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THE ROLE OF A DIELECTRIC BARRIER IN ELECTRICAL TREES INITIATION IN SOLID INSULATION

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This paper examines the role of a strong (high permittivity) barrier in a three layer dielectric arrangement. Specimens consisting from two layers of PMMA (Polymethyl methacrylate) and a third layer of ER (Epoxy Resin), were constructed and stressed under an constant AC 50 Hz voltage with a needle-plane arrangement, for a period of 6 hours. Partial discharge (PD) measurements were continuously taken and visual and microscopic observation was taking place at the tip of the needle area. The treeing inception time t_i and the breakdown voltage of the sample were examined as a function of the barrier position ξ, the ratio of the needle-barrier distance to the total distance between the electrodes. Finite element-2 dimensional simulation was run in order to examine the electric field in the specimen, especially the maximum electric field strength F_m at the needle tip. It was shown that the treeing inception time t_i has a maximum for an optimum barrier position ξ. This optimum barrier position minimizes the maximum electric field and the electric energy density D_{es} at the pin tip and consequently maximizes the tree inception time t_i. Finally, a very useful relation relating the initial tree length with electrical properties of the insulating materials was derived.

K e y w o r d s: dielectric barrier

1 INTRODUCTION

Solid insulation used in high voltage equipment usually consists of layers of different dielectric materials. In some cases barriers are created inside the main insulating material in order to increase its dielectric strength. The exact mechanism through which the barriers affect the dielectric characteristics of the insulation is not yet known, in spite of the fact that plenty of experiments have been carried out for that reason. It is known that both the position and the value of the dielectric permittivity of the barrier affect the dielectric characteristics of the specimen [1]. It is also known that permanent defects are caused in the bulk of solid insulation during its lifetime and electrical trees or bushes are formed under certain circumstances in specific regions inside the insulation. The first branches of the electrical trees appear initially in locations where the electric field strength has higher values due to the fact that the electric field is highly inhomogeneous. As time passes, the tree branches grow, bridging the insulating gap between the electrodes, resulting finally to the breakdown of the insulation [2]. A characteristic parameter is the treeing inception time t_i, which can even be years when the insulation is stressed under the nominal operation voltage of the equipment. On the contrary, the time between inception time until insulation breakdown is relatively smaller. Breakdown can happen very soon after the growth of branches with a specific size. The treeing inception time in solid insulation depends on the insulation design, the used insulating materials and the electrical and mechanical stresses [4,2]. In order to study experimentally the barrier effect on the growth of electrical trees in solid composed insulation, special specimens were designed and made of transparent insulating materials and experiments were carried out under AC voltage in high electric field strength levels, stressing the specimens while simultaneously partial discharges measurements were taken. At the same time, visual and microscopic examination of the specimens carried out to detect the electrical trees. In the following section the description of the samples and the experimental procedure is presented. Then the experimental results and theoretical relations are discussed and followed by a few concluding remarks.

2 EXPERIMENTAL PROCEDURE AND SAMPLES

The specimens were made of PMMA (Polymethyl methacrylate), a transparent insulating material, so that the detection and observation of the trees inside them would be possible during the tests. The specimens had the shape of a parallelepiped and inside them a barrier was formed of ER (Epoxy Resin), as shown in Figs. 1 and 2. The two layers, which have thickness d_1 and d_1 respectively, were made of PMMA and the third layer, which has thickness $\delta = 200 \pm 10\,\mu$m, was made of ER. The position of the barrier inside the insulation was specified by a parameter $\xi = y/x$ where x is the needle-plane separation and y is the needle-barrier distance. Several groups of specimens having various values of ξ were constructed, while x had a constant value of 7.5 mm$\pm 5\%$. The needle electrode was inserted inside each specimen with a special procedure, so that no mechanical pressure would remain

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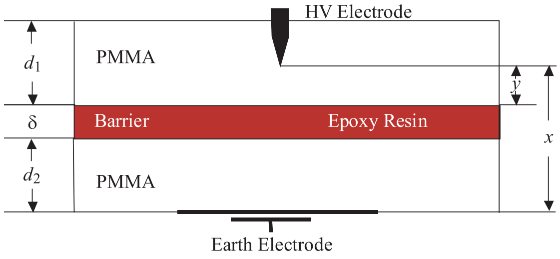


Fig. 1. Schematic diagram of the sample shape of a PMMA specimen. The barrier position is defined by the parameter $\xi = y/x$

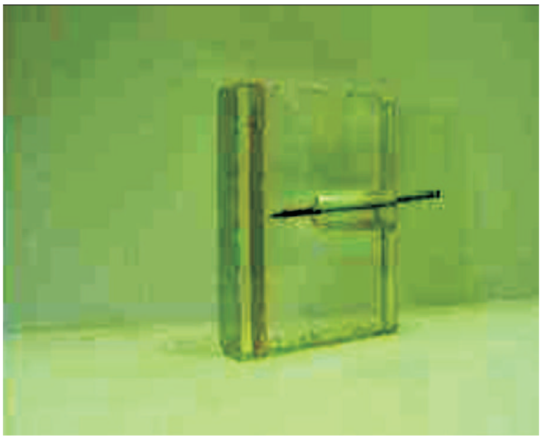


Fig. 2. Photo of a PMMA specimen with a barrier from ER

Fig. 3. Photo of the test cell filled with transformer oil, connecting to the coupling capacitor, quadripole and the output of the main transformer

in the main material of the specimen, a fact that would have affected the treeing inception time [5]. Each specimen was immersed in transformer oil inside a special test cell and was stressed under AC voltage of constant value (85 % of the pre-measured breakdown voltage in PMMA specimens with the same thickness but without barrier inside them), as shown in Fig. 3. The voltage value was chosen as high in order to accelerate the procedure of tree growth in the specimen and was applied to it for a constant period of 6 hours. During the experiment, partial discharge measurements were continuously taken and visual observation was made at the tip of the needle area with a microscope. After the voltage interruption, microscopic control was made for detection and more thorough investigation of the electrical trees. The experimental arrangement is shown in Fig. 4. The experimental apparatus consisted of the AC voltage source (1 and 2), the low and high voltage filters (3 and 4), the coupling capacitor (5) connected in series with the quantripole AKV, the partial discharge detection and measurement device (8) and the test cell (6) with the specimen. It is noted that for some specimens, immediate control was made for the detection of initial tree growth at the time that the first significant change in the measured partial discharge values occurred. Stressing of these specimens continued until the sixth hour and in the end, microscopic examination was taken again. In order to examine trees growth further, for some specimens the electrical stress continued after the limit of 6 hours until breakdown, and growth of new tree branches was examined again.

3 EXPERIMENTAL RESULTS

The treeing inception time t_i in each specimen was the moment at which the first significant change in the measured partial discharge values occurred, at the maximum amplitude of the apparent charge and their angle, as confirmed by visual examination and sample microscopic examination of the specimens. In Fig. 5 the change of the values of the partial discharges amplitude and their angle distribution are shown for a moment $t < t_i$ and for the moment t_i. At that moment, the first tree branches or bushes were locally formed in the main insulation starting from the tip of the needle electrode, as shown in Fig. 6. After t_i, subsequent fluctuations of the partial discharges values were observed, sliding to higher levels of values, as shown in the curves of the change of maximum values of partial discharge apparent charges in relation to the voltage appliance time, Fig. 7 for specimens with various barrier positions. From the microscopic examination of the specimens right after the moment $t = t_i$ and the microscopic examination that took place after the end of the experiment, it was observed that after the moment t_i, until the limit of 6 hours, carbonizing of some branches of the existing trees and growth of new branches occurred, as shown in Fig. 6. From the experimental results it was clear that the treeing inception time t_i depends on the barrier position ξ, as shown in Fig. 7. It is also obvious that at a specific barrier position ξ_{opt}, a maximum value of treeing inception time t_i appears. It is noted that the specimens whose barrier was formed at the optimum position ξ_{opt} had the maximum dielectric strength under AC voltage as it it indicated in the following section. In the case of specimens that the stress continued for more than 6 hours, until the final breakdown, it was found that while initially the branches were directed and reached the barrier's upper interface, the new branches grew parallel to that until the barrier was punctured down to the earth electrode.

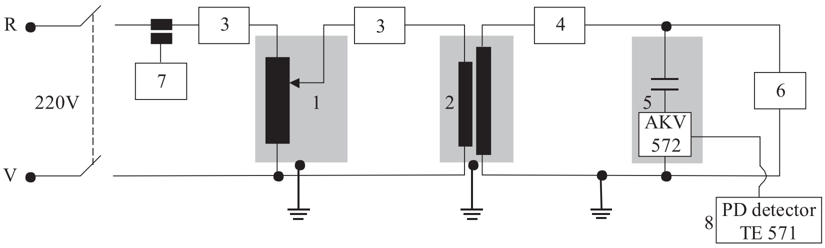
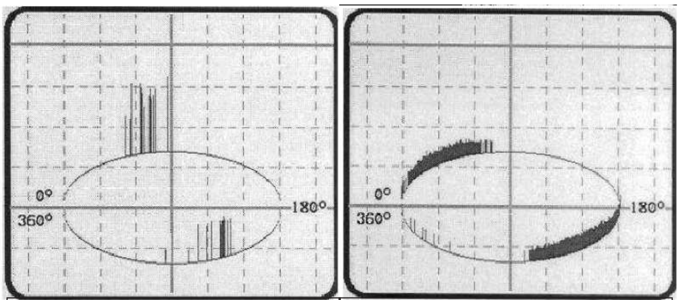


Fig. 4. Diagram showing the experimental arrangement with the apparatus used to carry out the experiments



PD Level	247 pC	PD Level	0.32 pC
Voltage	20.0 Kv	Voltage	20.0 Kv
	50 Hz		50 Hz
PD-Range:	200 pC/div	PD-Range:	1.0 pC/div
Noise Suppression:	10%	Noise Suppression:	10%
Synchronisation:	Auto	Synchronisation:	Auto
Gain:	Manual	Gain:	Manual

Fig. 5. Partial discharge measurements in a PMMA specimen stressed under 20 kV: at a moment $t < t_i$ (bottom part of the figure 0.32 pC) and (b) at the moment $t = t_i$ (top part of the figure 270 pC)

4 DISCUSSION OF THE RESULTS

Electrical trees inside solid insulation grow in constrained space inside the bulk of the insulation when the electric field strength exceeds a critical value. The electric field strength in some positions is higher as a result of defects on the surface of the electrodes and in the insulation structure, such as internal cavities, impurities of other materials etc. In the case of needle – plane electrode configuration, if the specimens are made of homogeneous materials, the maximum value of the electrical field is at the tip of the needle (Fig. 8). When the voltage applied to the specimen exceeds a specific value, the electric field at the tip of the needle may exceed the critical value, characteristic for the main insulating material of the specimen, and the deterioration mechanism of the material is activated either by injection of electrical charges inside the insulation at the needle area with formation of space charges, or by partial discharges activities in cavities at the same area. The repeating discharges deteriorate the walls of the cavities through a thermofluctuation mechanism [11,12] and create small channels at their edges. These channels keep becoming deeper and thus the electrical field becomes more inhomogeneous and the electric field strength is locally increasing so the mechanism of the growth of electrical trees or bushes is started. Practically, there is always a transition from bush to tree structure. During the electrical stress, tree branches begin to form from the crowns of the bushes. This fact may occur because of the relatively low conductivity of branches in bush like form [5]. In areas where the value of the electric field is extremely high, great pressure is practiced on the material as a result of the electrical forces applied to the electrical charges that exist in the area or might even be trapped inside the main volume of the insulation. The combination of electrical and mechanical stresses in the main insulating material at the area of the needle favors the growth of the trees. The observed gradual fluctuations of the partial discharge values after the formation of the first tree branches or bush structures show that the trees grow gradually (Fig. 7). The electric field energy from partial discharge activity is then transformed to structural damage at the bulk of the insulation and a redistribution of the field take place. It has been experimentally proven that the partial discharges taking place inside cavities of tree branches in many cases cause carbonization to their walls and create conducting parts in some branches, as shown in the micro photo in Fig. 6. Since several branches have bigger conductivity than the main insulating material, the configuration of the electric

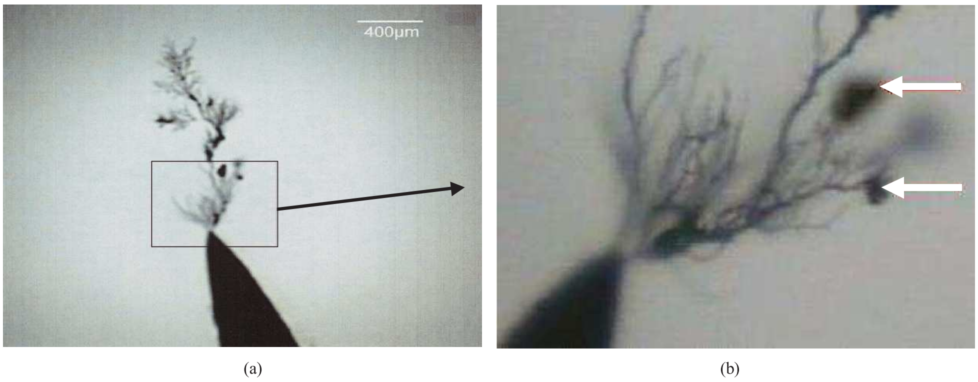


Fig. 6. Electrical trees in a PMMA specimen at the tip of the needle electrode. Figure (b) is actually a zoom of the part of figure (a) that the red rectangular indicates. The barrier was located at position $\xi = 0.2$, the applied voltage was 20 kV and the stressing time 6 hours. The red arrows in figure (b) indicate carbonized areas.

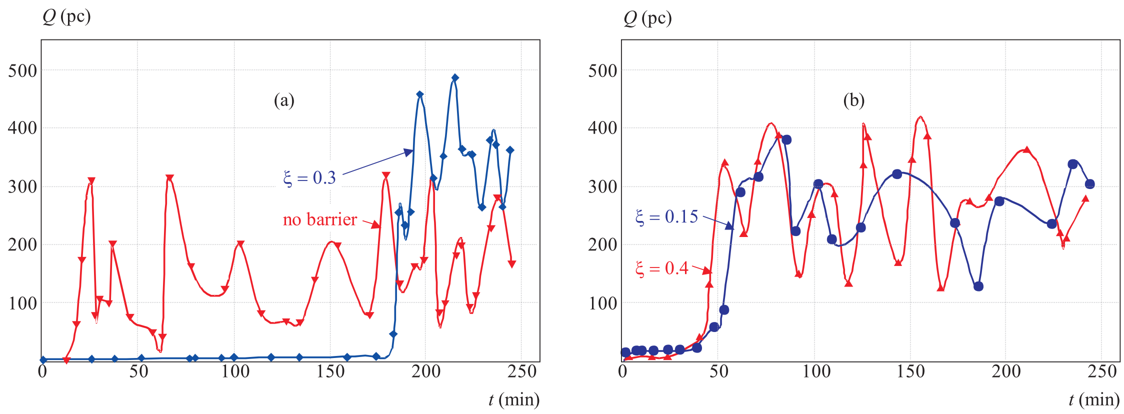


Fig. 7. Diagrams showing the variation of the maximum values of PDs charges in PMMA specimens in relation to the stressing time. Specimens with $\xi = 0.15$ 0.30, 0.40 and with no barrier. The difference in the inception time between specimen with $\xi = 0.30$ and the other specimens is obvious. Partial discharge activity of more than 200 pC starts after 180 min in the specimen with ER barrier at $\xi = 0.30$. The same activity is observed after 50 min in specimens with barrier at $\xi = 0.15$ or 0.40 and after only 20 min in the specimen without barrier.

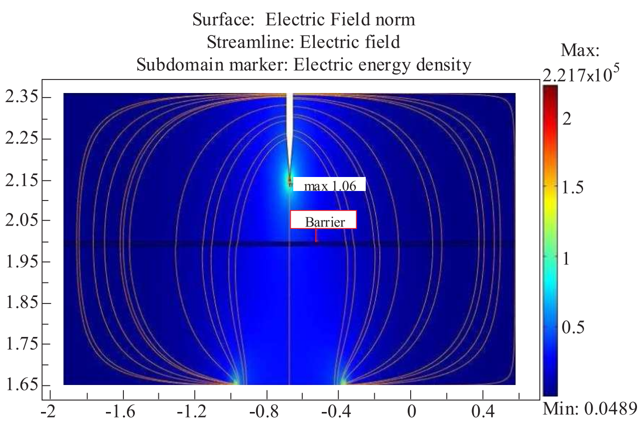


Fig. 8. Electric field analysis in a PMMA specimen with the ER barrier position at $\xi = 0,3$ and for applied voltage 20 kV. The sub domain marker indicates the maximum value of the electric energy density D_{es} that is always in the pin tip. At the pin tip we have also the highest values for the maximum of the local electric field strength F_l [1].

field inside the insulation changes [6]. Then the conducting branches direct the subsequent growth of the tree structure [7]. Initially trees are created in a very small area inside the insulation, but they do not lead to global catastrophic phenomena. For this reason it is very difficult to detect them visually. In the case of needle – plane electrode configuration, the external field causes the growth of the first tree branches and generally the branches follow the field lines. Subsequently, when the branches (which may have obtained conducting walls) grow far from the needle, a redistribution of the electric field takes place in the whole area and the resulting field starts playing a major role and affects the further growth of trees.

When solid insulation contains intermediate barriers whose materials have a greater threshold value than the corresponding value of the main insulation material, the tree growth inside the barriers takes more time than inside the main insulation and the barrier is assumed to act as a block to further tree growth in to the opposite electrode direction. The time taken to form a branch inside strong barriers is much greater than the equivalent time for the main insulation because of the difference of the two probabilities per unit time for branch formation inside the two materials. It has been experimentally concluded that in the case of barriers whose dielectric permittivity is greater than the one of the main insulation material, a thick structure of electrical tree branches parallel to the barrier surface [9] can be formed in the area between the needle and the barrier upper surface. It is also known that both the position and the value of the dielectric permittivity of the barrier affect the dielectric strength of the specimen [1,14]. In the following paragraph focus is given to the way that the barrier position affects the tree inception time and sequentially the dielectric strength of the insulation.

As it is well known, the interface between two dielectric films is determined by a charge density σ that is given [3] by the formula:

$$\sigma = \Big(\varepsilon_{r2} - \varepsilon_{r1}\frac{\kappa_2}{\kappa_1}\Big)F_2 = \Big(-\varepsilon_{r1} + \varepsilon_{r2}\frac{\kappa_1}{\kappa_2}\Big)F_1 \qquad (1)$$

where κ_1 and κ_2 are the conductivities of two materials forming the interface, ε_{r1}, ε_{r2} the relative permittivities of the same materials and F_1, F_2 the average electric field inside them. In our previous work [11], we have estimated the local electric field F_l as a function of the applied electric field F_a and the internal field F_i due to space charge accumulation in the first interface between the two dielectrics:

$$F_l = \alpha\frac{V}{x} - F_i(t) \qquad (2)$$

where V is the applied voltage, x is the polymer thickness (electrode spacing), α a local overstress factor which depends on the local morphology (local asperities, microvoids with special orientation *etc.*) and F_i the internal electric field. After a sufficient time, we can assume that internal field is due to the charge trapped in the upper interface between PMMA and ER in the form of a disk with charge density σ and radius R. From the formula:

$$F_{disk} = \frac{\sigma}{2\varepsilon_{r1}}\Big(1 - \frac{z}{[R^2+z^2]^{1/2}}\Big) \qquad (3)$$

that gives the electric field of the charged disk in the z axis (perpendicular to it's center), we take that the internal field in the needle tip in our arrangement is equal to:

$$F_i = \frac{\sigma}{2\varepsilon_{r1}}\Big(1 - \frac{y}{[R^2+y^2]^{1/2}}\Big)(1-\xi) \qquad (4)$$

where $\xi = y/x$ is the interface position in the specimen (see Fig. 1). The electric field at the needle tip in the absence of space charge, is given by Masons formula [13]:

$$F_{tip} = \frac{2V}{r\ln(1+4x/r)} \qquad (5)$$

where r is the needle tip radius, V is the applied voltage and x is the needle-plane separation. Then, the local electric field at the tip, is derived from Eq. 2 (through Eq. 4 and 5):

$$F_l = F_{tip} - F_i \qquad (6)$$

or:

$$F_l = \frac{2V}{r\ln(1+4x/r)} - \frac{\sigma}{2\varepsilon_{r1}}\Big(1 - \frac{y}{[R^2+(y)^2]^{1/2}}\Big)(1-\xi)\,. \qquad (7)$$

If we consider that $4x/r \gg 1$ and $R^2 \gg y^2$, the former equation gives:

$$F_l = \frac{2V}{r\ln(4x/r)} - \frac{\sigma}{2\varepsilon_{r1}}(1-\xi)\,. \qquad (8)$$

Considering the fact that tree initiation at the needle tip strongly depends of the energy density D_{esl} of the local Electric field and since the former quantity is proportional to the square of the local electric field $D_{es} \propto F_l^2$ we expect a quadratic relation (turns upwards) between D_{es} and ξ. The analysis of the internal electric field in our specimens with various barrier positions shows that the Electric field strength and Electric field energy density have their maximum values always at the needle tip and they are strongly affected by the barrier position. Finite element-2 dimensional simulation was carried out using the FEMLAB 3.1 package and a view of the electric field for $\xi = 0.3$ is shown in Fig. 8. The maximum Electric energy density D_{es} was monitored and its maximum value as function of the barrier position is presented in in Fig. 9. The graph shows the expected behavior. These results also agreed with the experimental results shown in Figs. 7 and 10 for the treeing inception time and with previously published results [1] for the dielectric strength of the specimens. For the barrier position ξ in which the F_m and D_{es} are minimized, the tree inception time and the dielectric strength are maxima.

Substituting Eq. 1, Eq. 8 becomes:

$$F_l = \frac{2V}{r\ln(4x/r)} - \Big(\varepsilon_{r2}\frac{\kappa_1}{\kappa_2} - \varepsilon_{r1}\Big)F_1\frac{(1-\xi)}{2\varepsilon_{r1}}\,. \qquad (9)$$

If we assume that F_1 is proportional to the applied electric field V/x, we see that F_l/F_1 is proportional to ξ:

$$\frac{F_l}{F_1} = \frac{2bx}{r\ln(4x/r)} - \Big(\frac{\varepsilon_{r2}}{\varepsilon_{r1}}\frac{\kappa_1}{\kappa_2} - 1\Big)\frac{(1-\xi)}{2} \qquad (10)$$

where b is a constant. Then the ratio D_{esl}/D_{esav} is proportional to ξ^2:

$$\theta \equiv \frac{D_{esl}}{D_{esav}} \propto \xi^2 \qquad (11)$$

where D_{esl} and D_{esav} are the local electric energy density at the needle tip and the average electric energy density respectively. We also believe that the initial tree length l_i is strongly related with the barrier position ξ and the two quantities can be related through factor θ

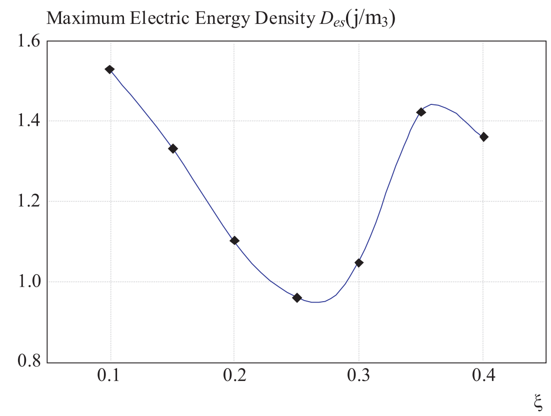


Fig. 9. Diagram showing the variation of the maximum of the Electric energy density D_{es} (at the pin tip) in relation to the barrier position ξ inside PMMA specimens. The data obtained from simulation

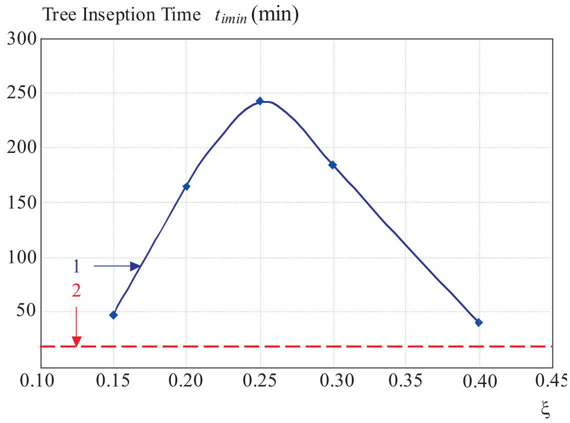


Fig. 10. Diagram showing the variation of the treeing inception time in relation to the barrier position inside PMMA specimens (line 1). Line 2 represents the inception time in specimens without barrier.

(Eq. 11) and Eq. 10, as it was verified by the work of other researchers [14].

5 CONCLUSIONS

The conclusions concerning the barrier effect on the electrical tree growth inside solid insulation are the following: The growth of electrical trees starts from small regions inside the bulk where the value of the electric field strength (and hence the electric energy density) is higher than a critical value because the field is highly inhomogeneous. In the needle-plane electrode arrangement the phenomenon starts at the tip of the needle where the electric field and the relevant energy density are at a maximum.

The partial discharges (PD) before the treeing inception time have usually low values but increase suddenly after the moment of the tree inception time. The partial discharges in the cavities deteriorate the insulating material and cause the electric field to be more inhomogeneous. The PD values fluctuate after the inception, going continuously to greater values, as the trees grow gradually and PD energy is accumulated as structural damage in the bulk of the insulation.

The treeing inception time and the initial tree growth are affected by the barrier position inside the main insulation, because the barrier position affects the electric field configuration inside the specimen and the value of the electric field strength at the tip of the needle electrode. The factor θ plays a very important role in the phenomenon and can be relate the barrier position with the initial tree length.

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