Citation: Dissado, L. A., Fothergill, J. and Bromley, K. S. (1998). Discharge-generated electrical fields and electrical tree structures. Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), Annual Report, 2, pp. 649-652. doi: 10.1109/CEIDP.1998.732981

Discharge-generated electrical fields and electrical tree structures

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Introduction

The discharge-avalanche (D-A) model [1-4] for electrical tree propagation in polymers is founded entirely upon basic physical concepts. Electrical discharges in an existing tree structure are taken to raise the electrical field in the polymer both along the discharge path and particularly at the tree tips. As a result of the field increase, electron multiplication avalanches occur within the polymer causing damage, possibly through ionisation of polymer molecules, which is accumulated over a period of thousands (or more) cycles and eventually leads to a tree extension of limited size. The assumption that the damage produced in an avalanche is proportional to the number of ionisations (see [4] for discussion) allows the model to be expressed quantitatively in terms of material properties; such as the ionisation potential, I, the impact-ionisation length parameter λ, the critical number of ionisations for tree extension N_c; discharge features such as the number of 1-electron initiated avalanches per half cycle, N_b; and the potential difference ΔV between the start and end of the avalanche over a distance L_b. This gives the fraction of the damage required for tree-extension, $f_{½}$, produced during a half-cycle for which ΔV is constant in the form

$$f_{½} = \left(\frac{N_b}{N_c}\right)\left[\exp\left\{\frac{L_b}{\lambda}\exp\left(-\frac{IL_b}{e\lambda\Delta V}\right)\right\}-1\right] \qquad (1)$$

A comparison with experimental data gives an average value for the minimum tree extension of 10μm and this is assumed to be the range L_b over which avalanche damage occurs. Taking a typical value of $I = 9eV$ for polymers allows estimates of λ and N_b / N_c to be made from treeing data [3]. The assumption that ΔV is *on average* the same value whenever avalanches occur has been justified through experimental evidence that the average time for a 10μm tree extension is constant throughout the fractal stage of tree propagation [4, 5].

Because of the limitation of tree extension to 10μm steps, the numerical expression of the model is made using a 10μm grid. The inception stage of tree formation is removed from the calculation by considering tree propagation to start from a single 10μm tubule at a point electrode [4] or a central void [1, 2]. The damage calculated per half-cycle is related deterministically to the local values of the material properties and ΔV. Accumulation over many half-cycles until $\sum f_{½} = 1$ allows both the tree-structures and length-time dependence to be calculated (Fig. 1).

Since its first presentation in 1992 [1] the model has seen several developments. In the earliest form of the D-A model the discharge in the tree structure was taken to act like a metallic conductor and the local value of ΔV was related to the calculated Laplace value by a ‘field-intensification’ factor γ which was treated as a limited-range random variable in both time and space. In this way it was shown [2, 4] that time-dependent fluctuations in ΔV were necessary to produce the observed fractal structures. Time-independent spatial variations in γ and N_b / N_c produced non-fractal structures following structurally weak or high-field paths with lightly branched structures. By imposing arbitrary limits on the dependence of the fluctuation range of ΔV upon the Laplace field estimated from the tree structure, the tree shape could be varied from branch to bush shape [4].

After these calculations the D-A model was developed into a form in which none of its parameters were treated as random variables. Instead the polymer was assumed to be homogenous on the 10μm scale, and the fluctuations in ΔV calculated from the deposition and rearrangement of space-charge by the tree discharges which were treated as having deposited positive ions on the tree-tubule walls and injected electrons into the polymer. Preliminary calculations showed that bush-trees resulted unless charge neutralisation occurred in the body of the tree over a few half-cycles [4]. It is our intention to develop the model to the point where discharges, occurring by charge separation along the tubules of the electrical tree, raise the fields (i.e. $\Delta V / L_b$) around the tubules causing avalanches to occur which cause damage and affect both the potential difference along the avalanche path and along the tree tubules themselves. The latter factors will influence the magnitude and possibility of subsequent discharges and avalanches. In this way we expect the treeing mechanism itself to generate the ΔV fluctuations that we have shown theoretically are necessary for fractal tree structures and the chaotic discharge behaviour that we have associated experimentally with different tree structures [4].

Incorporation of Space-Charge

a) Treatment of discharges

The gas discharges within the electrical tree structure are treated as being a set of discharges each effectively restricted to a single 10μm long cylindrical tube of $1\,\mu\text{m}$ radius. Each discharge deposits negative charge on the wall or in the polymer at the end of the unit-tubule. The charge in the polymer, is represented by spheres of 2/3μm diameter which may be arranged in such a way as to represent different space-charge arrangements and penetration depths. Each discharge deposits an equal amount of positive charge on the tubule walls represented by an annulus of a chosen width. It may be expected that the positive charge is deposited at specific positions along the tubules, we have, however, shown that the field due to such an arrangement can be represented by a single annulus [6]. Treating the tubule discharges as occurring tubule by tubule is in accord with the discharge magnitudes measured during the early stage of propagation [7] which increase in proportion to the number of tubules. It allows for the possibility of independent discharges when tubules separated spatially discharge at the same or subsequent phases of the ac-cycle. Discharge sequences may, however, be initiated if the space-charge field due to one discharge is sufficient to initiate a discharge in a neighbouring tubule and so on to the tree tip [6]. Where discharges occur in a tubule which does not end on the tree tip the negative charge is regarded as forming a negatively charged annulus at the junction with the subsequent tubule.

The space-charge fields have been determined as values of potential difference ΔV along the grid-lines adjacent to the end of a discharging tubule, including any existing tree-tubules. The calculation is made per unit quantity of space-charge in each specific contributing element, and stored in a programme library to be used according to the amount of space-charge accumulated in that element. Further away from the charges around a specific grid-point the fields are calculated under the assumption that they act like a point charge whose magnitude is the net amount of charge at the grid-point.

b) Penetration of negative charge

The negative head of a discharge contains electrons which may have up to $13eV$ in kinetic energy. Since the mean scattering length for phonon collisions in polyethylene is ~ 3.5 nm at room temperature [8] it can be expected that the maximum penetration distance will be $\leq$ μm. Electron-electron repulsions and the thermal energy of the discharge will spread the charge head across a substantial fraction of the tube width. If subsequent discharges can occur on the same half-cycle, the positive wall charge and the existing negative charge in the polymer at the tip will tend to displace the discharge to one side producing an asymmetric arrangement which can be allowed for by the arrangement of negative spheres used for its description.

c) Avalanche rearrangement

During electron-avalanches negative and positive charges are produced in equal amounts with the negative charges located at the end of the avalanche multiplication, i.e. here at the grid-point 10μm away from the initiating point on the tubule-discharge path. This charge is represented as before by an arrangement of negative spheres. The positive charges produced during the avalanche will be taken to be located in a positive sphere at an intermediate distance along the avalanche path dependent upon the average distance between ionisations, i.e. $\lambda \exp\left[IL_b/\left(e\lambda\Delta V\right)\right] \approx 1.7\,\mu\text{m}$ for ΔV = 450 volts. The net effect of an avalanche is thus to place negative charge at grid-points adjacent to the avalanche initiating grid point on the tree and to partly reduce the negative charge closer to the tree.

d) Image charges

The images of the space charge in both the needle and plane electrodes are included in the calculation by treating each grid-point as possessing a net point-charge. Images of images in both electrodes are included as we have previously shown these to be essential for an accurate estimation of the field [9].

e) Reversal of applied voltage

The reversal of discharge-rearrangements and avalanches depends upon reversal of the *local* field rather than the applied field. When a reverse local field of sufficient magnitude does occur, however, avalanches will transfer negative charge to the tree and tubule-discharges will move negative charge in the reverse direction with those discharges that terminate at the needle removing negative charge from the tubular tree-structure. There is thus an in-built asymmetry between positive and negative half-cycles.

Space-Charge Effects on Discharges and Avalanches

We have shown [9] that the displacement of positive charge on the tubule walls has a major effect on the ability of a discharge to propagate in a sequence from the needle to tree-tip and *vice-versa*. More detailed calculations [6] have shown that the displacement of positive wall charge during a discharge in a tubule enhances the potential difference in the subsequent tubule thereby favouring the continuance of the discharge in a sequence (Fig. 2). Simultaneously the potential difference in the prior (proximal) tubule is reduced thus inhibiting a subsequent discharge until the applied potential is substantially increased. Displacement of the wall charge also reduces the fields around intermediate tubules whilst increasing them at the terminating tip of the discharge. Thus a large displacement of wall-charge corresponds to long discharge paths and favours tip extension, i.e. branch-tree formation. It also seems that an existing branch structure reinforces this tendency [9]. A small wall charge displacement is more likely to allow independent local discharges particularly close to a zero level of applied voltage, and hence favours bush formation and wall erosion. A secondary effect will be a tendency to local neutrality after the zero-voltage crossing so that charge accumulation is unlikely to build-up to the extent that charge rather than damage accumulation dominates the average time for tip extension.

Wall charge can have a considerable effect on subsequent discharges. Positive charges may initially be pinched into the tubule centre but eventually pushed to the walls as a neighbour tubule is approached. Negative charge will be inhibited from further progress down the tube and will tend to be sprayed onto the tube walls. When the wall charge spreads out along a tubule the ratio of the axial field to transverse field at a tree-tip reduces [6]. This would tend to favour bush-type trees over branch trees. In addition spreading of the wall-charge over a substantial portion of the tubule length will tend to inhibit the full development of tube-discharges which will rapidly terminate on the walls.

After a discharge the value of ΔV will rise by some 20-100V at a tree-tip. This is sufficient to raise the ΔV in the polymer from a value of 350V for which an avalanche is negligibly small [10] to 450V which gives an appreciable amount of ionisation. At first an avalanche along the axial direction will be preferred especially close to the needle electrode. However, charge rearrangement by the avalanche itself tends both to favour local independent tubule-discharges at the tree-tip and inhibit further avalanches in the same direction [10]. Calculations have also shown [10] that the depth of penetration of negative charge at a tree-tip can have a major effect on the strength of the avalanche along the axial direction through changes in ΔV in equation (1).

Formulation Of Calculation

The ac cycle will be divided into a number of equal phase-segments. In each phase-segment the potential difference across each tubule will be calculated starting from the tubule at the needle. A discharge will be initiated where the potential difference exceeds the Paschen value, with the amount of charge involved estimated from the amount by which the Paschen value is exceeded. The discharge will be tested to see whether it is independent or initiates a sequence. After the discharge charge-depositions have been determined the fields (ΔV) are calculated. Avalanche damage is then calculated and accumulated. Charge rearrangements are evaluated. Since the value of N_b / N_c has been determined as a per-cycle value it is divided in proportion to the ratio of actual charge in the discharge with respect to the average value per cycle. The local fields are not allowed to exceed the critical field for mobility (see [5] for details) and charge may be further rearranged to prevent this. The calculation steps through the phase-segments to produce tree-structures, length-time relationships, and discharge behaviour in terms of number and magnitude of discharges as the tree grows. Factors such as the wall-charge displacement, the Paschen voltage for tubule discharge, rearrangement of negative tip-charge before and after avalanching as well as the material parameters are at the disposal of the programmer. It is interesting to note that the experimentally fitted value of λ = 60 nm [3] may provide a reason for the restriction of the avalanche to a range of 10μm over and above the limited duration of the discharge (~ few ns see [4]). If the mechanical damage associated with the formation of a tubular extension increases λ around the extension from an undamaged value of 5 nm to 60 nm, then there will be a limited range of material over which damage generating avalanches can take place. The extreme sensitivity of equation (1) means that any avalanche extending beyond the 10μm range into the undamaged region produces a negligible amount of damage.

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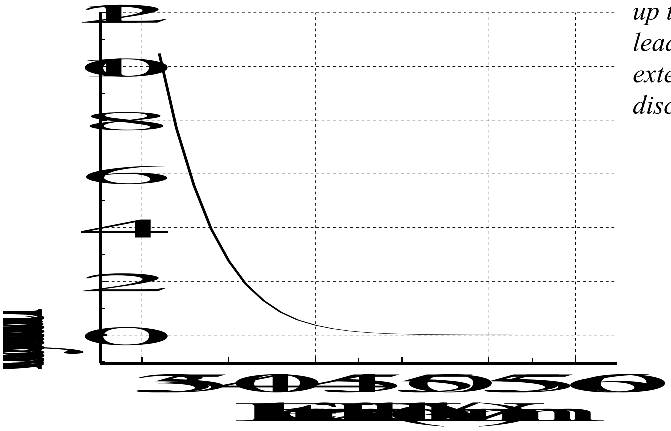
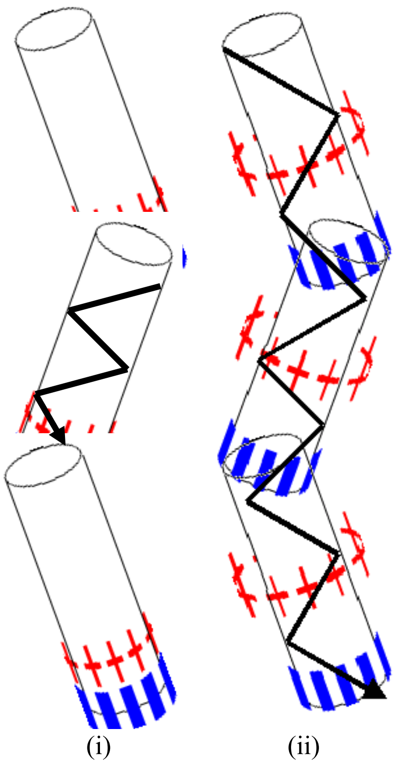


Figure 1. The time taken for a tubule to form is critically dependent on electric field.



(i) (ii)

Figure 2.

(i)Positive charge slower to move back up tubule leading to more independent discharges.

(ii) Positive charges faster to move back up tubule leading to extended discharges.