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TREEING IN MOLDED HIGH VOLTAGE INSULATION

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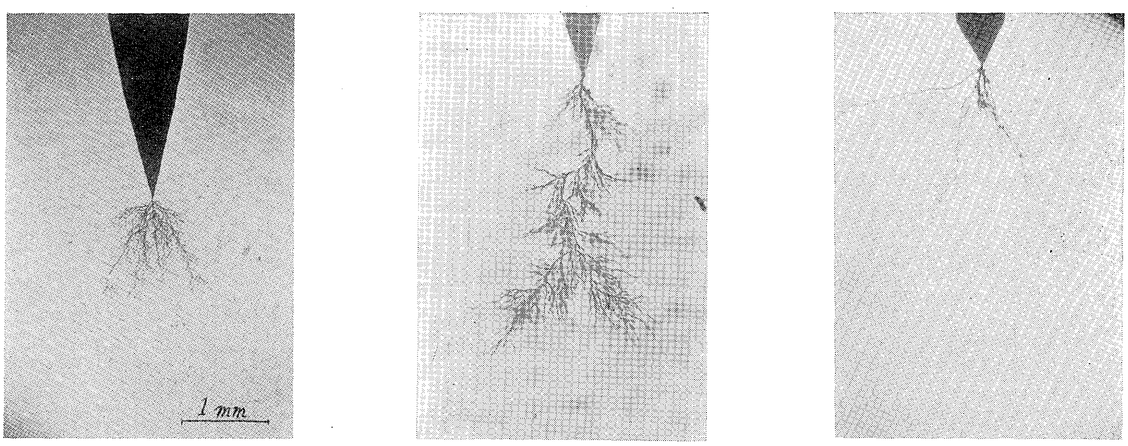
I. INTRODUCTION

Because of the progress made in synthetic resins and molding techniques, parts and devices made of molded resins are now often being used in place of the conventional oil-filled insulation and ceramic insulation. Some typical examples of this trend are the various types of molded resin parts used for high voltage insulation such as potential transformers, current transformers, bushings and support insulators which are employed in "fully-insulated metalclad high voltage switchgears," developed in order to make substations more compact.

As the parts become more compact and their voltages increase, the electric field in each part also increases and this causes a greater anxiety of deterioration due to voltage, i.e. voltage deterioration. To guard against this, our company has developed a a method of calculating the electric field distribution of insulation system by means of a computer(1) and research has been conducted on molding techniques so that weak points in insulation such as voids and cracks can be avoided as well as on discharge deterioration and its countermeasures(2). Discharge deterioration is divided into several kind : Those are partial discharge (corona), tracking, arcing and treeing deterioration. In this paper, treeing deterioration, which is extremely important in the use of molded materials as high voltage insulation and which is still not clear in many aspects, will be described.

Electric field concentrates in sharp points of solid insulation materials where there are electrodes, voids, etc. Because of this, local insulation breakdown begins and this breakdown expands in the shape of tree branches. This phenomenon is callded "treeing". This treeing is different from the case in which the insualtion material is eroded gradualy by discharges as when the so-called corona discharge deterioration occurs. Treeing occurs even with comparatively low voltages when the electrode tip is very sharp. Once it begins, it usually expands very rapidly and insulation breakdown develops in a very short time compared with corona deterioration even in very thick insulation materials. Therefore, treeing is an important factor in determining the life of the insulation and as one type of insulation breakdown phenomena in solids, it has become increasingly stressed recently both in theory and in practice. Research is now underway on this phenomenon from various aspects. Therefore, there is a relatively large amount of data from treeing research on polyethylene for use in plastic cable but there are still many points which have not been clarified in the research concerning molded resins such as epoxy resin for use in molded resin products.



(a) AC 19 kV applied to polyethylene for 10 minutes

(b) AC 16 kV applied to polymethylmethacrylate for 10 minutes (radious of curvature at needle tip: approx. 3 μ, insulation distance: 10 mm)

(c) AC 40 kV applied to epoxy resin for 10 minutes

Fig. 1 Treeing in various organic in sulation materials

In this paper, the treeing phenomenon will first be explained and then a detecting method of treeing by measuring the corona and the results of investigations concerning the inception of treeing in epoxy resins performed by the authors will be described.

II. TREEING PHENOMENON

Fig. 1 shows photographs of treeing which occurred at the tip of needle electrode buried in various types of organic insulation materials. The name of treeing is used because the path of the breakdown ressembles the branch of a tree as can be seen in the photographs. In 1930, Von Hippel, Inge and Walther revealed that the path of insulation breakdown in solid crystals of halogen compounds is in the form of directional tree-like branches, and considerable researches have been carried out from the standpoint of the solid theory[(3)]. Treeing is therefore not a new phenomenon if this work is considered. In 1951, however, Mason[(4)] showed that the last stage of corona erosion occurring in voids in insulation materials takes the form of a branch shaped breakdown. In 1958, Kitchin and Pratt[(5)] showed that treeing often occurs in polyethylene cable which has been impressed by voltage for a long time and that this treeing is closely related to insulation breakdown in the cable. After this work, considerable attention was focussed on treeing from the standpoint of insulation. Since treeing and other such phenomena are easily influenced by secondary factors and are highly complex, there are still many points which are not yet clear concernnig them. These points can be listed as follows:

(1) There are cases when treeing begins due to the concentratration of corona discharge at one point in the small air gap at the tip of the needle electrode[(6)]. However, treeing sometimes also occurs when there is absolutely no air gap at the tip of the electrode.

(2) Treeing sometimes occurs immediately after the voltage is applied, but it generally takes place after some time passes (a period which can be called the induction time)[(7)]. This induction time is generally smaller the larger the voltage is (refer to *Fig. 2*). Also as an particularly case, treeing occurs when an impulse voltage is applied.

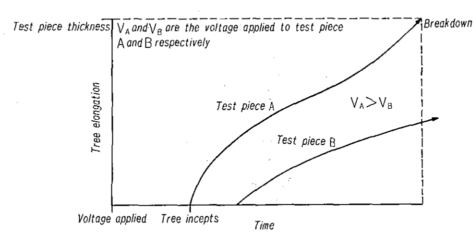


Fig. 2 Relation between tree elongation and voltage application time

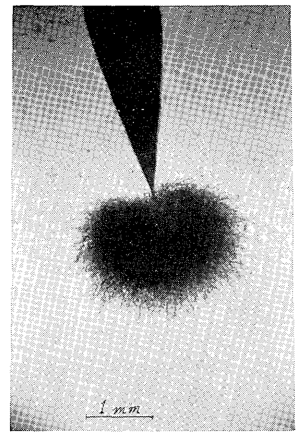


Fig. 3 An example of a tuft shaped tree

(3) The branch-shaped breakdown path is in the form of hollow tubes and the diameter of tubes is only a few microns[(9)]. In polyethlene and epoxy resins, there are no traces of carbonization on these tube walls and they have an electric conductivity.

(4) In the hollow treeing tubes, a pulse like discharge occurs as same as a corona discharge.

(5) The shape of the treeing generally ressembles tree branches but sometimes it takes the form of a tuft (refer to *Fig. 3*).

(6) As treeing progresses, a gas decomposed from the insulation material arises and the pressure inside the treeing tube generally increases. However, the changes in this pressure have a complex influences upon the progress of the treeing. The main components of this decomposed gas as analyzed in polyethylene were CO, CO_2, H_2, and H_2O[(10)].

Various theories concering the mechanism of treeing, such as local intrinsic breakdown, concentrated erosion due to partial discharges occurring in the small air gap at the tip of the needle electrode and mechanical breakdown of the material due to Maxwell tension arising because of the high electric field, have been proposed, but it is not yet clear which is the main factor.

Above are the main points concerning treeing. Reseach into treeing can roughly be divided into two cases: that which emphasizes the inception of treeing and that which emphasizes the progress of the treeing. The authors investigated the inception of treeing in epoxy resin as a typical molded resin. This work is desdribed below.

III. INVESTIGATIONS INTO THE INCEPTION OF TREEING IN EPOXY RESIN

The inception of treeing is basically a phenomenon occurring due to the concentration of an electric field but it can be divided into two cases: (1) treeing which starts when there is absolutely no void at the tip of the needle electrode and (2) treeing which occurs when there is a gap in the electrode. In the former case, treeing begins when there is no discharge but in the latter case, corona discharge occurs first and treeing inception due to local concentration of the corona discharge.

There are two methods to produce treeing under laboratory conditions. One is to insert a needle-shaped electrode into the insulation material and apply voltage to the electrode. The other is to make a needle shaped void in the material. The first method is also subdivided into two types: the double needle method in which two needles are inserted in opposite positions and the single needle method in which only one needle is inserted. In the single needle method, there is the direct ground system in which the lower part of the needle comes into direct contact with the material and also the remote ground system in which the lower part of the needle is separated from the material.

In this work the aim was to investigate the inception of treeing in epoxy resins when there are no voids at the electrode tip and therefore the single needle method with the direct ground system was used. Since in practice, the inception of treeing is emphasized more than the progress of the treeing, investigations mainly concerned (1) the relation between the inception of treeing and the sharpness of the needle electrode tip and (2) the relation between the inception of treeing and the insulation distance. These results were compared with the large amount of existing data concerning polyethylene, acryl reins, etc.

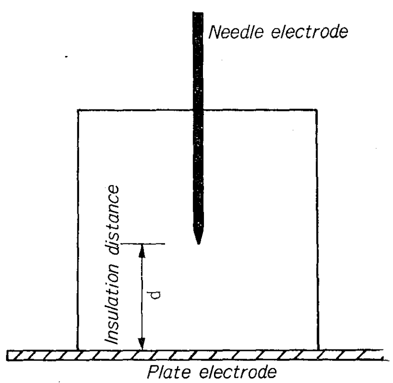


Fig. 4 Electrode arrangement

Table 1 Specimen and its preparation

Materials	Polyethylene	Poly methylmethacry late	Epoxy resin
Symbol	PE	PMMA	EPOXY
Contents	Lowdensity polyethylene	—	Araldite, hardner, acid an hydride
Method	Heatng and insertion method	Same of left	Vacuum injection method
Condition	1) After heating at 120°C for 5 minutes 2) Insertion of needle 3) Cooling	1) After heating 160°C for 15 minutes 2) Insertion of needle 3) Cooling	1) Resin combination at 100°C 2) After degassing, injection at 3 mm Hg, 100°C 3) Heating and hardening at 3 h, 130°C

1. Tree Inception Voltage in Epoxy Resins

The electrode arrangement in the test piece was as shown in *Fig. 4*. The electrode was an iron wire with a diameter of 0.5 mm processed to form a tip angle of 50° and a tip radius of less than 3μ. The insulation distance between the needle electrode and the lower electrode was 10 mm. The various types of material and their preparation is shown in *Table 1*. To measure the tree inception voltage, the test piece was immersed in insulation oil, and AC 50 Hz voltage was increased from 4 kV insteps of 2 kV at 10 minute intervals for polyethylene and acryl resin and from 10 kV in steps of 5 kV at minute intervals for epoxy resin. The test piece was removed at each voltage step, the presence of trees was checked using a microscope with a magnifying power of 100, and the tree inception voltages were obtained. It was judged that a tree had incepted when a tree of more than 10μ appeared. The results are shown in *Table 2*.

Comparing the tree voltages in the three types of material, the highest was for epoxy resin and the lowest for polyethylene. The tree inception voltage for epoxy resin is two or three times that for polyethylene. There are few deviation in the case of polyethylene but there are a relatively large number for epoxy resin. It is not clear whether the high tree inception voltage for epoxy resin is due to some inherent characteristics in the material itself or to differences in the method by which the test piece was formed, but since there are also clear differences in the data obtained by other researchers, it can be considered that they are due to the material itself. Along with the measurement of tree inception voltage, the partial discharge (corona) was also measured but no partial discharges were found previous to the inception of treeing (1 pc measurement sensitivity).

Table 2 Tree inception voltage of various materials

Materials	Averarge (kV)	Maximum (kV)	Minimum (kV)
Polyethylene	9	10	8
Polymethyl-methacrylate	15	16	8
Epoxy resin	28	45	15

(Needle tip radius $r=3\mu$, insulation distance $d=10$ mm)

2. Influence of Needle Tip Sharpness on Tree Inception Voltage

As was mentioned previously, the tree inception to form because of local concentration of electric field. In order to investigate the manner in which the tree

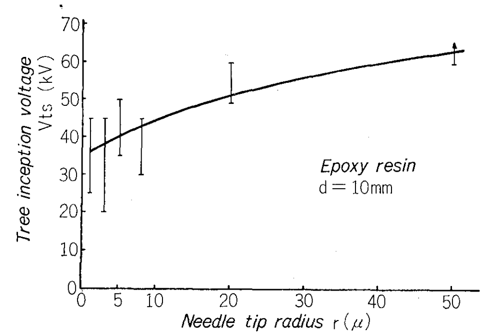


Fig. 5 Relation between tree inception voltage and needled tip radius

inception voltage charges in respect to the needle tip radius r, experiments were carried out in epoxy resin using needle electrodes with various tip radii.

The electrode construction and arrangement of the test piece were the same as in *Fig. 4* and *Table 1* respectively. The needle electrodes had a diameter of 0.5 mm and a tip angle of 50°. The tip radii were of 6 sizes: 1, 3, 5, 8, 20 and 50μ. The voltage applied was raised from 10 kV in 5 kV steps at 30 minute intervals. The results of the measurement are shown in *Fig. 5*.

For each needle tip radius r, a total of 16 test pieces were measured but the deviation were rather large. Considering the average values, however, it is evident that as the radius of the needle tip increases, the tree inception voltage also increases. On the other hand in practice, it has been found that the sharper the needle tip, the easier it is for treeing to incept. When considering the dependence of the needle tip radius on the tree inception voltage for a radius of 3μ was 36 kV and that for a radius of 20μ was 52 kV. The increase is only about 1.5 times which was less than expected. These will be discussed later.

3. Relation Between Insulation Distance and Tree Inception Voltage

If the inception of treeing is determined by the field strength in the needle electrode, the decrease in the needle field will be small even if the insulation distance d is increased in electrodes with a large field concentration such as needle-plate electrodes. Therefore, it can be assumed that the tree inception voltage will not be as high as this.

To investigate this, the tree inception voltage was measured in epoxy resin using a needle electrode with a constant radius of 3μ and varying the insulation distance in the range from 2 to 20 mm. The results are shown in *Fig. 6*. As was anticipated, the tree inception voltage was not very large even when the insulation distance d was increased when the needle tip was very sharp. Within the experimental range ($d=2$ to 20 mm, $r=3\mu$) the relation between the tree inception voltage and the insulation distance was almost linear and the experimental equation $V_{ts}=36+1.6\,d\,(V_{ts}\,[\mathrm{kV}],\ d\,[\mathrm{mm}])$ was obtained. From these results, it is evident that in order to prevent treeing in molded resins, it is better to make the needle tip radius as large as possible than to increase the insulation distance

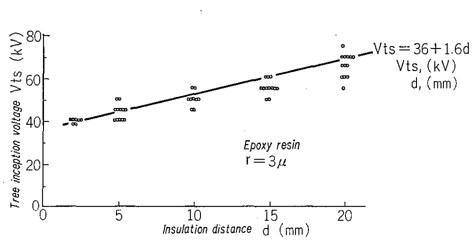


Fig. 6 Relation between tree inception voltage and insulation distance

4. Consideration Concerning Tree Inception

1) Field strength of needle electrode when treeing incepts

When the hyperboloid of revolution is considered for the type of electrode used in the experiments, i.e. a needle-plate electrode, the maximum field strength of the needle tip $E_{\max}$ can be expressed by the following equation:

$$E_{\max}=\frac{2\,V}{rl_n\,(1+4\,d/r)}\quad\cdots\cdots\cdots\cdots\quad(1)$$

where V: Applied voltage
r: Radius of needle tip
d: Insulation distance

When d is much greater than r, equation (1) will be

$$E_{\max}=\frac{2\,V}{rl_n\,(4\,d/r)}\quad\cdots\cdots\cdots\cdots\quad(2)$$

Using equation (2), the field strength of the tip at the inception of treeing was calculated from the tree inception valtages of the vorious materials shown in *Table 2* (hereafter, the tree inception field stength will be referred to as E_{ts}). The results of these calculations are shown in *Table 3*.

The inherent insulation breakdown strengths at the uniform field of these materials do not differ very much and are all in the order of 105 V/mm[12]. When comparing the tree inception field strength calculated by equation (2) and the inherent insulation breakdown strength, the value of the tree inception field strength is larger. Considering the differences in tree inception field strength among the materials, the ratio of polyethylene to epoxy resin is approximately three times larger.

Table 3 Tree inception field-strength of various materials

($r=3\mu$, $d=10$ mm)

Materials	Polyetylene	Polymethyl-methacrylate	Epoxy resin
Tree inception voltage (kV)	9	15	28
Tree inception field strength (V/mm)	6.3×10^5	1.1×10^6	2.0×01^6

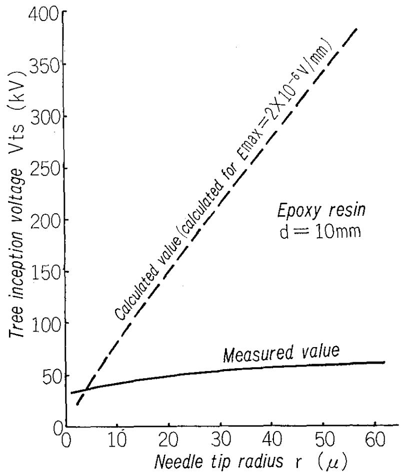


Fig. 7 **Relation between tree inception voltage and needle tip radius (Comparison between measured and calculated values)**

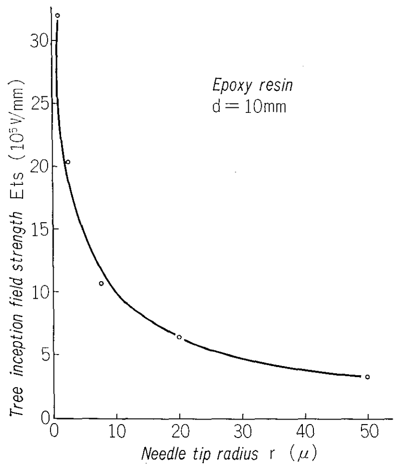


Fig. 8 **Relation between tree inception field strength and needle tip radius**

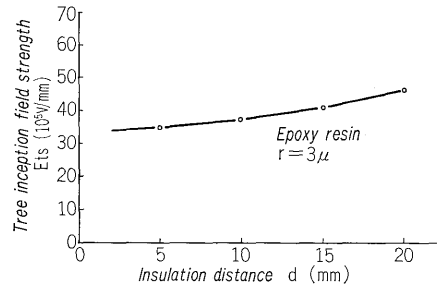


Fig. 9 **Relation between tree inception field strength and insulation distance**

There are no doubt problems such as whether or not equation (1) can be used to determine the field strength at the needle tip or the necessity of considering the field reduction effect at the needle tip due to the high field conduction, etc. but in any case, it is interesting to consider partial intrinsic insulation breakdown due to a treeing mechanism such as local field concentration.

Next, assuming that treeing occurs when the needle tip field strength is some constant value determined according to the material, the values from *Table 3* were substituted in equation (1) and the tree inception voltage when the radius r changes was calculated. *Fig. 7* shows a comparison between these calculated values and the actually measured values of the tree inception voltage (average values) for each r.

When the tip radius r was large, the tree inception voltage was large in both the calculated and measured cases but the calculated value is much larger and as r becomes larger, the difference between the calculated and the measured values becomes greater. This fact shows that the assumption that the treeing begins when the needle tip field strength becomes some constant value is not true. In other words, it shows that the tree inception field strength differs according to the needle tip radius r.

Fig. 8 shows the results of determining the tree inception field strength from the measured values of tree inception voltages at various radii r. The tree inception field strengte E_{ts} tends to be reduced remarkably when the value of the tip radius r is not constant and becomes large[14].

Next, changes in the tree inception voltage when the insulation distance d is changed were considered. It was found that when the needle tip radius r was very small, the tree inception voltage did not increase even when the insulation distance was increased. From these results, the relation between the tree inception field strength E_{ts} and the insulation distance d was obtained using equation (2). This relation is shown in *Fig. 9*.

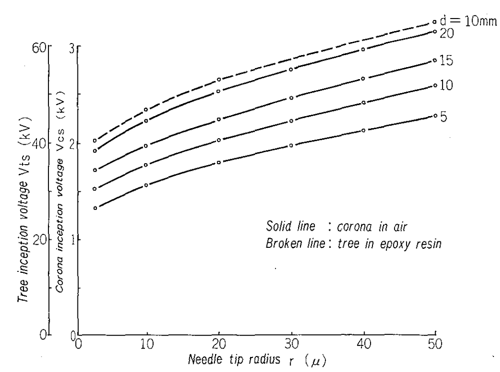


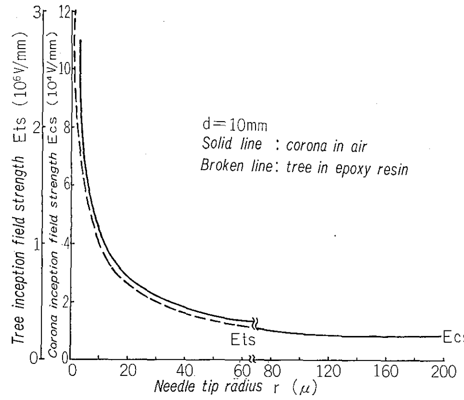
Fig. 10 **Relation between corona inception voltage, tree inception voltage and needle tip radius**

E_{ts} increased slightly when d was made larger and it did not remain constant in respect to d. However, the amount of increase of E_{ts} in respect to d was not as large as the dependence of E_{ts} on r.

The above are the results of various investigations conducted concerning tree inception phenomena from the standpoint of the field strength at the needle tip when the tree incepts. According to these results, tree inceptson is not determined only by the maximum needle tip field strength when the needle tip radius r and the insulation distance d are changed. When r is large, the tree inception field strength drops remarkably and when d is large, E_{ts} increases slighly but this comparatively small. These results indicate that this phenomenon ressembles the gas discharge in a non-uniform field in a gas.

2) Comparison between treeing and gas discharge in needle-plate electrodes

For this comparison, a corona discharge in air when a voltage of AC 50 Hz was applied to the same electrode construction (needle-plate) as was used in the treeing experiments was investigated. The corona



F.g. 11 Relation between corona inception field strength, tree inception field strength and needle tip radius

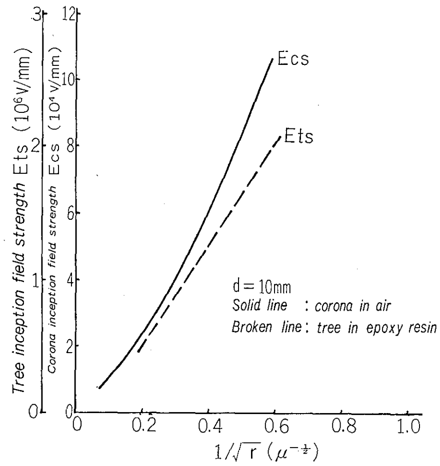


Fig. 12 Relation between corona inception field strength, tree inception field strength and needle tip radius

inception voltages when the needle tip radius r and the insulation distance d were altered, were measured. *Fig. 10* shows the relation among the corona inception voltage V_{cs}, the tree inception voltage V_{ts} and the needle tip radius r.

As is evident from *Fig. 10*, the treeing V_{ts} at which there is a partial breakdown of the solid and the corona discharge V_{cs} at which there is a partial discharge of gas both show a very similar dependence on the needle tip radius r. In the experimental range $d=10$ mm, $r=3$ to 50), the tree starting voltage for epoxy resins is generally always about 25 times the corona starting voltage in air.

Next, the needle tip field strengths E_{cs} and E_{ts} at corona inception and tree inception respectively were obtained from the corona inception and tree inception voltages using the same methods as described previously. The results of an investigation of the relation between these values and the needle tip radius r are shown in *Fig. 11*.

Both E_{cs} and E_{cs} decrease remarkably when the needle tip radius is large and both decrease ressemble each other very closely. Ryan et al[16] has reported the establishment of an experimental equation showing the relation between the needle tip radius r and the breakdown field strength E for electrodes in air

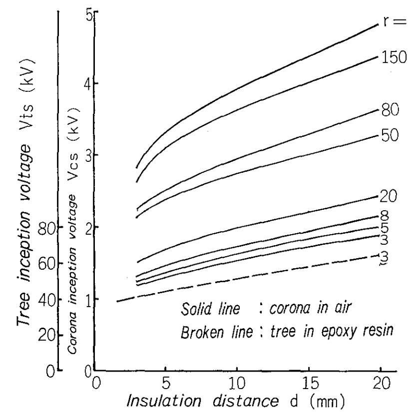


Fig. 13 Relation between corona inception voltage, tree inception voltage and insulation distance

such as the parallel cylinder and the spherical flat plate. This equation is as follows:

$$E=A+B/\sqrt{r} \quad \cdots\cdots\cdots\cdots\cdots\cdots (3)$$

where A and B are constants.

Fig. 12 shows the results of substituting E_{sc} and E_{ts} in the above equation. When the radius r is large, the linear relation is lost, the slope is gradual and the value is near that of the breaknown strength in uniform field. However, when r is relatively small, a linear relation is established in both cases and the relation among E_{cs}, E_{ts} and r closely resembles that of equation (3).

Fig. 13 shows the relation between the corona inception voltage and the tree inception voltage for epoxy resin when the insulation distance d is varied between 3 and 20 mm. The corona inception voltage in air does not increase much when the insulation distance is increased and the amount of increase is even less the smaller the needle tip radius r. When the needle tip radius is less than 10μ, the corona inception voltage is almost linear in respect to the insulation distance. Both the treeing and corona characteristics ressemble each other very closely in

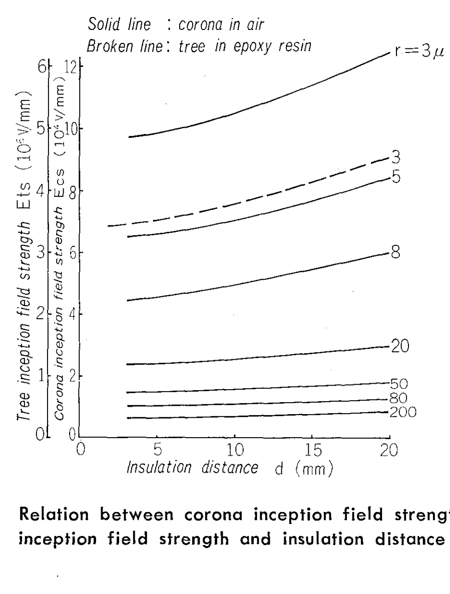


Fig. 14 Relation between corona inception field strength, tree inception field strength and insulation distance

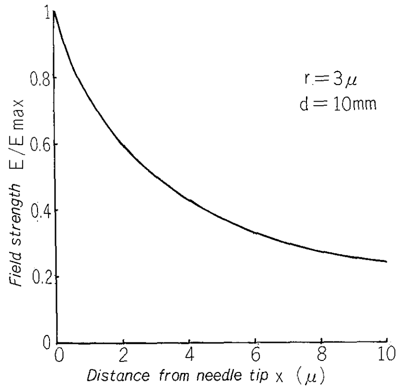


Fig. 15 Field distribution in vicinity of needle tip

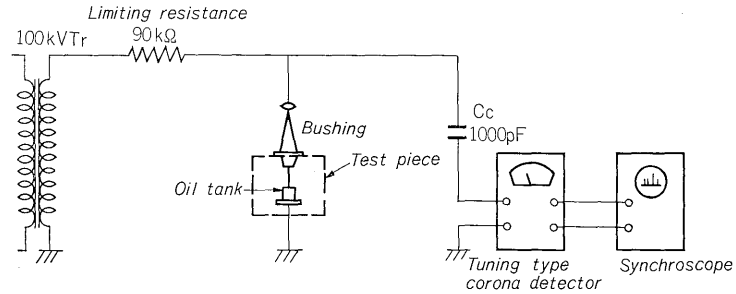


Fig. 16 Corona measuring circit

their dependence on the insulation distance d as they did for the needle tip radius r. *Fig. 14* shows the relation among E_{cs}, E_{ts} and the insulation distance. Both E_{ts} and E_{cs} increase considerably as the insulation distance increases when the needle tip radius is small but when the radius is large, there is little increase in respect to the insulation distance and at $r=200\mu$, E_{cs} is almost constant in respect to d.

The above are investigations conducted to compare the treeing characteristics in epoxy resin and the corona characteristics in air using a needle-plate electrode. From the results it was evident that there is a very close ressemblance between the tree inception characteristics for which there is a partial brekdown in the solid and the corona inception characteristics for which there is a partial breakdown in air. Therefore, in spite of the basic differences between a solid and a gas, the tree formation mechanism seems to be very similar to the gas discharge mechanism. In particular, considering the field strength when a tree incepts, it is eveident that, as in the case of breakdown of a gas in a nonuniform field, tree inception is determined not only by the maximum field strength at the needle tip but also by the field distribution in the vicinity of the needle tip. *Fig. 15* shows the field distribution in the vicinity of the needle tip for a needle-plate electrode ($r=3\mu$, $d=10$ mm).

The amount of field concentration is extreme and the high portion of the field strength is all near the needle tip. At a distance of several microns from the needle tip, the field strength has already dropped to about 1/2 of its maximum value. The above-mentioned assumptions are all backed up by the existence of this extremely non-uniform field.

IV. TREE DETECTION BY CORONA MEASUREMENT

Up to this point, tree inception and progress have been observed visually using a microscope. This method is limited to materials which are both transparent and small and it is not possible to observe treeing in materials such as those containing fillers which are not transparent or treeing which occurs in molded machine parts actually in use. Therefore, utilizing the before-mentioned fact that a pulse type discharge similar to the void discharge occurs in the treeing tubes, invetigations were carried out to determine whether or not it would be possible to detect the presence of treeing and treeing progress indirectly by measuring the corona discharge.

1. Experimental Method

The test piece was the same as that described previously. Measurements were made of the changes with time of the corona discharge magnitudes (apparent discharge, rate of repetition, etc.) when a constant voltage or a voltage with stepped increases was applied to the material. Every 1 to 5 minutes the test piece was removed and the tree elongation (maximum elongation in needle axis direction) was observed. *Fig. 16* shows the circuit used for corana measurement.

Corona measurement was conducted inside a shielded room and external noise was cut-off by the use of filters, etc. With these measurement, corona of up to 1 PC could be measured. Special care was also taken to eliminate completely the formation of any corona except in the test piece.

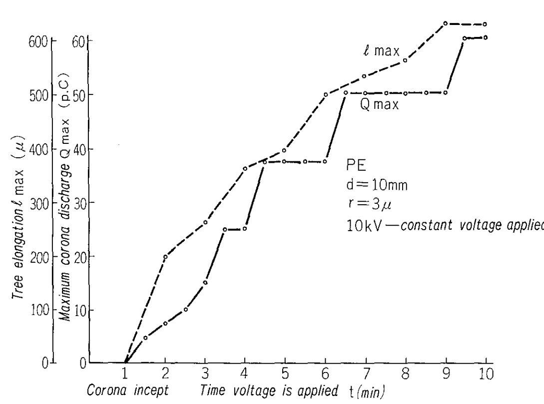


Fig. 17 Relation between elongation of tree, maximum corona discharge and time

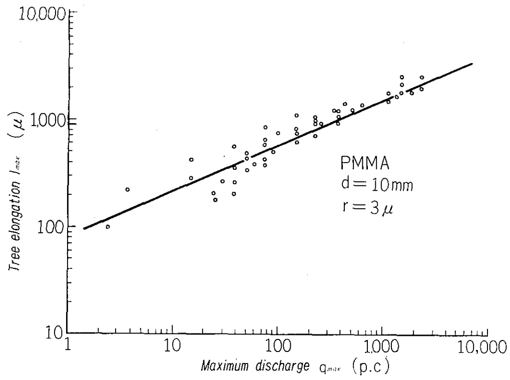


Fig. 18 Relation between l_{max} and q_{max}

2. Results and Considerations

Fig. 17 shows the changes with time of the maximum tree elongation l and the maximum apparent charge q_{max} when a constant voltage was applied to a polyethylene test piece ($r=3\mu$, $d=10$ mm).

The corona was not measured directly after the voltage was applied but about one minute later, a corona of several PC was measured, and a tree was observed simultaneously. Subsequently, the corona magnitude increased in accordance with the elongation of the tree and these increases corresponded closely.

Fig. 18 shows the relationship between l_{max} and q_{max} when an initial voltage of 4 kV is increased in 2 kV steps at 10 minute intervals for an acryl resin test piece ($r=3\mu$, $d=10$ mm). In this case, there is a mutual relation between q_{max} and l_{max} which can be expressed by equation (4).

$$l_{max}=Aq^{n}{}_{max} \cdots\cdots\cdots\cdots\cdots\cdots \quad (4)$$

Where A and n are contants which depend on the type of material and the shape of the tree (branch-shaped, tuft-shaped, etc.).

When the tree elongation is comparatively small (less than approx. 1,000 μ), there is almost a proportional relation between the tree elongation and the maximum apparent charge. To be more exact, a 10 PC corona corresponds roughly to a 100 μ tree.

The same results were also obtained for epoxy resin. However, compared with the other materials, corona formation conditions are intermittent and changes in the corona magnitude are rather large. These are features of epoxy resins.

In the above-described observations of corona simultaneously with tree formation, a mutual relation was found between tree elongation and maximum apparent charge. Therefore, it is possible to know indirectly the presence and extent of trees by measurement of the corona without directly observing the trees. In this way, trees can be detected through corona measurements even in molded parts actually in use and it is thus possible to maintain such parts.

V. CONCLUSION

This paper has been mainly described tree inception in epoxy resins, a typical example of a molded resin and a method of detecting trees by the measurment of corona.

There have been conclusions made previously concerning the inception of treeing. So as to prevent the treeing in molded resin parts sufficient causions are required to cases when there are no cracks and voids in the molded parts and when these electrode tip is not sharp but rounded as much as possible. Increasing the insulation distance is not very effective in preventing the inception of trees. When maintaining the molded parts, it is possible to detect the inception of trees by means of careful corona tests.

The so-called voltage stablizer method has appeared as a means of increasing the tree inception voltage in polyethylene and it will be interesting to find out whether this method can be used also for epoxy resins. Considering the life test or accelerated life test, it will be important to conduct investigations in the future concerning the dependence of voltage on the induction time up to the tree inception voltage in order to clarify the tree inception mechanism.

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