Critical Parameters for Electrical Tree Formation in XLPE

Grace Jiang
Electrical Insulation Research Center
Institute of Materials Science
University of Connecticut
Storrs, CT 06269-3136

Jinbo Kuang
Department of Electrical Engineering
University of Toronto
Toronto, Canada M5S 1A4

Steven Boggs
Electrical Insulation Research Center
University of Connecticut
Storrs, CT 06269-3136
Department of Electrical Engineering
University of Toronto

***Abstract*:** Published data for electrical tree inception field at a defect in XLPE vs. the Laplacian field at the tip of the defect are explained on the basis of a minimum distance which the space charged limited field must extend from the defect tip into the XLPE in order to damage enough dielectric in the field direction to facilitate PD inception and tree initiation.

INTRODUCTION

In two recent publications [1,2], a graph (Figure 1) based on limited measured data was presented for the Laplacian field in XLPE required for tree initiation vs defect tip radius. No indication was provided for the geometry in which the experiments were carried out; however, the tip radii employed suggest the use of Ogura needles in a needle-to-plane geometry. No hypothesis is provided for the data other than the vague statement that they probably result from space charge at the tip of the needle. The purpose of this contribution is to provide a physical and analytic basis for Figure 1, and in doing so provide an indication if the Figure is likely to be accurate for small tip radii.

For any dielectric, the conductivity increases with the electric field at very high fields. With increasing field under AC conditions, a point is reached where $\sigma(E_{lim}) = \varepsilon\,\omega$, where $\sigma(E)$ is the field-dependent conductivity, ε is the absolute dielectric constant, and ω is the angular frequency. When this condition is reached, the resistive current density is equal to the capacitive current density, and space charge is generated to limit the field to approximately E_{lim}. Thus as the applied voltage on a stress enhancement is increased, a point is reached at which the peak field at the defect reaches E_{lim}. As the applied voltage is increased above this value, the field at the tip no longer

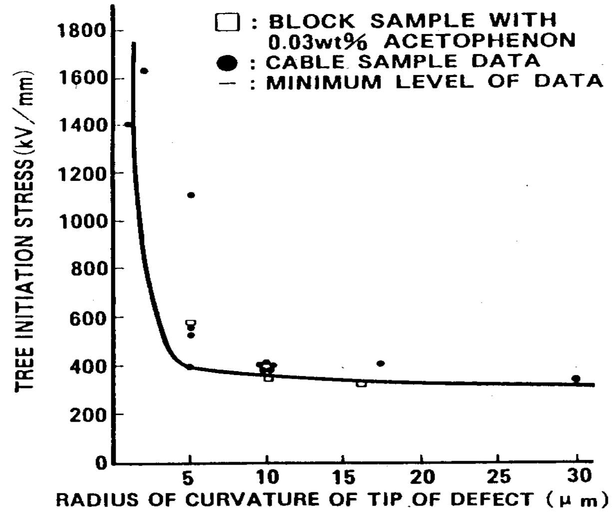

Figure 1. Graph of Laplacian field for electric tree initiation vs defect (needle) tip radius, reproduced from [1,2].

increases but rather a region of approximately constant field (E_{lim}) spreads out from the tip. This can be seen in Figure 2, which shows the field vs position on axis as computed both without the effect of space charge (the Laplacian field) and with the effect of space charge (the Poisson field) for a field-dependent conductivity given by Eq (1) below.

Our hypothesis to explain Figure 1 is that initiation of an electrical tree requires sufficient damage to the XLPE at the defect tip that electro-chemo-mechanical (or in the case of impulse waveforms, electro-thermo-chemo-mechanical) effects create a cavity at the defect tip which can support partial discharge. In previous publications [3-5], we have pointed out that electrical trees inevitably grow more easily than they initiate as a result of the transient nature of the electric field at the tree tip during tree growth. Presumably, the cavity created at the defect tip must have a minimum extent along the direction of the electric field in order to support partial discharge of sufficient energy to facilitate tree growth. We assume that the region of appreciable damage in the XLPE is limited to the space charge limited field region, in which the mobility of charge carriers is relatively high. The combination of UV photons and "hot electrons" generated in this region break

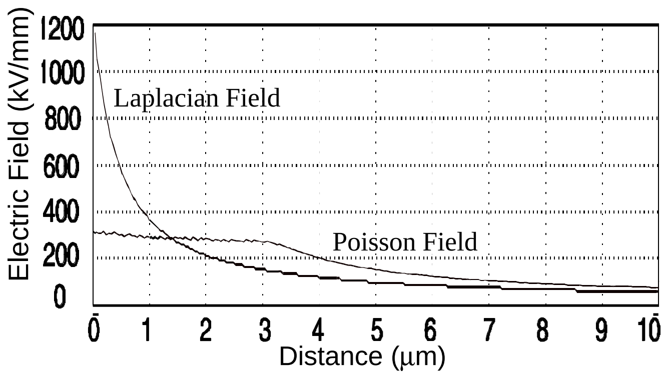

Figure 2. Typical plot of the Laplacian (without the effect of space charge) and Poisson (with space charge) electric field on the axis of symmetry vs distance from a needle tip when the Laplacian field at the needle tip is appreciably above the limiting field value defined by $\sigma(E_{lim}) = \varepsilon\,\omega$. Note the space charge limited field region of the Poisson field, which is the focus of the present investigation. The space charge limited field region extends from the tip of the needle (0 distance) to the point at which the Poisson field starts dropping rapidly, slightly over 3 µm in the above graph. The data in Figure 1 are for the Laplacian field, which is not the true field within the dielectric.

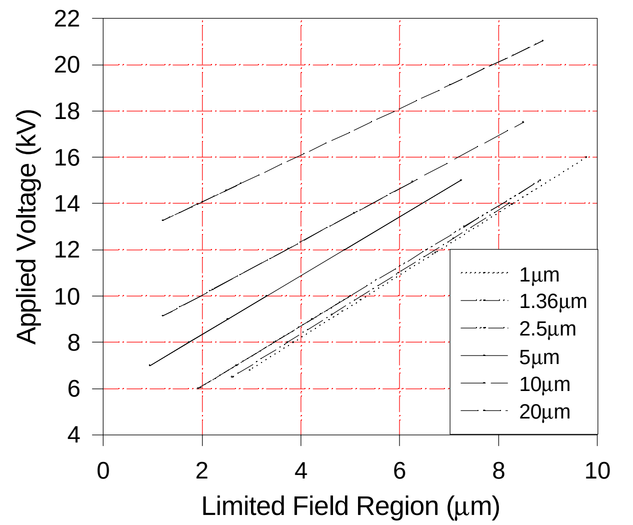

Figure 3. Extent of space charge limited field region vs applied voltage for various tip radii.

chemical bonds which weakens the dielectric [6-7]. The combination of substantial space charge (several thousand coulombs/m^3) and electric field ($E_{lim} \approx 250$ kV/mm) results in an electromechanical force density and mechanical stress which can be a few percent of the yield stress of XLPE at room temperature, rising to 20% of the room temperature yield stress for an impulse waveform. In addition, impulse waveforms can cause substantial heating above the normal dielectric operating temperature [4] which can lower the yield stress of XLPE by a factor of 100.

COMPUTATIONAL APPROACH

As noted in the introduction, our hypothesis is that a minimum space charge limited field region is required in the direction of the electric field in order to initiate an electrical tree. Based on this hypothesis, we can compute data corresponding to Figure 1 for various needle tip radii and various extents of space charge limiting field in the direction of the applied electric field. To do this, we must assume a conductivity vs electric field for the XLPE. Based on both the data of Figure 1 and measurements of the threshold field for high charge mobility for two commercial XLPE compounds [8], we deduce that the power frequency limiting field for cable XLPE is approximately 250 kV/mm and that the conductivity vs field is given by (1).

$$\sigma(E) = \frac{5.497\ x\ 10^{-9}}{|E|}\exp(7.796\ x\ 10^{-8}\ |E|) \qquad (1)$$

Our previous computations [4] indicate that the exact nature of the equation for $\sigma(E)$ has little effect on the power dissipation, electromechanical forces, etc., as long as the limiting field, E_{lim}, defined by $\sigma(E_{lim}) = \varepsilon\ \omega$, remains constant. In particular, we have investigated the case of $\sigma(E)$ proportional to $\exp(k \cdot \sqrt{|E|})$ rather than $\exp(k \cdot |E|)$ and have found only minor differences in the resulting phenomena. The underlying phenomena are so fundamental that details such as the functional dependence of conductivity on the electric field have little effect. Basically, either the conductivity must rise to the point that space charge limits the field, or the field will go to totally unreasonable levels. The only effect of the functional dependence of the conductivity on the field is in the slope of $\sigma(E)$ vs E in the region where $\sigma(E) = \varepsilon\ \omega$, and this has a minor effect on the change in the limiting field with the Laplacian field. Thus we have reasonable confidence in our computations even though we do not have high confidence in our knowledge of the exact functional relationship between the conductivity and the field other than the condition that $\sigma(E) = \varepsilon\ \omega$ for a field, E, of approximately 250 kV/mm.

Under AC conditions, the temperature rise is negligible, so that we can ignore the temperature dependence of the high field conductivity. Given (1), we can employ a program for transient, nonlinear finite element analysis written by one of us (JK) to solve for the field distribution around tips of various radii. The geometry employed is needle-to-plane with a tip to plane separation of 3.25 mm. The geometry is not critical since the data are plotted as a function of the Laplacian field, as in Figure 1. The primary parameter which determines the distance to which the space charge

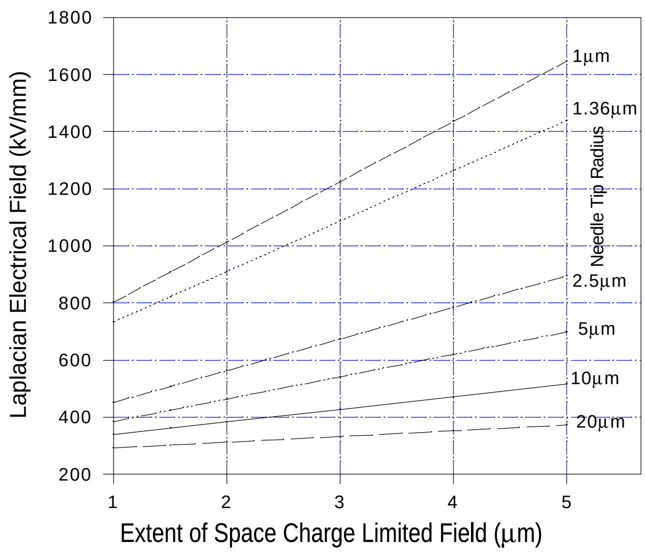

Figure 4. Laplacian field at the needle tip vs extent of space charge limited field region for various needle tip radii.

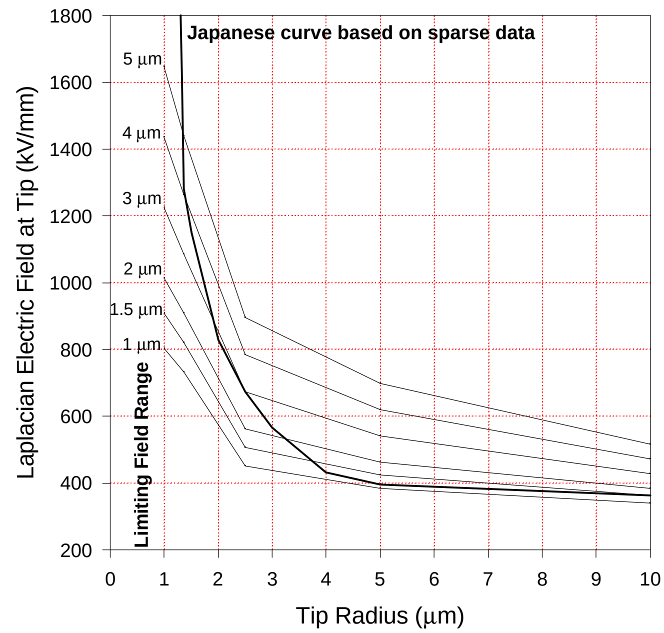

Figure 5. Plot of Laplacian field for tree initiation vs needle tip radius for various assumed space charge limited field extents. The line from Figure 1 is superimposed on the data.

limited field extends is the ratio of Laplacian field to space charge limited field. For a "large" needle tip radius, the Laplacian field near the tip is relatively constant, as very near the tip surface, the tip looks like a plane. The distance from the tip surface to which the field is relatively constant decreases with the tip radius. On the other hand, smaller tip radii result in a large Laplacian field at the tip surface for a given geometry and applied voltage. As a result, the distance to which the space charge limited field extends is a complicated function of the tip radius, Laplacian field at the tip, and, to a much lesser degree, the geometry.

The present analysis consists of the following steps:

1. The geometry is defined, and the voltage-normalized Laplacian field is determined at the tip surface.
2. The space charge limited field region in the direction of the field is determined through use of the transient, nonlinear finite element program with an applied voltage which increases linearly over a period of 5 ms. This is a cumbersome computation, as the finite element solution for the electric field is computed thousands of times as the voltage is increased, so that the high field conduction-induced space charge developed between one pair of solutions affects the field distribution during the next solution. A linearly increasing voltage is employed rather than a sine wave, as for a sine wave, the space charge relaxes and the extent of the field limited region increases as dV/dt drops near the peak of the sine wave. This makes a definitive determination of the extent of the space charge limited region difficult. We therefore employed a linearly increasing voltage with a dV/dt similar to that for a power frequency sine wave (i.e., a voltage risetime of 5 ms). Since the limiting field goes as ln(ω), the effect of the slight change in dV/dt is immaterial. A typical plot of the field vs distance on axis from the needle tip is shown in Figure 2.
3. A linear least squares fit is made to data for the voltage vs radial extent of the space charge limited field for each tip radius. As seen in Figure 3, the slopes for the various tip radii are similar. We have also demonstrated that data for various peak voltages (differing dV/dt) overlap for a given tip radius.
4. The applied voltage of Figure 3 is converted to the Laplacian field at the needle tip by multiplying the applied voltage by the voltage-normalized Laplacian field as determined in step 1. Figure 4 shows the resulting graph.
5. From Figure 4, the Laplacian field and extent of the space charge limited field region can be determined for each needle tip radius. This allows the data to be plotted as the Laplacian field vs tip radius for various space charge limiting field extents, as seen in Figure 5, which also shows the line of Figure 1.

DISCUSSION

In examining Figure 5, we note that a limiting field extent in the range of 1 to 1.5 μm provides the best fit in the range of 5 to 10 μm tip radius. For tip radii below 4 μm, the computed

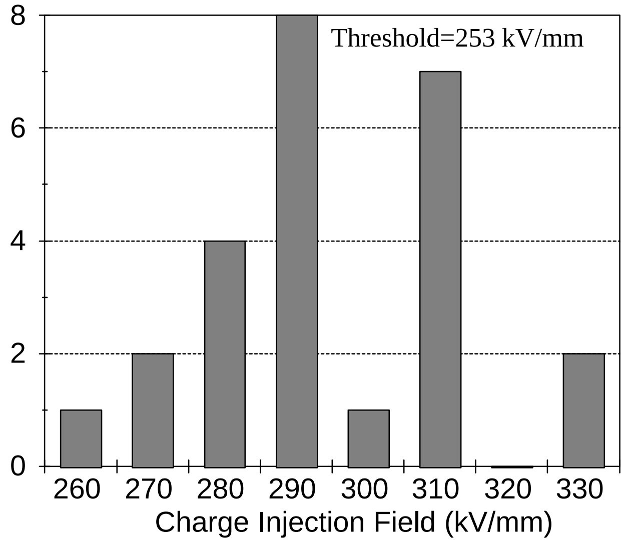

Figure 6. Histogram of the space charge limited field (minimum tree inception field) vs the number of locations at which that field occurs for a commercial XLPE cable compound [6,8]. A statistical analysis of the data indicates a minimum threshold field of approximately 250 kV/mm.

data fall seriously below the data of Figure 1 and the line drawn therefrom. We must therefore consider two aspects of the problem, viz., (i) the meaning of the data points and the line fitted thereto in Figure 1 and (ii) the meaning of the present computations.

The data of Figure 1 represent the Laplacian field at the needle tip at which tree initiation occurred for various needle tip radii. The experimental procedure is not provided, but one must assume that the experiments were carried out by applying successively higher voltages to the needle until tree initiation occurred. Presumably, the needle was left a relatively long time at each voltage level. This experiment suffers from several forms of variability, including

1. The tree initiation field varies with the local morphology of the polyethylene. Figure 6 shows a histogram of the tree initiation field vs position for a commercial XLPE cable compound as measured with a needle tip radius of 3.8 μm. Note that the tree initiation field (space charge limited field) varies greatly with position as a result of inhomogeneity of the polyethylene, i.e., variability of the local environment at the needle tip depending on the location at which the needle is inserted in the XLPE [8].

2. As the needle tip radius is reduced, the volume of XLPE "sampled" by the tip decreases, and we expect the variation in the electrical tree initiation field with position to increase.

3. Obviously, needle-based tree inception experiments can never determine the "minimum possible" tree initiation field. Experiments are doomed to measure a greater tree initiation field, and how much greater is unknown. However, the variability undoubtedly increases with decreasing tip radius, with the result that we place little confidence in the very few measurements at small tip radii shown in Figure 1.

Finally, the Laplacian field at the needle tip is a poor variable with which to correlate electrical tree inception, as the Laplacian field never occurs. In reality, only the space charge limited field occurs, and as seen in Figure 6, this field varies with local morphology throughout the dielectric. We have no idea how the variation in space charge limited field goes with the volume of material over which we average the measurement; however, we expect the variability to increase as the volume decreases.

Thus we have reason to question the data of Figure 1, both in terms of the relevance of the coordinates on which the data are plotted and the degree to which the data approximate the minimum tree initiation field. We can be quite certain that the reliability of the data decreases with decreasing needle tip radius; however, we cannot estimate the degree to which the reliability decreases.

In the present computations, we have based our estimate of the minimum Laplacian field for electrical tree initiation on the assumption of a minimum extent of space charge limited field region in which material damage occurs at a relatively high rate. We have assumed a value of power frequency limiting field based on both experimental measurements of the minimum limiting field for a commercial XLPE cable compound and the data in Figure 1. Based on our computations as presented in Figure 5 and through comparison with the data of Figure 1, especially at 5 and 10 μm tip radius where the data are well clustered, we can suggest that the extent of space charge limiting field region required for electrical tree initiation is in the range of 1 to 2 μm. If this is true and if our hypothesis is correct, then the minimum Laplacian field required to initiate electrical treeing for small needle tip radii is substantially less than predicted by Figure 1, with the Laplacian field increasing by about a factor of 2, from 5 μm tip radius to 1.5 mm tip radius, rather than the factor of 3 suggested by Figure 1. The difference is even more dramatic for smaller tip radii.

CONCLUSION

Our analysis, based on the hypothesis that a minimum extent of material along the direction of the electric field must be damaged through exposure to a space charge limited field within the dielectric in order to initiate an electrical tree, suggests that the tolerable Laplacian field at a defect increases by roughly a factor of two as the defect radius decreases from about 5 μm to about 1.5 μm. At 1 μm tip radius, the minimum Laplacian field for tree initiation would be about 2.25 times the field for tree initiation at a 5 μm radius tip, which is well below the >4 times suggested by the curve in Figure 1. We thus suggest more conservative design rules than those suggested by the authors of [1,2].

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Grace Jiang received her Bachelor degree in electrical insulating materials in 1990 and her Masters degree in high voltage engineering in 1993 from Xi'an Jiaotong University. She is presently pursuing her Ph.D. in materials science at University of Connecticut in the area of dielectrics.

Jinbo Kuang (M) is a Ph.D. candidate in Electrical Engineering at the University of Toronto. He previously completed a Master of Engineering degree at McGill University (1993), and Master of Science (1988) and Bachelor of Science (1986) in Electrical Engineering at Tsinghua University, Beijing. Mr. Kuang's studies have been in the areas of fiber optic communications, high frequency circuit design, on-line monitoring systems for power apparatus, and computer simulation of power electronic circuitry. While employed by Guangzhou Electric Power Supply Co. (1988-1991), Guangzhou, China, Mr. Kuang worked in the areas of reduction of power frequency harmonics in distribution systems, development of on-line monitoring systems for power apparatus, test and maintenance of power transmission and distribution apparatus, and power quality. Mr. Kuang's Ph.D. studies involve applications of transient, nonlinear finite element analysis with coupled fields and time-dependent boundary conditions.

Steven Boggs (F) received his Ph.D. and MBA degrees from the University of Toronto in 1972 and 1987, respectively. He spent 12 years with the Research Division of Ontario Hydro, 6 years as Director of Engineering and Research for Underground Systems, Inc., and is presently Director of the Electrical Insulation Research Center at the University of Connecticut with appointments in materials science, electrical engineering, and physics, and is an Adjunct Professor of Electrical Engineering at the University of Toronto. He has published widely in the areas of partial discharge measurement, SF_6-insulated systems, high frequency phenomena in power apparatus, and solid dielectrics.