter-ions are mobile, they can be transported by the application of an electric field which moves both the ions and the water through the polymer.

Tanaka [27] theorizes that water in the microvoids is thermally expanded due to selective heating of water in high electric field regions by dielectrophoresis or joule-heating. Yoshimura's [59] theory is similar, stating that water is evaporated by dielectric heating. If the electric field and frequency are both high, then the vaporization of this water forms microcracks due to the high vapor pressure.

Birks and Hart [60] and Tanaka [23] suggest the possibility of joule heating which could cause dielectric breakdown. Joule heating occurs when a high electric field is applied to a solid dielectric. Work is done on the free electrons (the current carriers) which transfer some energy to the lattice and raise the temperature. If there is a permanent change in the lattice, then this is dielectric breakdown [60]. Joule heating may also have an effect on water microvoids as they expand or contract [23].

A potential gradient has also been suggested as a primary cause of water treeing [3]. Water concentrates in polyethylene - depending on these gradients - in an area of abnormal electric field such as caused by protrusions, voids, and impurities. These water-pockets form pointed water electrodes, increasing the potential gradient and eventually causing local fatigue and breakdown.

Chan [61] and Isshiki [3] each support a diffusion controlled mechanism for water penetration into polyethylene. The propagation of trees is accompanied by the diffusion of water and in some cases, ionic impurities.

Isshiki relates the diffusion of water to a temperature gradient, stating that the difference in equilibrium vapor pressures accelerates the rate of water diffusion.

Tabata [62], Matsuba [44], and Wilkins [63] also relate their findings to a temperature gradient. The temperature gradient can induce damaging water movement [63]; the water movement generates pressure [44], eventually leading to breakdown. The effect of a temperature gradient on water treeing can be large, especially when the cables are also subjected to a large voltage gradient [62].

It has also been suggested that breakdown of polyethylene may be due to the dissociation of molecular bonds due to collisions of high-energy charged particles [42,43,46,64]. This theory tends to be related more to electrical treeing than water treeing and will not be discussed further.

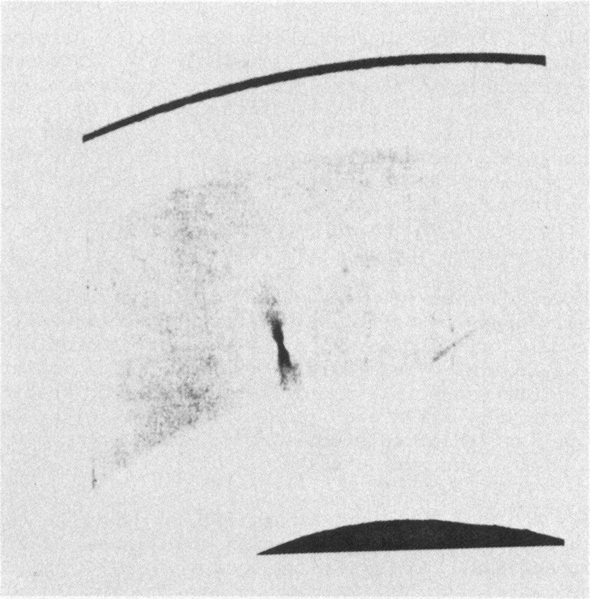


Fig. 7: Tree growing in direction of electric field. It is possible that the dark phase is migrating acetophenone, which would shed controversy on the "acetophenone-as-a-treeing-suppressant" issue.

In general, it is agreed that tree formation occurs in very high stress areas such as impurities and voids [2,20,22,61,63,65] and that these high concentrations of stress increase the rate of tree growth. From observations, these trees seem to grow in direction parallel to the electric field lines [7,10,22,23,32, 48,66] (Fig. 7), although Luther [67] has noticed one instance of a tree growing perpendicular to the electric field as sketched in Fig. 8. Clearly any mechanism of water-tree initiation and growth must be consistent with these observations.

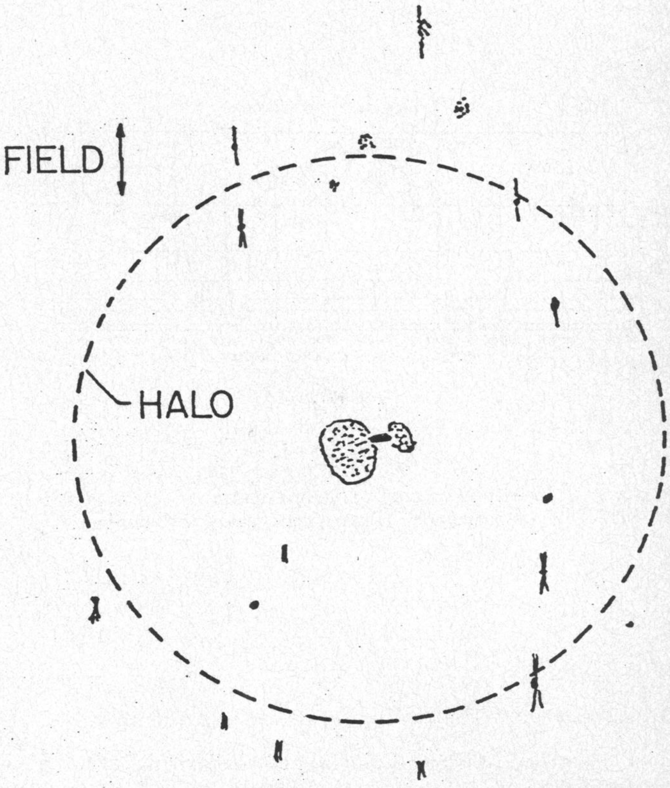


Fig. 8: Tree growing perpendicular to electric field.

C. *Mechanical*

A major theory of water treeing invokes mechanical breakdown of the polymer matrix. Tanaka [23] noticed the formation of submicrovoids resulting from mechanical stress created by water expansion within micropores and described water trees as chains of microvoids produced by a tensile stress due to expanding water within existing microvoids (Fig. 4). The water expansion was from joule heating as previously explained.

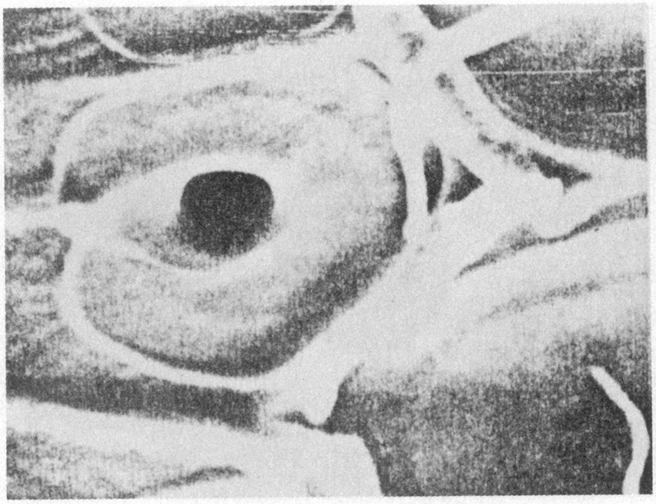
A similar type of stress blamed for dielectric breakdown is the local cracking of the polymer under the influence of a liquid in the presence of internal stresses. This local cracking is the result of an electric field acting on the water voids and causing successive expansion and contraction of the voids which cause increased pressure [27]. The source of the deformation is the Maxwell stress, which comes about during application of an ac voltage. This repeated flexing causes local fatigue, then breakdown [3,4,8, 42,58]. The process occurs rapidly if the applied mechanical stress, amplified by the voids, is greater than the mechanical strength of the insulant [6]. Temperature gradients coupled with this mechanical stress can also increase the chances for breakdown [44,62].

It has also been proposed that environmental stress cracking (ESC) contributes to dielectric breakdown [68]. This is a type of environmental fatigue fracture that occurs when a high voltage field decreases the surface tension at the polyethylene/water interface. When the ratio of yield stress to surface tension is small, ESC occurs. Because the yield stress decreases with temperature increase (the surface tension is relatively temperature independent) tree growth should increase with temperature. This prediction conflicts with reports by Bernstein [69] and it would be interesting to see some actual data of tree-growth rate vs. temperature in order to see which theory holds true.

The direction of growth of the microvoids (trees) depends on a) the electric lines of force; b) the large radius direction of the elliptical microvoid; and c) the proximity of mechanically weak areas [23] Propagation is most likely in the weaker amorphous areas or along a series of microvoids, as these paths offer the least resistance to tree growth [3,16,30,38,69-71].

In a series of experiments, treeing inception rate was found to decrease with increasing rigidity of the polymer [43]. Singh [72] noticed a retarding effect on treeing when fillers were added to the system. This supports Morita's theory of stiffness [43] since fillers tend to increase the rigidity of the system. Isshiki [3], by varying materials in experimental work, found water trees easier to grow in soft materials. In contrast to these findings, Bernstein [69] found an increase in tree growth at low temperatures, and suggested that it may be due to increased chain stiffness, and the inability of the polymer to dissipate fracture energy.

Another phenomenon, microporosity, has been found to play a very important role in the breakdown strength of polyethylene [13,73]. Auckland [70] found the absorption of water by molded polyethylene to decrease at high molding pressure suggesting that density - as related to the number of micropores - is very important in water absorption. Heat treatments of the polymer, causing partial melting and recrystallization, can also cause an increase in density and a decrease in water absorption [74]. McNamara [66] claims that small voids "heal themselves" during heat treatments by shrinking, therefore increasing the density of the system (Fig. 9) [88].



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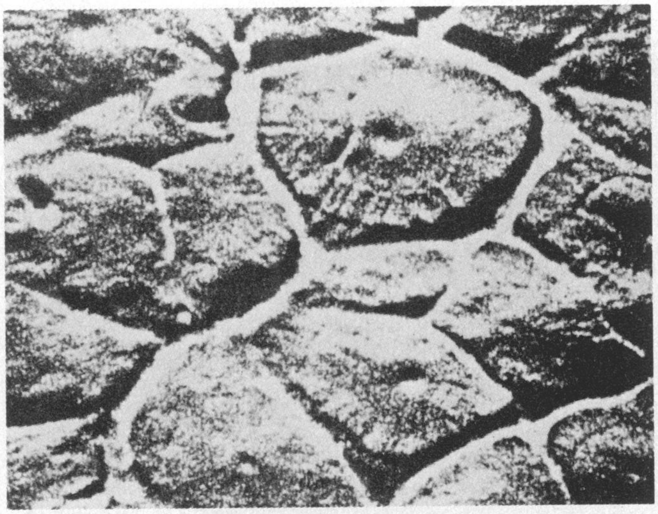
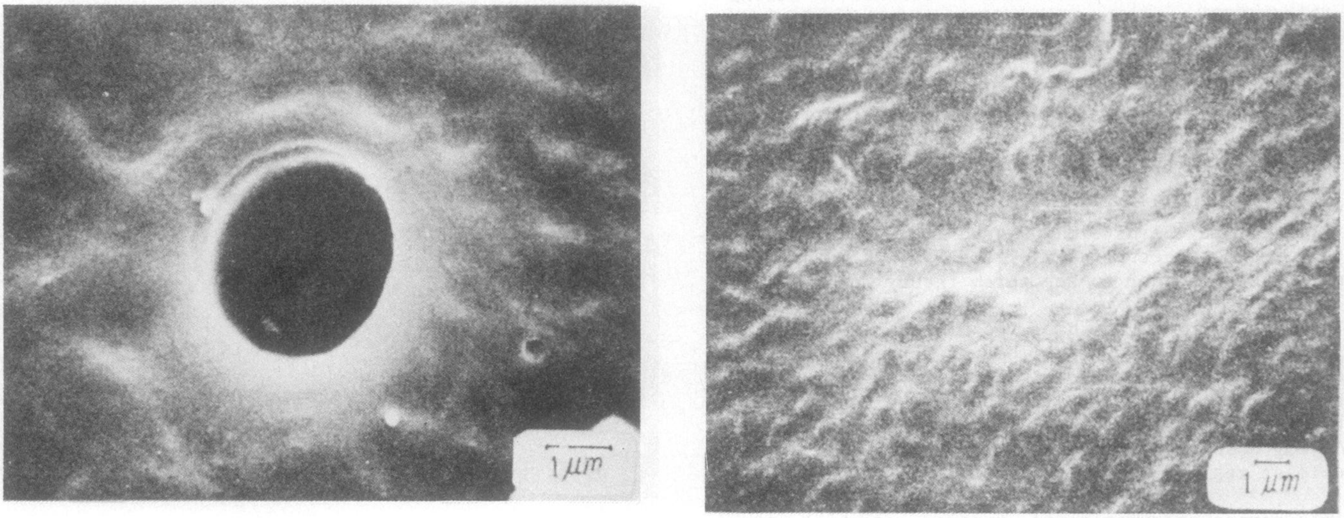


b

Fig. 9: Void collapsed by heat; a) untreated and b) heated at 100°C.

Namiki et al. [75] heat-treated cable samples containing microvoids and found that the microvoids were transformed into spherical particles. Upon analysis these spherical particles were found to be low molecular weight polyethylene microcrystallites formed when polymer from areas surrounding the void migrates into the void upon heating. From 60 to 110°C, spherical particles were observed, but samples heat treated above 110°C showed no signs of voids or spherical particles (Fig. 10). Bow-tie trees grew easier from the particle-filled voids than from the empty voids, perhaps because of higher stress in the cracks between the particles and the void walls.

To test the theory of water permeability as related to micropores, several investigations have been carried out using nitrogen-cured samples and steam-cured samples [14,61,65,76,77]. Overall, the gas-cured samples contained fewer voids than the steam-cured ones. It has been proposed that the steam-cured samples contain a significant amount of water which influences water tree growth. During crystallization



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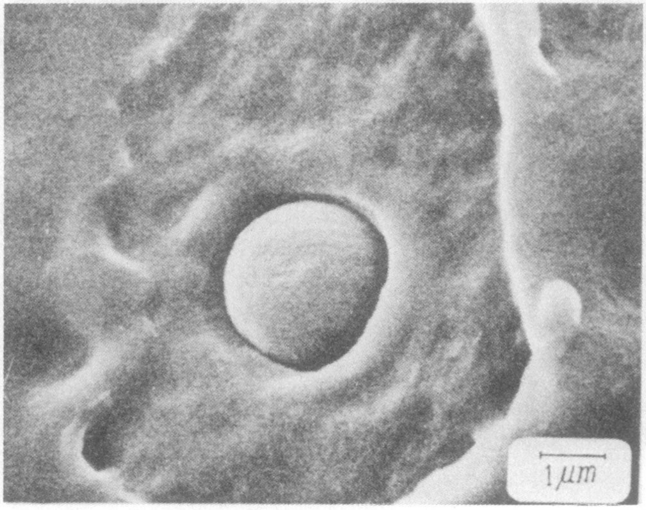

b

Fig. 10: a) original microvoid; b) heated at 80°C for 24 hours; c) heated at 130°C for one hour.

of the polyethylene, the water separates and condenses into tiny droplets due to its negligible solubility in polyethylene crystals. These droplets are pushed ahead of the growth fronts of the spherulites during polyethylene crystallization and collect in boundary areas or interstices. Muccigrosso and Phillips [76,78] found cavities at the impingement site of three or more spherulites and associated these cavities with the collected water droplets (Fig. 11). This cavity network at the boundaries exists throughout the polymer and therefore gives rise to a weak pathway which probably facilitates tree propagation, possibly through a discharge mechanism [30,78] (Fig. 12)[89].

As mentioned in a previous section, Zhurkov [46] and Tanaka [23] have theorized a mechanochemical reaction for cable breakdown. This is a little-mentioned mechanism but could be of importance in both electrical and water treeing. With respect to electrical treeing, Yamanouchi [45] mentions the possibility of the scission of carbon-carbon bonds due to bombardment of accelerated electrons. Tanaka [23] found some evidence for this in infrared absorption, indicating the possibility of polyethylene chain scission which would lead to microvoids.

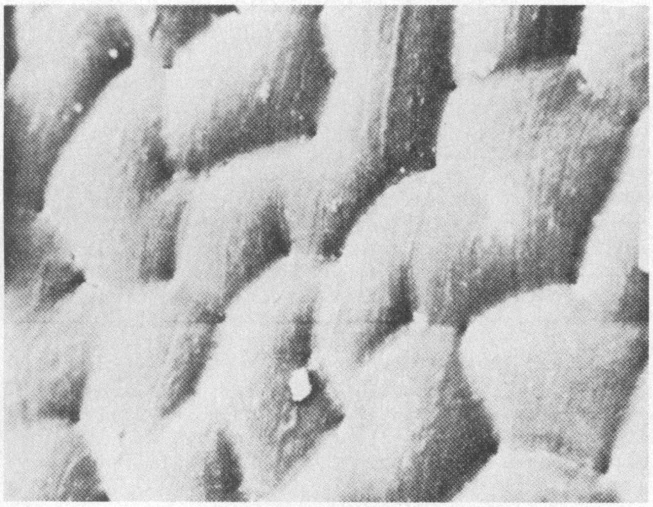

Fig. 11: Etched insulation showing spherulites, interstitial voids, and microvoids.

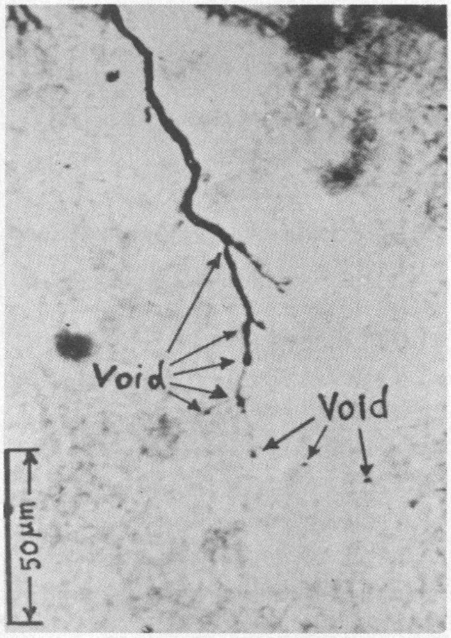

Fig. 12: Treeing channel along voids

In Zhurkov's studies, absorptions in the IR also indicate the presence of scissioned chemical bonds. Macroradicals were detected by EPR (electron paramagnetic resonance), and microcracks by SAXS (small-angle x-ray scattering). Zhurkov's mechanism is outlined as follows: 1) A deformation of interatomic bonds under heavy loading causes a decrease in energy needed for bond scissions; 2) scission of these strained bonds, as a result of thermal fluctuations, forms chemically active free macroradicals; 3) nucleation of submicrocracks occurs after the scission of several adjacent macromolecules (Fig. 13).

This theory also connects with the stress-related theories, since Maxwell stress, environmental stress cracking, or stress due to discharges could lead to deformations and bond scission. The submicrocracks then formed are a very probable path of treeing and eventual breakdown in the polymer system.

4. DISCUSSION OF PROPOSED MECHANISMS

Most researchers involved in water treeing seem to agree that there are at least two mechanisms governing water trees [17]: a mechanism for inception, and one for propagation. Results from experimental work seem to show a significant difference in characteristics for tree inception and tree propagation [80]. There is also a strong possibility that deterioration due to water tree propagation is a function of several parallel mechanisms, depending on the insulation's structure, processing and handling, and exposure environment.

On the chemical front, breakdown due to some type of oxidation seems to be a very popular theory. Several workers have cited infrared spectra as evidence of an oxidized cable. Once the water has diffused into the polyethylene, oxidation and combined mechanical stresses along weak paths seem to be the most likely mechanisms for breakdown. Unfortunately, no conclusive proof has been forwarded concerning the sequence of events. Certainly oxidation is very likely in the water-tree channels, but it may occur well after the channel is formed. The fact that the channels can be dyed is very weak evidence for the role of oxidation in the initial formation of the channel.

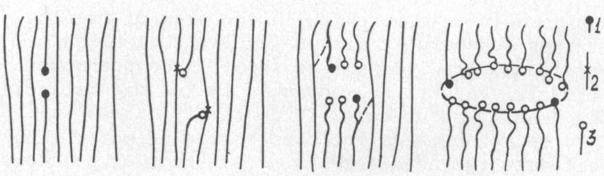

Fig. 13: Creation of a microcrack: a) bond scission with formation of two end-radicals; b) end-radicals interact with adjacent macromolecules forming internal free radicals (X) and stable end groups (O); c) scission of internal free radicals resulting in stable groups and end-radicals; d) formation of microcrack due to chain degradation.

The advocates of the physical-mechanical breakdown of the polymer have not addressed thoroughly some very fundamental questions as well. One obvious question is "Can trees be grown in the absence of an electrical field?" The interesting and isolated experiment performed by Nitta [40] suggests that tree-like structures can be formed by mechanical means alone. Nitta subjected polyethylene to 300 atm. gas (type not specified) in an autoclave and then released the pressure suddenly. This action produced tree-like cracks, but the nature of these cracks and the minimum required pressures were not reported. Klinger [84] also reports the growth of tree-like structures in polyethylene under the influence of a hydrostatic pressure.

Another favorite mechanism involves the environmental stress cracking of the polyethylene [79]. Unfortunately, the details of this phenomenon -- the cracking of polyethylene in the presence of stress and polar non-solvents -- have not been worked out completely. Polyethylene is also known to be susceptible to a stress-activated oxidation process [79]. It is certain that the mechanical mechanisms require stress: the "how much" and the "where from" questions have received meager attention. We are not even able to report with confidence on the effect of external stress on the rate of growth of water tress, although recent results [84] indicate an acceleration effect at very high pressures.

The final exasperating feature of water tree research is the variability of results. As an example, Sletbak and Botne [34] find that field strength has only a mild influence on the number of bow-tie trees, whereas Morita et al. [43] find a strong effect. We suggest that a laboratory test with high reporducibility must be developed. Furthermore, because the growth of trees - and perhaps even their appearance - is dependent on the morphology of the polymer, the test specimens must be purified, characterized and brought to a standard state by annealing.

The morphological aspects of tree growth as proposed by Muccigrosso and Phillips [78] certainly cannot be overemphasized. Growth between spherulites is a very important concept and suggests methods of reducing tree growth. As previously stated, it is believed that trees propagate in weak areas. From morphological studies it can easily be seen that interspherulitic boundaries are far weaker than the spherulites themselves. However, no concerted effort has been made, to the authors' knowledge, to determine if trees indeed cannot initiate and propagate in a spherulite. Studies with annealed HDPE or polypropylene might be fruitful in this respect.

With more intense research in the area of treeing mechanisms - hopefully with carefully controlled materials and conditions - we should soon see more experimental results and advances in the understanding of the treeing phenomenon. Undoubtedly, these will lead to better methods for suppression of water trees. We reiterate the need for the development of a laboratory treeing test with excellent sensitivity and reproducibility. Currently the tree inception voltage test and the Union Carbide test for water-tree growth rate, both described in the appendix, are the best tests available for small samples. However, both tests are highly dependent on the shape of the defect-producing mandrel and the details of the preparation of the defect using this mandrel. This tends to give a high uncertainty in the results.

5. POSSIBLE METHODS FOR REDUCING TREE GROWTH

A major reduction in cable treeing comes when a smooth, perfect insulation is formed. This means that the cable should have no protrusions, skips, or contaminants, and existing pores should be well within the specified limits [12]. Suggestions have also been made to incorporate a metal sheath or lining over the insulation to prevent water absorption [81]. This would decrease water treeing due to water ingress from the outside of the cable, but would do little to help water treeing if there is indeed a microconcentration of water within the cables due to the manufacturing process.

There is much commercial activity in the area of additives to reduce tree growth. DuPont Treban(R) 100 has met with success [81] and Union Carbide has introduced graft-modified polyethylenes with increased water tree resistance [82].

Muccigrosso and Phillips' treeing theory also lends support to the possibility of additives reducing tree growth. The additives could either block propagation paths by filling in cavities or spherulite boundaries, or they could act as a voltage stabilizer to suppress treeing by discharge mechanisms. The effect of fillers on tree suppression has also been discussed, the rigid fillers increasing polymer stiffness, giving increased mechanical resistance to tree growth.

Another method of decreasing tree growth is by controlling the spherulitic growth during crystallization. Small spherulites produce smaller, but more, cavities while larger spherulites produce larger, but fewer, cavities. Muccigrosso and Phillips [76] tried to determine an optimum in the growth of spherulites and found a completely different morphology with the use of an aliphatic crosslinking agent: the spherulites were very small and gave no appearance of macroscopic voids. Amorphous EPR is thought to be less susceptible to water treeing [47] because of its greater homogeneity. However, other studies [18] indicate that water-tree growth rate in EPR and XLPE are quite similar.

Using gas-cure cable systems rather than steam-cure systems seems to be a promising possibility with respect to decreased water treeing. The gas system decreases the amount of residual water in the cable, thereby decreasing the number of water cavities which are believed to be the propagation paths for trees.

Nitta has taken a novel approach to the problem of reducing tree growth [15]. He blended 5 to 20% high density polyethylene with low density polyethylene and observed an increase in treeing inception voltage. This combination works by giving an overall increase in density with respect to the low density polyethylene previously used. When this new system was crosslinked, a thirty percent increase in treeing inception voltage was measured.

A similar technique was undertaken by Mangaraj [83] and coworkers. They impregnated a cable with monomer-catalyst solution and performed in situ polymerization. Lauryl methacrylate and vinyl toluene were used for the monomer. The number of voids was decreased by this treatment, and an increase in the breakdown strength was observed.

6. CONCLUSION

The combined results of the experiments discussed in this paper show a step forward in the problem of reducing water treeing in electric cables. After careful laboratory testing on well-characterized materials, the results of more promising experimental work must be tested under actual field conditions to assure realistic solutions. Finally, the relationship, if any, between failure probability and tree distributions must be established. Hopefully a major breakthrough will soon solve this dilemma of cable deterioration by water trees.

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APPENDIX

Tests for Water Treeing Resistance

A standard defect test has been established by A. C. Ashcraft [2] that gives accelerated testing of small samples (under 300 g) of polymer used in cable manufacture.

The geometry of the sample is a compression molded dish-shaped specimen having 24 conical depressions molded into the bottom at regular intervals. The sample is tested by pouring approximately 100 ml of an electrolyte solution into the molded dish which is then put into a grounded bath containing the same electrolyte. A 50-mm diameter platinum wire ring is immersed into the dish and the other end is connected to a power supply. (A Universal Voltronics Model GAHF-15-GPD2 resonant power supply was used by Ashcraft.)

To limit the effects to water trees, voltages are confined to between 2 and 8 kV. Ashcraft found low density polyethylene to develop water trees up to 240 μm long at the tips of the molded cones. These trees were found within 24 hours at 5 kV, 8.5 kHz using 0.01 N NaCl in distilled water as the electrolyte solution. The trees are then stained according to a modified staining procedure of Matsubara's [48]. A typical tree grown in these tests is shown in Fig. 14. To quantify the tree growth, measurement is taken perpendicular to the side of the cone to the maximum tree width. This test is becoming a standard one in treeing research since it gives rapid results and permits the effects of frequency and voltage on treeing to be studied. Very careful control of the radius at the tip of each cavity is required for reproducible results [2,84].

Another "standard defect" test deals with resistance to tree inception. The defect mimics a contaminant or irregularity in that it concentrates the stress, thereby enhancing tree growth. This type of test is a double needle test, first described by McMahon and Perkins [85]. The standard defect consists of an extremely sharp steel needle specially inserted into the face of a 25×25×6 mm^3 block of compression molded dielectric material. The needle is inserted until it is 12 mm from a dull needle inserted simultaneously into the opposite face of the block. The double needle characteristic voltage (DNCV) is defined as the voltage that, when applied between the two needle electrodes, will initiate growth of trees in half of a group of replicate specimens in a one hour period. Normally, a high-voltage 60 Hz ac source is used.

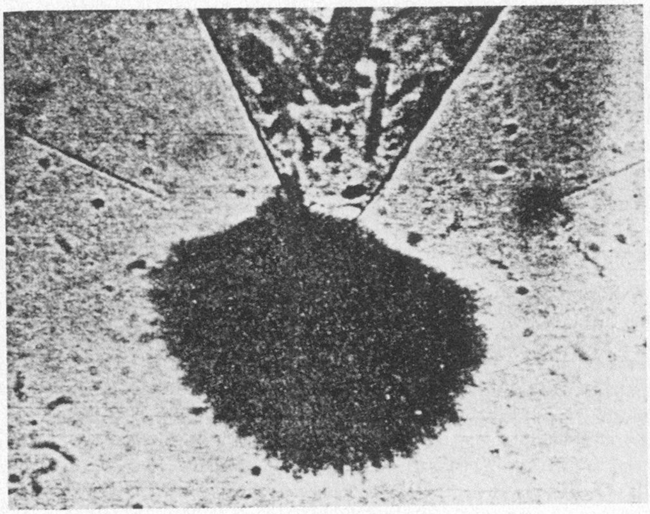

Fig. 14: Water tree grown from Ashcraft's standard defect test (5 kV, 8.5 kHz)

Ashcraft et al. [86] report the results of DNCV with various polymers. This is a common test, but is used to determine resistance to initiation of electrical trees. Isshiki et al. [3] have used a similar test using one needle in order to develop water trees. The bottom of the sample is coated with semiconductive paint and the needle is inserted into the opposite side of the block. By carefully withdrawing the needle and injecting water into the defect with a syringe, a water electrode is formed which is then stressed to develop water trees. Again, care must be taken to control the diameter of the needle tips, as a small variance will produce a large deviation in results.

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