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Simulation of electrical treeing in solid dielectrics

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The mechanism of failure of insulations (such as CT 200 and CT1200 epoxy resins) used on high-voltage equipment and cables is recognized to be electrical treeing, in which breakdown channels grow from a region subjected to a high electric field and reach the other electrode. The regions around the tips of sharp conducting intrusions are the regions of high electrical field. Such intrusions are present due to manufacturing defects and can become more severe with aging. Insulation failue occurs when the tree channels join the electrodes and a large destructive current can flow. The insulation systems in service are designed to withstand fields which are well above the theoretical onset values for the various breakdown mechanisms. However, defects or voids can be introduced during manufacturing. The defects can be sharp asperities or "pins," which lead to high local electric fields. The voids are filled with air, which has a breakdown strength much lower than the insulation dielectric. The electric trees can be either "branched" (having a fractal dimension in the range of 1.2 to 1.8) or "bush" type (having a fractal dimension in the range of 2). In similar conditions, the branched trees grow faster than bush-type trees and hence can more easily cause catastrophic failure of the insulation. The bush-type trees can even stop growing if an internal field is present. Thus, it is important to understand the reason for defect induced breakdown in solids, and the formation of electrical trees and their fractal dimension.

The models for the study of electrical tree growth are either stochastic [1, 2] or deterministic [3, 4] in nature. In stochastic models the fractal characteristics of the electrical tree are decided by the probability distribution of sites, which depends on the local electric field. In the case of deterministic models, avalanche damage at the tips of the electrical trees are considered to lead to tree extensions.

The earliest stochastic model of Niemeyer, Pietronero, and Wiesmann [5] simulates electrical treeing on a square lattice. The discharge starts at an electrode and one lattice bond is added per growth step. The whole tree structure remains at the electrode potential. The potential distribution in the lattice is computed from the Laplace equation. The probability that a new bond will form from a point on the discharge structure and an adjacent point is decided by the local electric field. After a point is added to the discharge structure, the Laplace equation is solved again for potential computation on the lattice. This model does not incorporate features of a breakdown field, or the presence of an internal field. Wiesman and Zeller [6] introduced a critical field for growth. The growth probability was assumed to be proportional to a local electric field, if it was greater than a fixed value of critical field, and it was considered to be zero otherwise. An internal field within the structure was also introduced. The potential in the structure was not fixed, but decreased by a fixed amount for each addition of a bond. Such simulations produced tree structures, which changed in morphology with these parameters.

In this paper we investigate the effect of different base diameters of pins on the fractal nature and morphology of the electrical discharge patterns. Though the dimension of the tip of the pin influences the value of the electrical field in the immediate vicinity of the pin, the potential distribution on the lattice points, computed by the Laplace equation is not effected. The change in diameter of the needle electrode influences the potential distribution in the lattice and hence the morphology of discharge patterns.

The 75 × 100 lattice in our simulation work represents the region between the electrodes. The separation between the electrodes is typically 1–2 mm. The dimension of the pin tip is a few microns, which also represents the region covered by each lattice point. The potential distribution in the lattice is computed from the Laplace equation, with the boundary conditions of "0" and "1" on the electrodes. Initially the region within the needle forms one of the electrodes and is at the same potential. As the discharge progresses, if the internal field is set to zero, each lattice point on the discharge is also set to the potential of the needle electrode. If the internal field is set to a small value, at each addition of a discharge point, the potential at that point is reduced by the value of the internal field, from the preceding discharge point. The probability of extensions to the next lattice point on the perimeter segment j is defined as

$$\varphi = (E_j - E_0)\Big/\sum(E_j - E_0), \qquad (1)$$

where E_j is the field in the perimeter segment j, $\sum$ is the sum over all the perimeter segments of the discharge path in the structure, and E_0 is the critical field for discharge propagation.

The simulation of the discharge tree is completed when all the fields in the perimeter segment become less than the critical field. In the case of an internal field being present, the tree growth can stop even before the two electrodes are connected. In the Niemeyer, Pietroner, Wiesmann model, the considerations of critical field and internal field are not present and the tree growth is completed after connecting the two electrodes.

The damage caused by the discharge is considered to be related to carrier impact, thermal effects, and instantaneous high local fields at the tips of the trees. The damage during tree growth can be considered to be due to the discharge process and also due to the high electric field. The former would be more important in a large tree and would tend to promote a bush-like tree. The damage due to high electric fields would be more important in the initial period of tree growth and at the tips of the trees. The formation of an actual tree shape is determined by the competition between these two kinds of damage.

The breakdown patterns observed in Figs 1 to 4 showthe fractal behavior of the discharge initiated from the tip of pins with different base dimensions. The depth to which the pin intrudes inside the lattice is the same in all the cases. The electrodes are assigned a potential of "0" and "1". The internal field in these simulation runs was taken as "0".

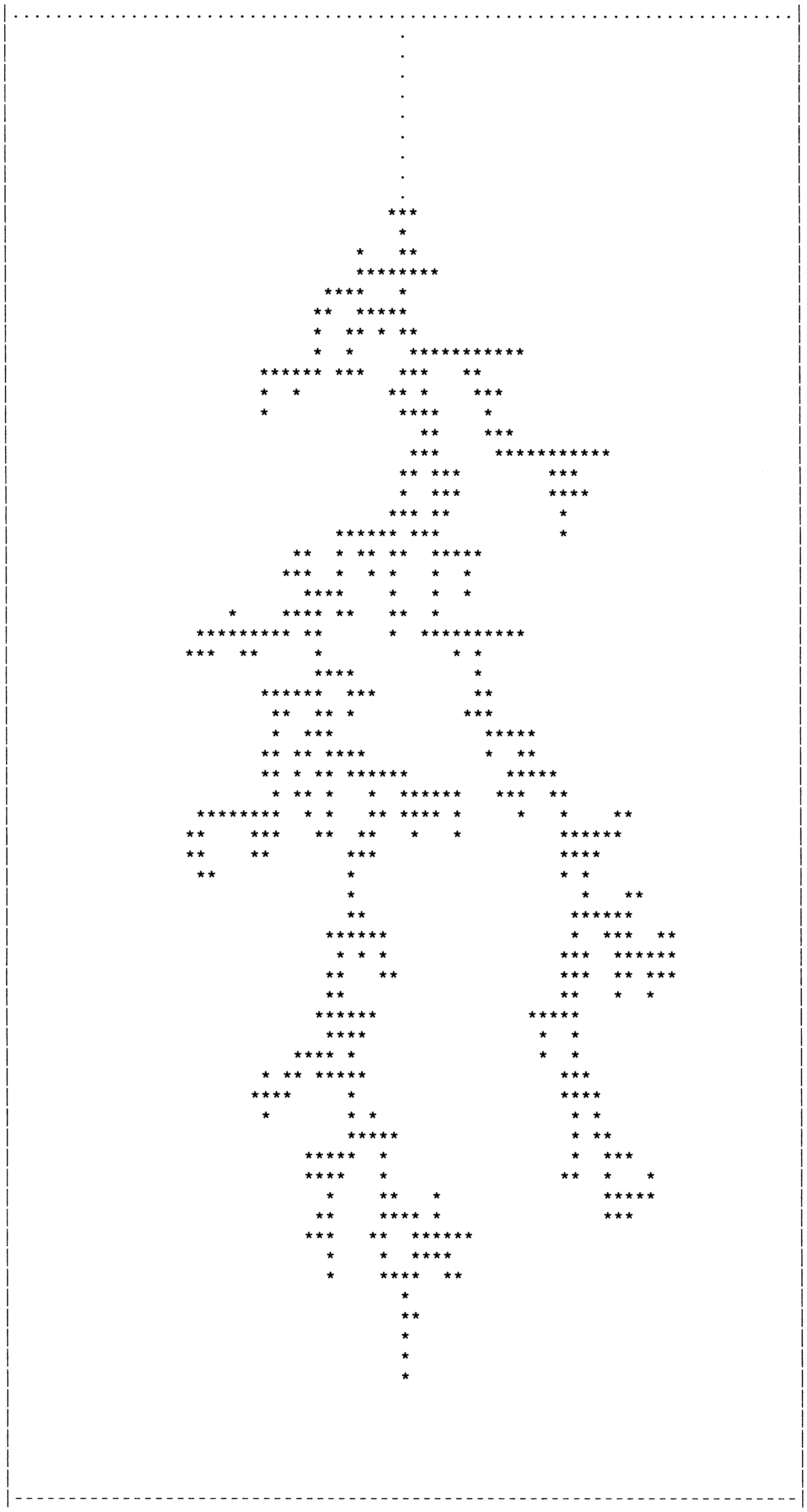

Figure 1 Discharge pattern for tip 1 (base width 1), with critical field value 0.01.

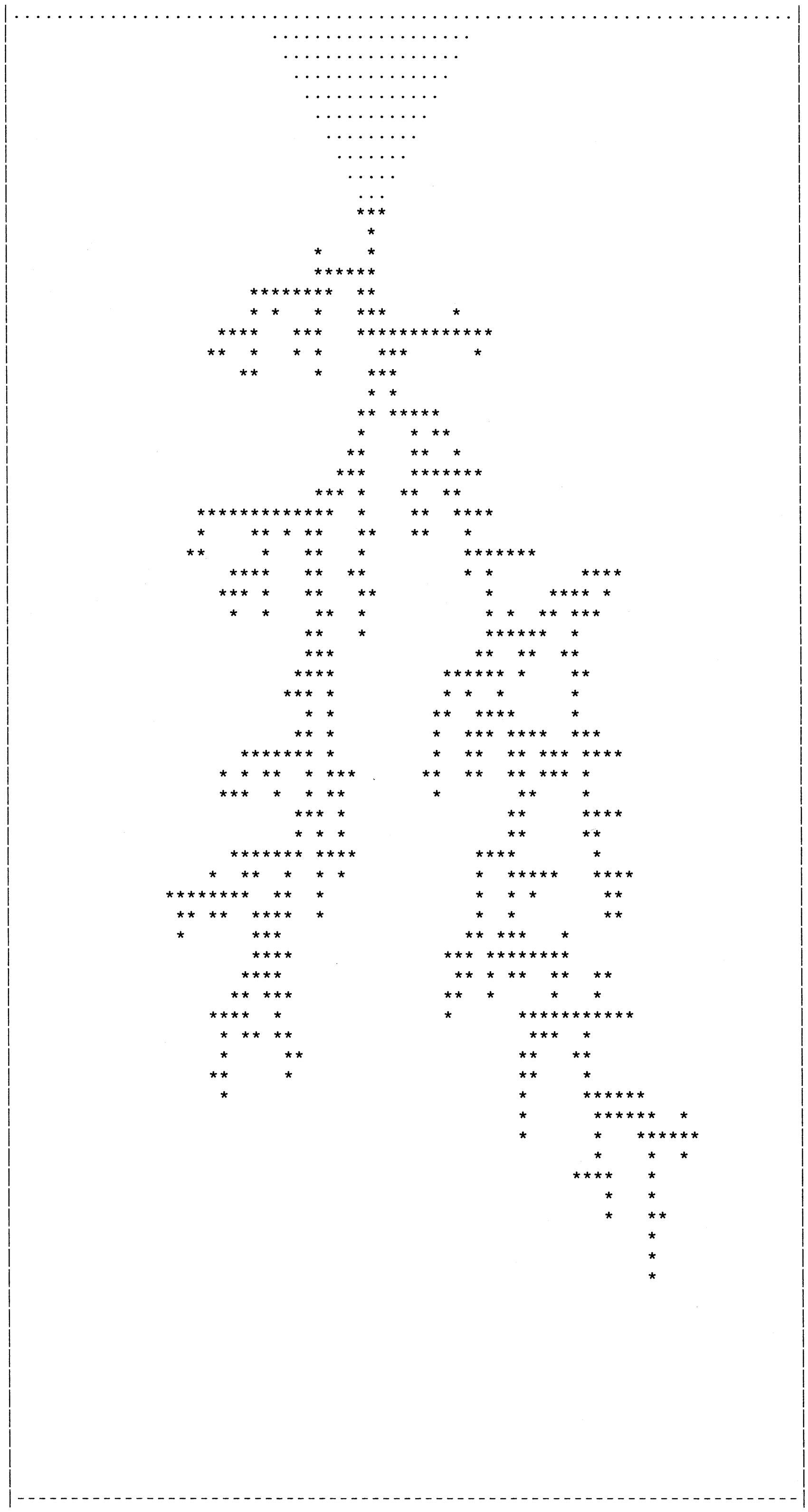

Figure 2 Discharge pattern for tip 2 (base width 21), with a critical field value of 0.01.

In the discharge breakdown studies of materials [7], the inter-electrode gap is typically 1–2 mm. Experimental studies of electrical tree growth show that branch extension occurs in increments of 5–10 μm. In our simulation model, a 75 × 100 lattice represents this experimental situation.

The assessment of the discharge breakdown patterns as "rarified" or "dense" is too subjective. So fractal techniques were used to examine the scaling behavior of mass with length. The slope of the mass versus distance on a double log plot gives a fractal dimension, which can be used to compare these patterns. The extreme cases of fractal dimension are the dimension of a straight line, which is "1", and the dimension of a completely filled plane, which is "2". Tree patterns show fractional values of dimension between these two extremes.

The fractal dimension of the tree structures shown in Figs 1 to 4 are calculated from the slope of the double

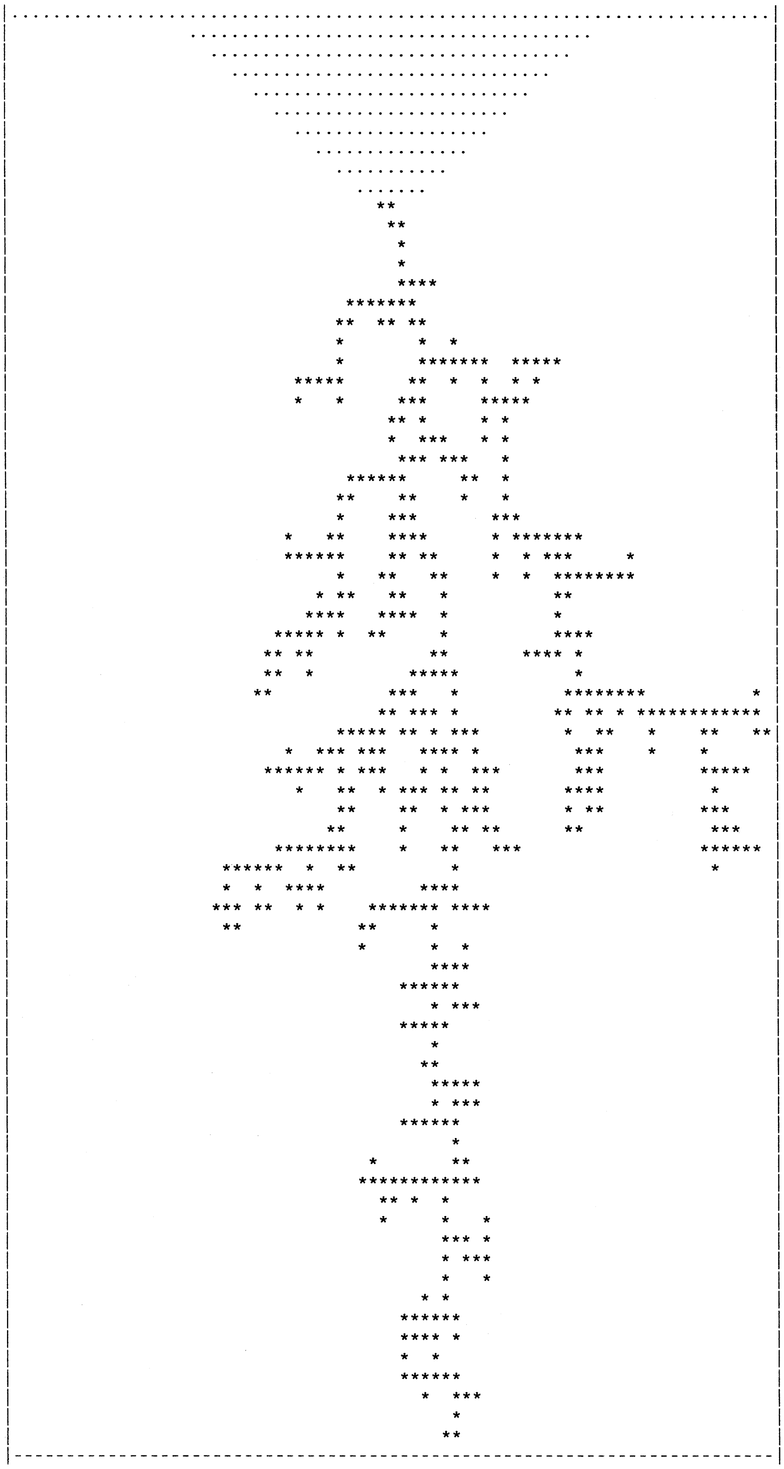

Figure 3 Discharge pattern for tip 3 (base width 41), with critical field value of 0.01.

log plots of the number of lattice sites in discharge versus distance. A linear fit of the data points in the central region is used to estimate the fractal dimension. The results of the calculation are given in table below.

These results show that changes in the base diameter of the pin influence the fractal dimension, which is an indication of the nature of the tree. At the smallest pin diameter, the fractal dimension is small, indicating

Critical field = 0				Critical field = 0.005				Critical field = 0.015			
Pin type	Base diameter	Fractal dimension	Number in initial 10 lattice sites	Pin type	Base diameter	Fractal dimension	Number in initial 10 lattice sites	Pin type	Base diameter	Fractal dimension	Number in initial 10 lattice sites
tip 1	1	1.11	96	tip 1	1	1.36	75	tip 1	1	1.21	68
tip 2	21	1.11	74	tip 2	21	1.36	76	tip 2	21	1.40	66
tip 3	41	1.39	71	tip 3	41	1.49	54	tip 3	41	1.62	50
tip 4	60	1.40	69	tip 4	60	1.65	38	tip 4	60	1.65	40

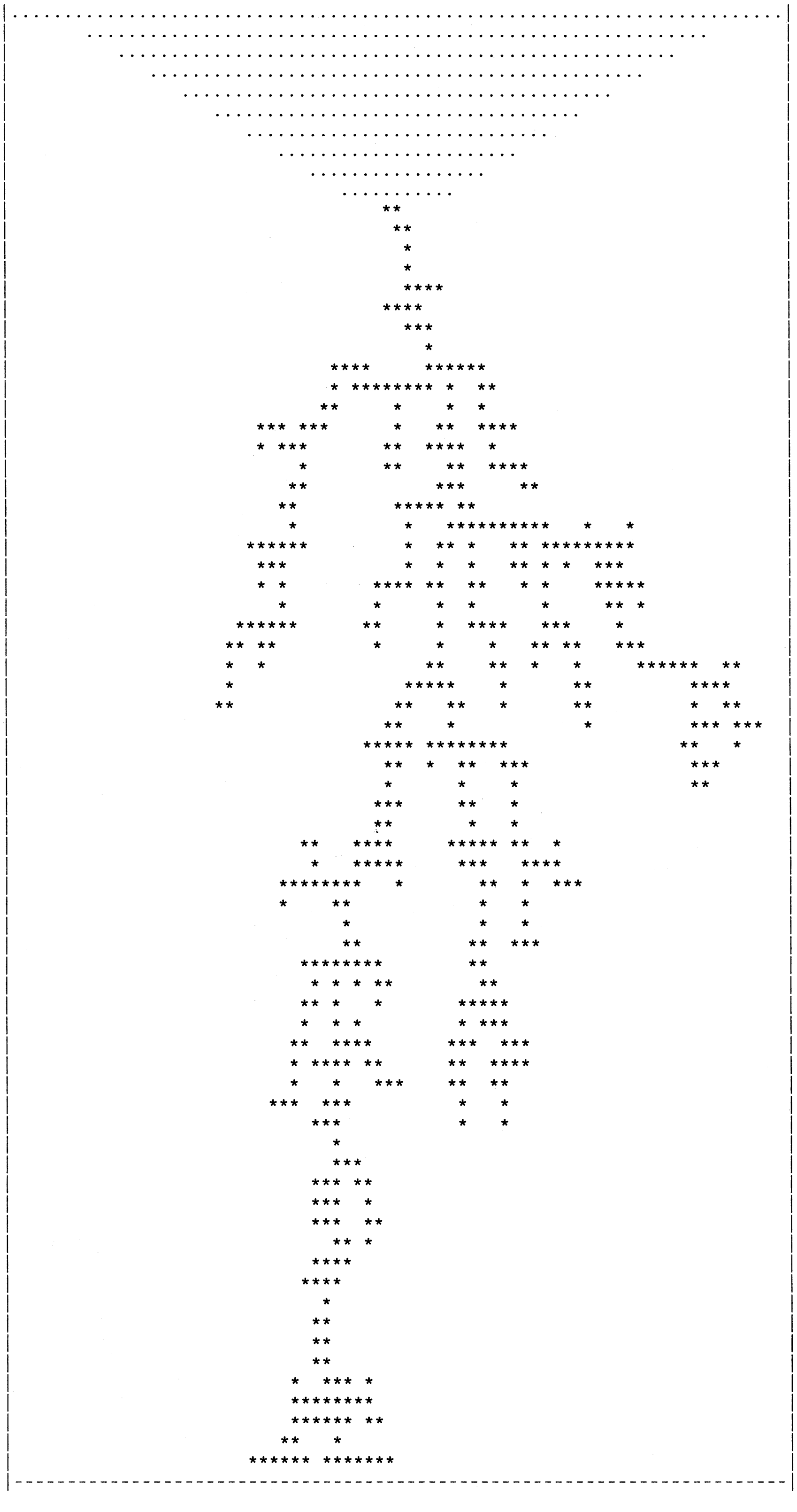

Figure 4 Discharge pattern for tip 4 (base width 60), with a critical field value of 0.01.

a highly branched nature of the tree. As the base diameter is increased, the fractal dimension increases, indicating a more bush-type tree structure. The effect of the increase in the critical field is to increase the fractal dimension of the trees. The different values of the critical field are an indication of the increasing relative permittivity of the material.

The changes in the base diameter of the pin influence another aspect of the trees. An indication of this is obtained by the number of discharge lattice sites within a depth of 10 lattice points, beyond the tip of the pin, inside the lattice structure. As the base diameter of the pin is increased, the potentials on the initial region surrounding the tip of the pin would be effected the most, and these would change probability distribution around each discharge point. As the base diameter of the pin is increased, the number of discharge sites around the tip region decreases. The increase in the critical field also leads to a decrease in the number of discharge sites around the tip region.

The electrical tree morphology has been investigated for different values of the base diameters of the pins. The effect of changes in the critical field has also been studied. The fractal dimension of the trees increases with increase in the base diameter. This suggests an increasing tendency toward formation of bush-like trees rather than highly branched trees. The increase of the critical field tends to increase the fractal dimension. This effect is more pronounced for larger base diameters. The number of discharge sites in the region around the tip decreases for larger base diameter of the pins.

These results suggest that large base diameter sharp conducting intrusions in solid dielectrics would be less damaging than vertical pin-type intrusions. The materials with higher relative permittivity show formation of electric trees having larger fractal dimension.

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