by surface discharge and ozonator discharge, will be used with discrimination with respect to the nature or the object of the test.

Hopefully, the above results will contribute to further research on corona-degradation phenomena. The authors and their associates plan to make successive examinations of the following problems in the future: 1) further application of the above two testing methods to thicker sheet samples or composite materials; 2) development of reasonable testing method for internal (void) discharges; 3) elucidation of progressive behavior of dendritic channels (treeing) originated from discharges such as void corona.

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# Deterioration of Water-Immersed Polyethylene-Coated Wire by Treeing

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***Abstract*—Although some reports of the water-resisting life of polyethylene-insulated wires have been made, studies of mechanism of the deterioration phenomenon have been scarcely reported. In this paper, it is pointed out that a major cause of the deterioration of polyethylene-coated wire in water is the occurrence of the "treeing" phenomena. An accelerated deterioration test through the use of high-frequency voltage has been developed. Using this accelerated test, experiments were conducted on the deterioration phenomenon of insulating wires under various conditions. The causes of tree generation were elucidated and a new type of insulating wires was developed.**

**It has been discovered that when the polyethylene-insulated wire is immersed in water and voltage is applied (as occurs in a submersible pump) treeing will occur at extremely low voltages and is sensitive to the copper in the conductor. A metal barrier over the conductor greatly increases the insulation life owing to the effect of double layers.**

## I. INTRODUCTION

IN RECENT years, submersible pumping units have been winning greater recognition for their economy and good performance. As a result, they have found wide use in the manufacturing industries. The stator of submersible motors is often wound with wires coated with polyethylene. Since the stator windings are immersed under water for prolonged periods of time, they are required to have highly reliable insulation. For this reason, they must be extremely stable from the chemical point of view and must maintain a high insulation resistance as well as good voltage-endurance characteristics.

For many years we have been engaged in research aiming at improvement of the waterproof insulation characteristics of insulating wires [1]–[3]. Observations of the deterioration of insulating wires have shown that whenever the insulation performance declines within a relatively short span of time, the cause is chiefly "trees," which spread out in the dielectrics. It has been discovered that accelerated deterioration tests, in which high-frequency waves are applied, can efficiently bring about such deterioration within a short time [4].

## II. DETERIORATION TESTS OF INSULATING WIRES

### A. Tests Using Commercial Frequency Voltage

The following methods can be used to study the insulation deterioration of polyethylene coated wire with voltage applied in a water immersed state: 1) decline in the insulation resistance; 2) number of insulation break-

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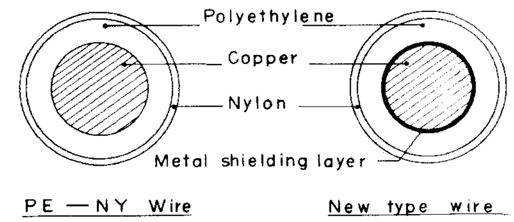



Fig. 1. Structure of PE-coated wires.

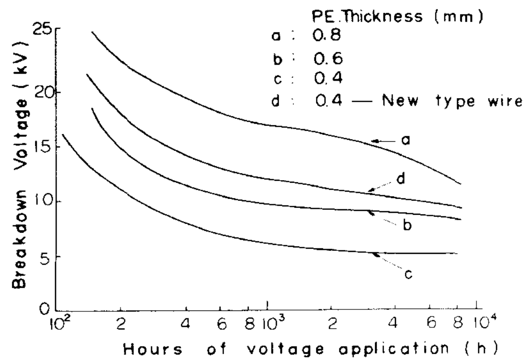



Fig. 2. Breakdown voltage of deteriorated PE wire. 50 Hz, 1 kV peak applied under 60°C test water.

downs under voltage application; and 3) sampling at definite time intervals and seeking the short-time breakdown voltage.

Since there is almost no decline in the insulation resistance until immediately before breakdown, the insulation resistance is unsuitable for predicting the deterioration trend. The method of counting the number of breakdowns is the most suitable one for finding the real life, but there is the drawback that a prolonged testing period will be necessary unless quite severe test conditions are adopted. For this reason, we adopted a mixed method. That is, deterioration samples were taken at definite intervals, and the deterioration trend was sought from the relationship between the decline in the breakdown strength and the deterioration time.

The structure of the insulating wires used in the tests are shown in Fig. 1. The PE–NY wire indicates the low-density polyethylene on the conductor, over which a thin nylon layer is extruded for mechanical reinforcement. The new type of insulating wire is characterized by the fact that a metal shielding layer is provided between the conductor and the polyethylene layer. In order to improve the permeation of the water, the samples were put into water in which a surface activator and a small amount of electrolyte were dissolved (test water) before applying the voltage. One of the results is shown in Fig. 2. There is a lower breakdown strength the thinner is the polyethylene layer, but the newly developed insulating wire has superior characteristics in spite of the thinness of its polyethylene layer.

The reason why the breakdown strength declines as a result of application of voltage during immersion in water can be explained from the tests shown in Table I. When ac voltage is applied (sample 3), the breakdown

TABLE I
BREAKDOWN VOLTAGE OF PE-COATED WIRE DETERIORATED BY VARIOUS CONDITIONS

| Sample | Condition of Deterioration | Ac Breakdown Voltage ±95 Percent Confidence Limit, Mean Value (kV) |
|---|---|---|
| 1 | immersed in 60°C test water for 1200 h, no voltage | 16.1 ± 2.4 |
| 2 | drying sample 1 under low pressure | 18.7 ± 2.3 |
| 3 | immersed in 60°C test water for 1200 h, 50 Hz, 1 kV peak applied | 5.5 ± 1.2 |
| 4 | drying sample 3 under low pressure | 18.0 ± 1.5 |
| 5 | immersed sample 4 in 60°C test water for 30 h, no voltage | 5.2 ± 0.7 |
| 6 | immersed sample 4 in 60°C test water for 30 h, 50 Hz, 1 kV peak applied | 4.1 ± 1.1 |
| 7 | immersed in 60°C test water for 1500 h, dc 1500 V applied | 16.2 ± 2.1 (+, inner electrode)<br>15.7 ± 1.9 (−, inner electrode) |

strength declines considerably in comparison to wires that have merely absorbed water. However, when drying is performed under a low pressure (sample 4), the value is closed to that of sample 2. If these same wires absorb water again (samples 5 and 6), the breakdown strength drops to the value of sample 3 in only 30 h.

There is also a small decline in the breakdown strength when a dc voltage is applied (sample 7). This suggests a mechanism by which the application of an ac voltage produces a path of water along the electric field in the polyethylene layer.

However, even when such a water path is produced, it is extremely minute in size. Therefore, the breakdown strength does not decline in the dry state. However, in the state of water absorption, this water has a function similar to that of a needle electrode, and this is thought to bring about a conspicuous decline in the insulation characteristics. If we suppose that deterioration is accelerated in this manner by ac voltage, it may be assumed that the deterioration will be even further accelerated by increasing the frequency of the voltage applied. The following tests were made to check this assumption.

### *B. Acceleration Tests Using High-Frequency Voltage*

Fig. 3 shows the results obtained when high-frequency voltage of 1 kV peak was applied for six hours to polyethylene of 0.3-mm thickness. When the frequency is increased above 1 kHz, the breakdown strength suddenly drops. It takes 120 h at 50 Hz to initiate the decline in breakdown strength. Thus, if these results are expressed in terms of voltage cycles, the deterioration characteristics will coincide more or less with those of 50 Hz, and

TABLE II
BREAKDOWN VOLTAGE OF DETERIORATED PE WIRES AFTER APPLICATION OF 30 kHz, 1 kV PEAK FOR 150 h IN 60°C TEST WATER

| Kinds of Wires Thickness of PE (mm) | Breakdown Voltage after Deterioration (kV) |
|---|---|
| 0.8 PE | 10.0, 14.5, 15.5, 15.5, 16.5 |
| 0.6 PE | 11.5, 12.5, 12.5, 15.5, 16.5 |
| 0.4 PE | all wires break down during deterioration |
| 0.3 PE new type | 7.0, 7.5, 7.5, 8.0, 8.5 |
| 0.4 PE new type | 10.5, 11.5, 12.0, 12.0, 12.0, 12.5, 12.5, 12.5 |

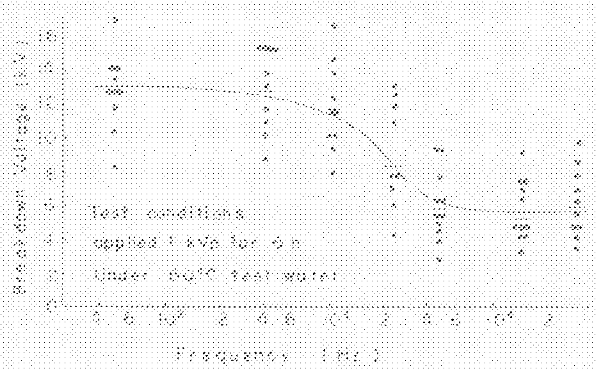



Fig. 3. Breakdown voltage of deteriorated PE wires, accelerated at high frequency.

it may be assumed that deterioration can be accelerated by means of frequency of voltage applied [4]. In all cases in this paper, the voltage applied during deterioration is expressed in terms of the peak value $V_p$, and the insulation breakdown voltage is given in terms of the effective value.

Table II shows the results obtained in acceleration tests applying a high-frequency voltage of 30 kHz. It is clear from this table that the new type of insulating wire displays extremely good properties in spite of the thinness of its polyethylene layer.

In acceleration tests using high frequencies, the wires are immersed in water for only a short time. Therefore, long-term chemical deterioration cannot be estimated from these tests. However, almost no chemical deterioration of the polyethylene layer was observed in wires taken from submersible motors that had been in use for about five years.

When observations were made of polyethylene layers that had deteriorated under application of voltage, it was found that the causes of deterioration were chiefly in the trees occurring in the polyethylene layers. Various types of trees are shown in Fig. 4. The motors in which they occurred had been operated at a voltage of only 200 V, and it is amazing that trees should occur at such a low voltage. In a great many cases, the trees would spread out centering around foreign matter. This must have been caused by the formation of a local high field at these locations.

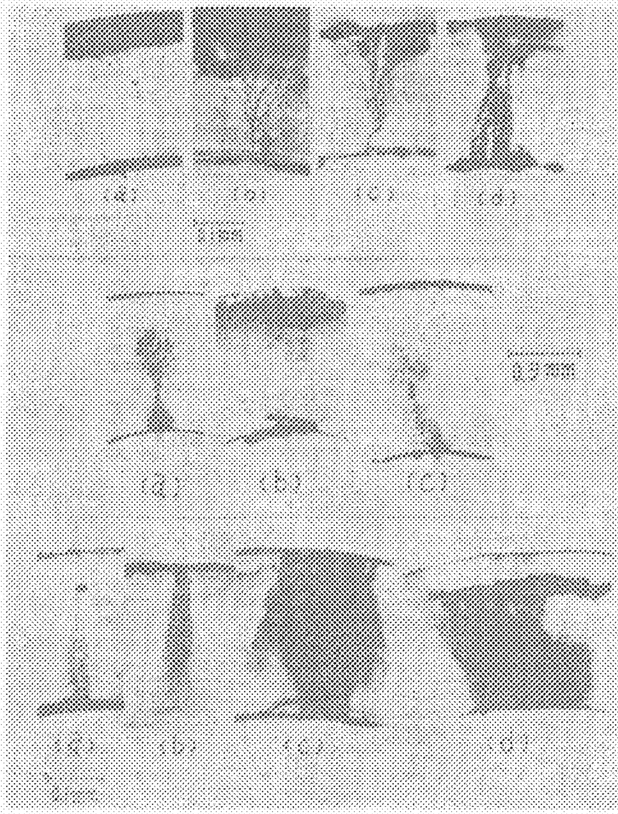



Fig. 4. Trees of PE-coated wires. I: (a)–(d) Trees found in water-immersed motor coil that had been used for many years. II: (a)–(c) Trees of PE wire 50 Hz, 1 kV peak for 1000 h applied in 60°C test water. III: (a)–(d) Trees of PE wire 30 kHz, 1 kV peak applied for 150 h in 60°C test water.

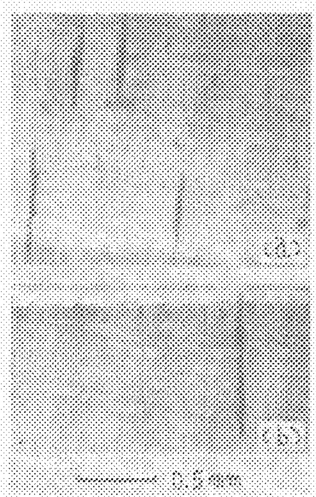



Fig. 5. Trees seen in high-density PE similar to stress cracks. (a) Surface view. (b) Section view. 50 Hz, 4.67 kV peak applied for 3000 h in 60°C test water.

Low-density polyethylene is believed to have waterproof insulation characteristics superior to those of high-density polyethylene. It is suggested that one of the causes of this is the treeing phenomenon shown in Fig. 5. That is, in high-density polyethylene, trees shaped like stress cracks tend to form easily because of bending, etc., even when there is only a slight residual stress that would not occasion any abnormalities at all in low-density polyethylene wires. In high-density polyethylene,

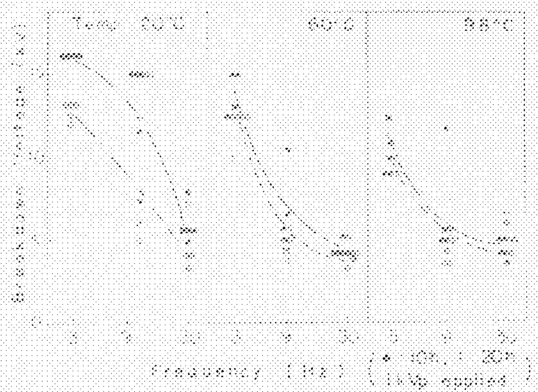



Fig. 6. Decline of breakdown voltage of pinholed PE wire after deterioration from high-frequency voltage.

there are also many cases in which the presence of foreign matter causes the growth of trees. However, as is clear in the figure, there are also some cases where the presence of foreign matter has no particular causative effect on the occurrence of trees.

## III. Study of Treeing Phenomena Caused by Pinholes

### A. Testing Methods

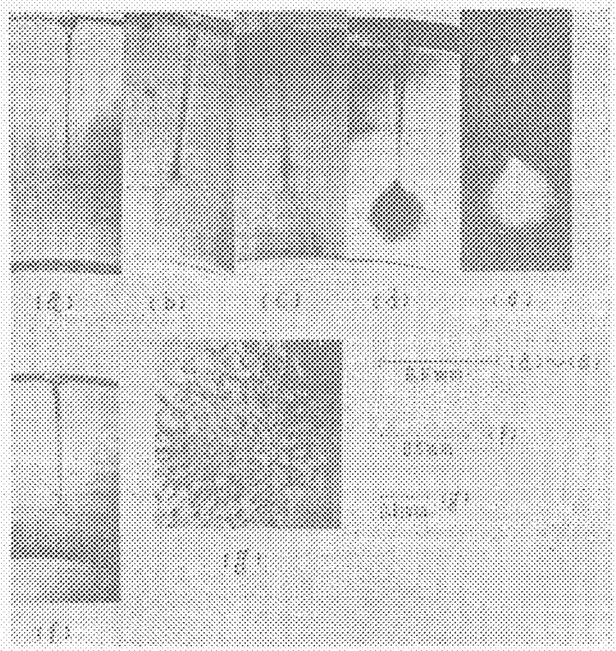
The most widely applied method of research in treeing is that of embedding a needle electrode inside a solid to cause a tree to be produced at the tip of the needle. Since this is a simple testing method, it is effective in screening tests for materials and also in elucidating various phenomena [5]. The trees shown in Fig. 4 do not occur in all parts of a polyethylene layer that has deteriorated under voltage application. Rather, they are caused by faults that occur only quite rarely, and for this reason much effort is needed to find them. In order to obviate this necessity, a method of testing was devised that used artificial faults in order to allow the trees to develop uniformly. In this method, a local high field is produced that is the same for each fault.

Low-density polyethylene wires with a thickness of 0.8 mm or 1.0 mm were used. A needle with a radius of curvature of approximately 2.5 $\mu m$ at its tip was inserted from the surface of the low-density polyethylene wire in such a way that there would be a polyethylene thickness of approximately 0.3 mm between the tip of the needle and the inner conductor. Then the needle was withdrawn. These pinholed polyethylene-coated wires were immersed in water, and voltage was applied between the water and the inner conductor.

### B. Factors Affecting Treeing

Fig. 6 illustrates the decline in the breakdown voltage caused by treeing under various conditions. In order to minimize dispersion of the breakdown voltages, six pinholes were produced in one sample. After trees had been produced by applying the high-frequency voltage, the voltage (50 Hz) was raised in 750 V steps of 15 s each in the water at room temperature. This was continued until breakdown. The breakdown voltage at a frequency of 3 kHz was quite high in comparison with that at the frequencies of 9 and 30 kHz.

When checks were made of the growth of the trees, at the frequency of 3 kHz, it was found that the trees had merely come out slightly. At the frequencies of 9 and 30 kHz, most of the trees had penetrated through the polyethylene layer. However, it was ascertained by other tests that the breakdown voltage was still about 4–6 kV even when the trees had penetrated through the polyethylene layer. As for the effects of the deterioration temperature, it could only be discovered that there was a higher breakdown voltage at 20°C, but no clearly defined differences appeared within the range of 60°–90°C.



| | (a) | (b) | (c) | (d) | (e) | (f) | (g) |
|---|---|---|---|---|---|---|---|
| Test temperature (°C) | 80 | 60 | 98 | 98 | 98 | 60 | 60 |
| Applied voltage (kV peak) | 1.0 | 1.5 | 1.5 | 2.0 | 2.0 | 0.2 | 1.5 |
| Frequency (kHz) | 3 | 9 | 9 | 9 | 9 | 3 | 30 |
| Applied hours | 10 | 21 | 11 | 4 | 4 | 168 | 71 |

Fig. 7. Trees of various types.

Various types of trees occurring at the tip of pinholes are illustrated in Fig. 7. Example (a) shows a tree that did not grow along the extension of the needle hole, but rather grew in the circumferential direction where there was a weaker field. Trees of this type are relatively few, while those of (b) are more frequent. Type (b) is characterized by the fact that the envelope plane at the tree tip has a shape similar to a sphere electrode. Example (c) is one in which the tree is in the process of developing into a breakdown channel. Example (d) is one in which very fine trees are crowded closely together. Example (e), which is just the same tree as (d), is a photograph taken with reflected light. Example (f) is one in which trees occurred even when a voltage of only 0.2 kV peak was applied. (g) is a tree like the one in (b), which was photographed after cutting vertically to the paper surface. It has a round shape more or less centered around the needle hole.

TABLE III
INFLUENCES OF VOLTAGE WAVE SHAPES ON THE GROWTH OF TREE (UNDER 28°C TEST WATER)

| Applied Voltage (1.5 kV peak 3 kHz) | | Growth of Tree ±95 Percent Confidence Limit, Mean Value (%) Hours of Voltage Application: 5 | 10 |
|---|---|---|---|
| Sine Wave | | 31.8 ± 2.82 | 44.7 ± 5.02 |
| Sine half-wave | hole + | 59.7 ± 2.21 | 97.5 ± 3.02 |
| | hole − | <5 | <5 |
| Square-wave pulsewidth 30 μs | hole + | 41.1 ± 4.25 | 100 ± 0 |
| | hole − | <5 | <5 |

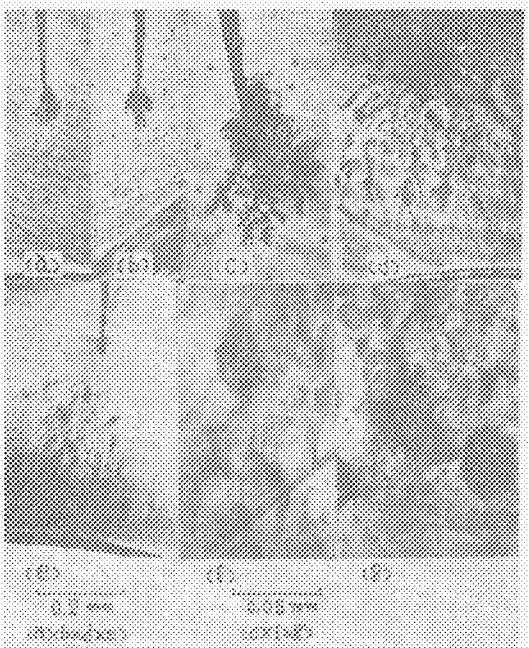


Fig. 8. Trees grown by positive and negative square wave. (a)–(c) Negative to a hole. (d)–(g) Positive to a hole. 3 kHz, 1.5 kV peak square wave applied for 10 h in 28°C test water, pulse duration—30 μs.

Table III shows the growth ratio of the trees when the voltage wave shape was varied. The growth ratio is defined as the ratio between the length of growth of the tree and the distance between the needle hole point and the inner electrode. These values are all the mean values of measurements of 20 samples.

When half-sine waves or square waves with positive polarity to the hole are applied, trees tend to grow more easily than with sine waves. However, there is almost no growth when negative polarity is applied to the hole. Fig. 8 depicts a tree produced when a square-wave voltage was impressed. With negative polarity, the trees are thick and short, but with positive polarity they are thin and long. These polarity effects are believed to be attributable to the following reasons. First, as Mason [6] points out, negative points emit electrons copiously so that space charges of the negative polarity can be produced easily. Because of this, it is supposed that the

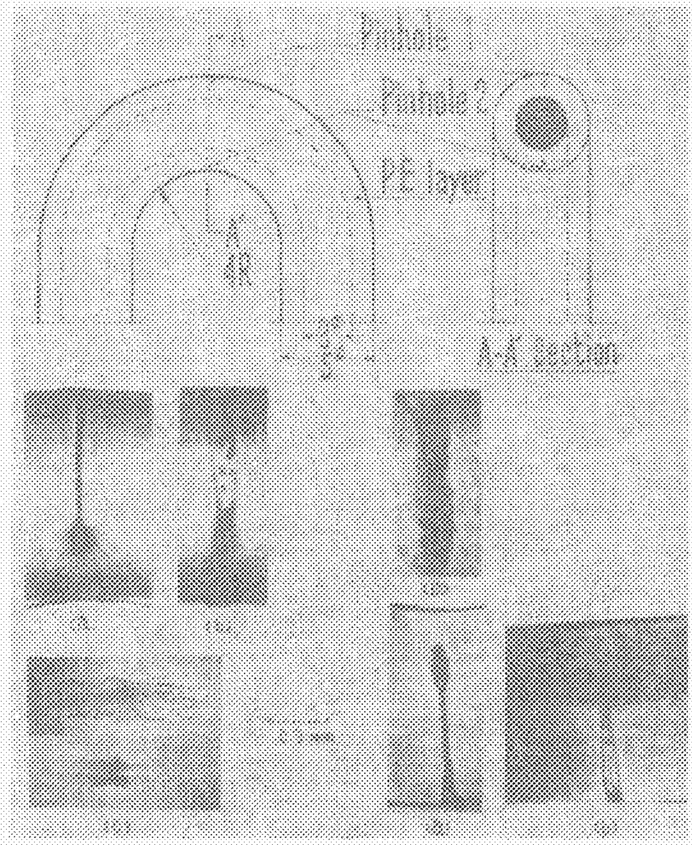



Fig. 9. Shapes of trees affected by mechanical stress. 9 kHz, 2 kV peak applied for 10 h in 60°C test water. (a) Front view, A–A' section, pinhole 1 or 2. (b) Side view. (c) Bottom view.

field at the needle tip is alleviated, and that it becomes more difficult for the tree to grow as a result.

In trees with a positive polarity, bubble-shaped agglomerations are observed as in (f) and (g), but these are not produced when sine waves or negative polarity waves are impressed. The reasons for this are unclear. When sine waves have been applied, in most cases a shape such as that in Fig. 8(b) will be formed. Since field alleviation occurs on the envelope plane at the tip of the tree, it is supposed that tree growth is more difficult than in cases when positive polarity square waves are applied.

In the polyethylene wires used in the experiments shown in Fig. 9, pinholes were produced beforehand. They were then vigorously bent, and the effects of the stress were examined. In Fig. 9, I(a)–(c) is shown the incidence of trees of the same type as cracks appearing on the outside of a rubber hose when it is bent. However, the trees differ from those resembling stress cracks, which are shown in Fig. 5. Fig. 9, I(a)–(c) shows trees that were produced under the identical conditions, although the examples were all cut out from separate trees. Two examples were given in (c) because trees with different shapes were found. Probably these shapes were produced in this manner because the free space inside the polyethylene was increased by elongation, and the trees grow out preferentially in that direction. Fig. 9, II(a)–(c) shows trees that spread out in exactly the

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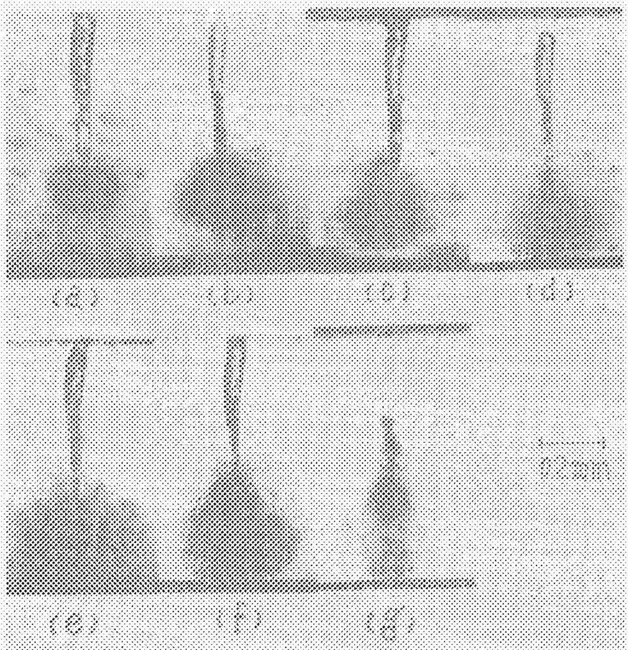


Fig. 10. Relation between tree growth and hours of voltage application. 9 kHz, 2 kV peak applied in 60°C test water. Hours of voltage application: (a) 1; (b) 8; (c) 12; (d) 28; (e) 44; (f) 73; (g) 120.

opposite manner to those in 1. It is a noteworthy fact that the shapes of the trees vary depending upon the mechanical stress.

When the conductivity of the aqueous solution was varied from $10^{-6}$ to $10^{-3}$ $(\Omega - cm^{-1})$, the trees tended to grow more easily when there was a greater conductivity, and there was almost no tree growth in pure water. Besides, even at the same conductivity, differences in tree growth were observed depending upon the type of electrolyte dissolved in the water.

### *C. Developments from Trees to Breakdown Channels*

The manner of tree growth with the passage of time was studied. The results of this are shown in Fig. 10. These photographs were obtained in the following manner. The tree at one pinhole was taken up at certain time intervals, immersed in oil, and photographed. Then the oil was removed, and application of voltage was continued. This process was repeated. The tree penetrated through the polyethylene layer within 28 h. Subsequently, a voltage of 2 kV peak was applied for 120 h, but there were very few changes in the tree shape, and insulation breakdown did not occur.

It is reasonable to assume that, after the tree has penetrated through the polyethylene, this channel will become thicker and will lead to the final breakdown. In other words, even though the tree has penetrated through the polyethylene layer, the breakdown voltage is still 4–6 kV, and it would require a very long time before breakdown could possibly occur with an actual voltage of only several hundred volts being applied. Fig. 11 shows test samples indicating the process from tree formation until breakdown. After high-frequency volt-

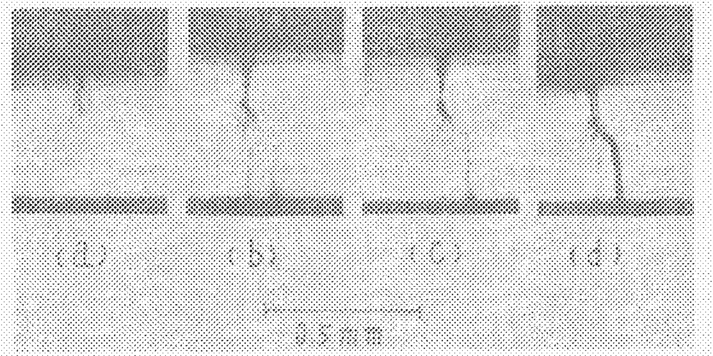


Fig. 11. Development of breakdown channel from a tree. After a tree had been produced by applying 9 kHz, 1.5 kV peak for 10 h in 60°C test water, 50 Hz, 6 kV peak was applied in water. (a) Tree before 50 Hz, 6 kV peak application. (b)–(d) Development of breakdown channel with the lapse of time is shown in order.

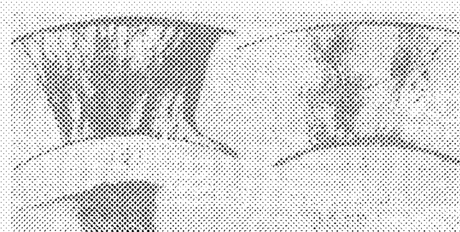

Fig. 12. Trees in a fluorocarbon resin coated wire. 50 Hz, 1 kV peak applied for 5000 h in 60°C test water.

age had been impressed on (a) to produce a tree, the sample was immersed in water, and the formation of the breakdown channel was observed microscopically while voltage was being applied between the water and the conductor. A 100-MΩ resistance was inserted in series with the specimen in order to slow down-the-channel formation process.

It was learned that the water inside the tiny tree is vaporized by the excessive current, that electric discharge occurs here, and that the tree becomes thicker as a result. It is believed that this process of expansion of the tree channel will take a longer time to lead to breakdown when a lower voltage is applied.

## IV. Causes of Insulation Deterioration

In summary, polyethylene does not deteriorate merely by the absorption of water. Rather, the deterioration process is accelerated by the interaction between the electric field and the water. Furthermore, since chemical deterioration cannot easily occur within a short period of time, it is reasonable to assume that treeing is the chief cause of deterioration occurring within a short period. It should be remarked that trees develop in a fluorocarbon-resin-coated wire as shown in Fig. 12.

### *A. Causes of Tree Incidence*

There are many examples of trees resulting from foreign matter or faults in the polyethylene layer. The

same phenomenon has been reported also in tests conducted in air atmospheres [7]. However, there are cases when trees were produced even when foreign matter could not be observed microscopically. When voltage is applied to samples immersed under water, it is supposed that the same process as if foreign matter were present would occur if water were to enter microvoids present in the amorphous region in which corona discharge would not occur.

### B. Causes of Development

Investigations were made of corona discharge in samples in which trees had occurred. When voltages of 2.8 kV peak or less were impressed, no discharges with a discharge magnitude of 0.5 pC or more were detected. It is unclear whether or not minute discharges of less than this occur. However, it is thought that tree growth can occur even in the absence of corona discharge, because trees can grow even when a minute voltage of only 0.2 kV peak is applied (Fig. 7). Consequently, the following may be considered to be partial causes of tree development: partial breakdown of the polyethylene; dissociation of molecular bond resulting from collisions of high-energy charged particles; oxidation by activated oxygen; or mechanical pressures applied to the tree tips. It is not possible to determine from the experimental facts which is the chief factor. However, it is presumed that tree growth results from a combination of these causes. At any rate, the formation of a local high field is definitely a precondition.

### C. Local Field

In view of the influence of the voltage wave forms on the ease or difficulty of tree growth, it is necessary to consider treeing from two standpoints: the local high-field-generation mechanism, and the field-mitigation mechanism. As the high-field-generation mechanism, there is the generation of reverse-polarity space charges. The field-mitigation mechanism includes space charges of the same polarity and increased conductivity at the high field. At the same time, field mitigation can occur as a result of the various tree shapes. The test results described in this paper can, it is thought, be explained more or less satisfactorily by a combination of the phenomena mentioned.

### D. Causes of Breakdown

A tree is produced; it develops gradually as time passes; and finally it penetrates through the polyethylene layer. After this, the tree channel expands, and complete breakdown results (Fig. 11). In this case, forced deterioration was performed by applying 6 kV after the tree had penetrated through. However, if a voltage of only several hundred volts were to be applied, almost no variations would be observed in a tree that had passed through the polyethylene layer. Tree-channel expansion at low voltages requires a long time, and the expansion mechanism is more complicated, but it is thought to pass through the same sort of process.

It is assumed that, after the water inside the tree is removed, the channel expands gradually because of the occurrence of discharge in the void left by the water, because of the occurrence of electrochemical deterioration, or for some other reason. The copper in the conductor has an important influence on this sort of deterioration. In this respect, metal shielding layers have a pronounced effect.

## V. Conclusions

1) Treeing occurs chiefly as a result of deterioration during application of voltage while the wires are immersed in water, this is accelerated at high frequencies. Trees originate from foreign matter or from porous regions in the polyethylene. Water has important effects on treeing.

2) There are polarity effects in tree growth. When pulse waves are used, the trees tend to grow easily with positive polarity applied to the pinhole. These polarity effects result from space charges. The tree shape changes on account of mechanical stress. This is a noteworthy fact in relation to generation mechanism of trees.

3) Double-layer insulation wires were developed in order to increase the reliability of the insulating wires. They have a much longer life than the conventional insulating wires used in the past, and remarkable effects have been observed in improving the insulation reliability of submeraible motors.

As outlined in the preceding, acceleration tests using high frequencies were carried out to reproduce treeing phenomena at extremely low voltages. This has made it possible to progress one step forward in the elucidation of the deterioration mechanism during actual use.

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