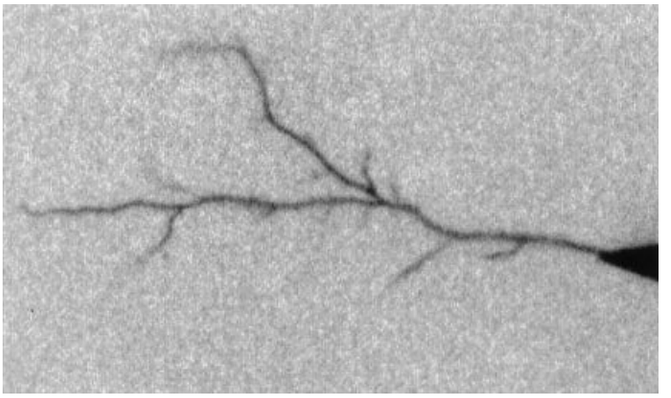

Figure 1. Electrical tree at the tip of a metallic needle embedded in polymeric insulation.

ELECTRICAL TREES, PHYSICAL MECHANISMS AND EXPERIMENTAL TECHNIQUES

Dielectrics used in high-voltage devices such as capacitors, transformers, and underground high-voltage cables are susceptible to degradation due to the electric field. In solid dielectrics subjected to an electric field in a dry environment the degradation takes the form of a tree-like growth and is called electrical treeing. An electrical tree consists of a filamentary pattern of permanent hollow channels. Another type of treeing degradation, called water treeing, occurs in solid dielectrics operating in wet environment where moisture is present. Water trees are opaque and disappear when dried out. In contrast, some water trees are visible even after drying because they are stained by certain minerals and are sometimes referred to as electrochemical trees. However, there is no difference in the treeing mechanism of water and electrochemical trees, and the term *water tree* has been adopted to all trees that grow in a dielectric operating in wet environment. Many physical and chemical aging processes that occur in a dielectric in the absence of an electric field can be accelerated when the field is applied. Surface tracking and erosion can also occur, but treeing is concerned only with bulk degradation and is now acknowledged to be the major cause of potentially avoidable electrical failure. However, the electric stress required to cause treeing can be orders of magnitude below the breakdown strength of the dielectric.

Electrical trees are initiated at regions of high electric stress, such as metallic inclusions and impurities, and are easily visible under an optical microscope in transparent and translucent dielectrics. At the surfaces of voids in the dielectrics, electrical trees are formed by partial discharges within the voids. Figure 1 shows that an electrical tree consists of interconnected channels, a few micrometers in diameter and tens of micrometers in length, which look like the branches of a natural tree. Electrical treeing has been known to occur in almost all solid organic dielectrics, such as polyolefinic polymers, rubber, epoxy resins, and oil-impregnated paper insulation systems. Once an electrical tree inception occurs, dielectric failure is inevitable within a short time, usually less than a year at service voltage. The growth of the tree can be retarded, but not entirely stopped until the electric field is removed. The tree propagates through the dielectric and ultimately leads to an electrical breakdown, but it is also possible for a breakdown to be initiated before an electrical tree completely crosses the dielectric. Thus, electrical treeing essentially contributes to the cumulative damage of the dielectric under electric stress by increasing the probability of dielectric failure.

Descriptive names have been applied to the different types of electrical tree patterns that occur in dielectrics. Electrical trees that start at the surface of the insulation can grow through the dielectric, and their shapes can be dendritic, branched, or bushy. Figure 1 shows that dendrites or streamers are long and narrow. Branch-type electrical trees (see Fig. 1 of ELECTRICAL TREES IN SOLIDS) usually have a trunk that is tens of microns in diameter and multiple branches with diameters ranging from a few microns to around 1 μm at the tip. Figure 2 shows a bush-type tree that is short with densely packed hollow channels having diameters in the micron range. A bushy tree can also have one or more branched projections (see Fig. 2 of ELECTRICAL TREES IN SOLIDS). The crossover from a bush to a branch occurs if the electric field is decreased, while a branched tree converts to a bush if the field is increased. Electrical trees that start from contaminants or cavities which are remote from the surfaces of the dielectric and grow in both directions parallel to the electric field are called bow-tie trees. Figure 3 shows a bow-tie tree that has grown from a microvoid in polymeric insulation.

Electrical treeing occurs at cryogenic, room, and high temperatures under alternating current (ac), direct current (dc), and impulse voltage as well as during polarity reversal. A high electric stress—for example, 100 kV/mm for polyethylene insulation—is required for electrical tree inception, and the type of tree that develops depends on the magnitude and frequency of the electric stress and ambient conditions. Trees which have access to free air are capable of growing until they bridge the dielectric across the conductors and cause failure. Bow-tie trees do not have a free supply of air, and their growth is usually limited. Electrical trees in mechanically

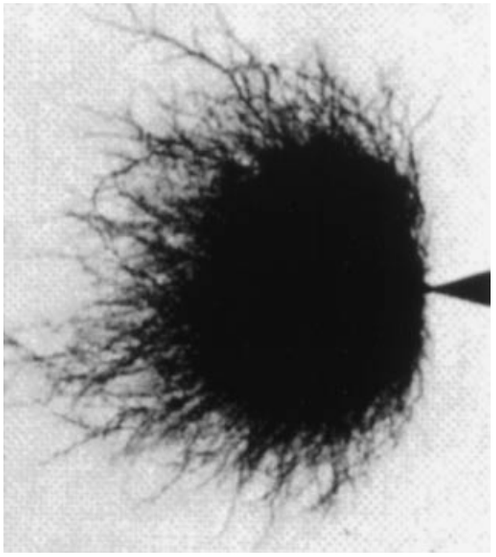

Figure 2. Bush-type electrical tree at the tip of a metallic needle in low-density polyethylene.

strained dielectrics have few branches, and the branches grow perpendicular to the direction of mechanical strain. Trees that grow in dielectrics held at high temperature also tend to have fewer branches and propagate more rapidly than those that grow at room temperature.

HISTORY

As early as 1935, photographs of electrical tree growth in paper-oil cable insulation and solid dielectrics were published. An exhaustive bibliography on the history of treeing is cited in Ref. 1. Although studies on electrical treeing and methods of resisting it were carried out in the 1960s, serious consideration was only given when electrical treeing was observed in newly developed polymeric insulation of underground power cables. In the past two decades, considerable evidence has been accumulated to relate the breakdown in cable insulation to the treeing phenomena. In distribution class power cables removed from service, water trees were prevalent at the overlap of the semiconducting tape wound on the insulation, and electrical trees were found at imperfections in the cable. The recently developed triple extrusion process (2) in which the semiconducting layers, known as semicons, are simultaneously extruded on the inner conductor and outer insulation has substantially reduced the occurrence of electrical treeing. However, even with the present-day technology, defects could be accidently introduced in the polymeric insulation during material processing and cable manufacture. Figure 4 shows the cross-sectional view of a high-voltage cable. The manufacturing defects could be (a) protrusions, either at the conductor or the insulation shield, (b) inclusions such as metal particles and fiber, or (c) voids that are formed due to shrinkage or gas formation, such as during cross-linking. All of these defects would act as points of electric stress enhancement where treeing could occur.

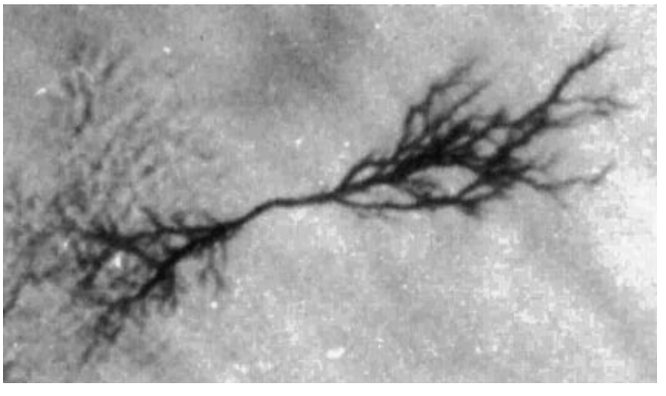

Figure 3. Bow-tie electrical tree with filaments, in the direction of the electric field, at a defect in polymeric insulation.

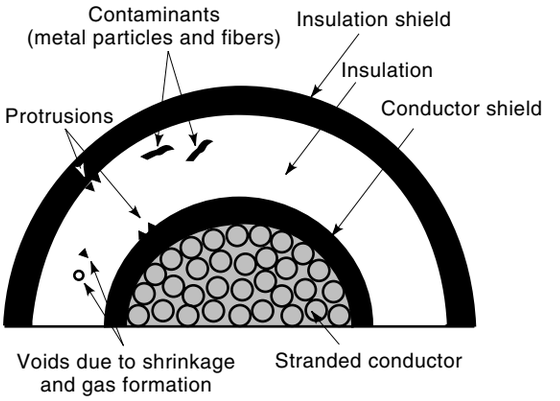

Figure 4. Possible defects in the polymeric insulation shown in a cross-sectional view of a high-voltage cable.

STAGES OF ELECTRICAL TREEING

Figure 5 shows that prior to a breakdown, electrical treeing has two distinct time periods:

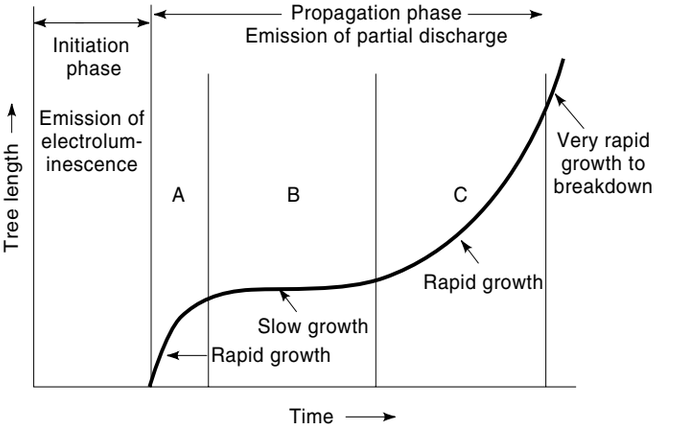

Figure 5. During the initiation phase, electroluminescence is emitted but partial discharges do not occur until the propagation phase of electrical treeing.

1. the incubation period or the initiation phase until the first partial discharge occurs,
2. the propagation period or the growth phase during which partial discharges cause tree growth.

In recent years, some insight has been gained into the growth and propagation mechanisms of electrical treeing but the initiation phase has not been well understood. The time to electrical tree inception is defined as the time until the first channel is formed, and it strongly depends on the electric field and the type of contact between the electrode and the dielectric. For poor contact—that is, when voids exist at the interface of the electrode and the dielectric—the time to tree inception is drastically reduced because partial discharges set in very rapidly.

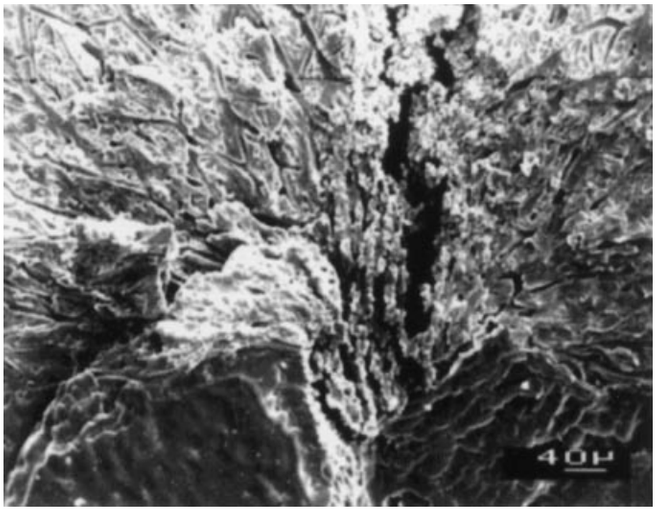

Figure 6. The channels of an electrical tree are revealed by the scanning electron micrograph.

PARTIAL DISCHARGES

Tree initiation could easily occur in voids in the dielectric or at the interfaces of inclusions having poor contact with the dielectric. Field enhancement occurs at the voids because they are filled with gases which have a lower permittivity than the rest of the dielectric. The enhanced electric field will ionize the gas and cause the void to discharge or breakdown. Since these localized discharges or avalanches do not cause the breakdown of the whole dielectric, they are called partial discharges. The electric field for the inception of partial discharges depends on the void size and ranges from ~3 kV/mm for voids larger than 1 mm to more than 1 MV/mm for submicron-size voids. Partial discharges as low as 10 fC have been measured under laboratory conditions with sensitive electrical techniques. Due to the ionization of the gas, partial discharges always give rise to light emission having spectra in the ultraviolet (UV) and visible ranges. The light of partial discharges can be pulsating, and its maximum intensity occurs at wavelengths below the visible range. In polyethylene, the light of partial discharges has its maximum intensity at 369 nm and is caused by the formation of CO_2 gas due to the decomposition of the polymer. Once partial discharges start in the void, they cause electrical tree inception.

DIFFERENCES BETWEEN ELECTRICAL AND WATER TREES

Although treeing occurs in dielectrics operating in dry and wet environments, there are several differences between electrical and water trees:

1. Electrical tree inception occurs in dielectrics at points of electric stress enhancement where the electric field is higher than the rest of the dielectric. Water trees start in dielectrics operating in a wet environment at much lower fields than that required for electrical treeing.
2. During the growth of electrical trees partial discharges occur, decompose the material, and give rise to permanent hollow channels. The scanning electron micrograph of Fig. 6 reveals the channels in an electrical tree. On the other hand, partial discharges do not occur during the growth of water trees, which consists of water-filled microcavities having radii of 1 μm to 10 μm. The scanning electron micrograph of Fig. 7 shows the voids in a water tree. There is practically no evidence of interconnected channels within water trees.
3. Prior to electrical tree inception, light is emitted in a small volume (r ~5 μm) around the point of electric stress enhancement in the dielectric. This light is not due to partial discharges but is instead due to the phenomenon of electroluminescence. No light is emitted prior to water tree inception or during tree growth. For water treeing under ac voltage, ionic species and moisture from the surrounding area penetrate the dielectric due to electrophoretic and dielectrophoretic forces of the electric field.

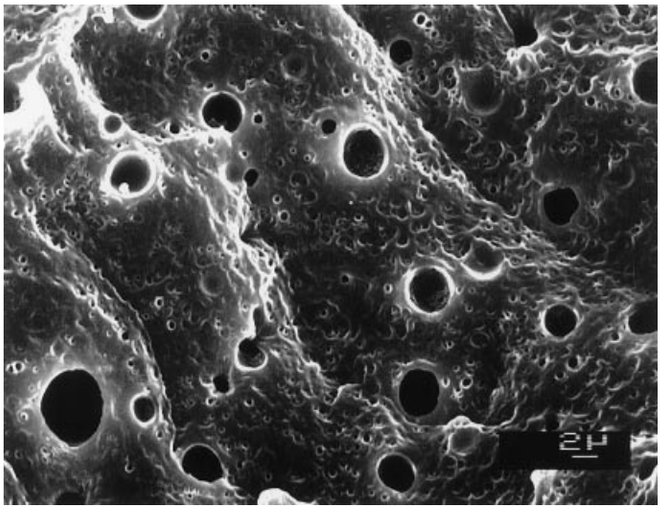

Figure 7. Water-filled microcavities in a water tree are shown in the scanning electron micrograph.

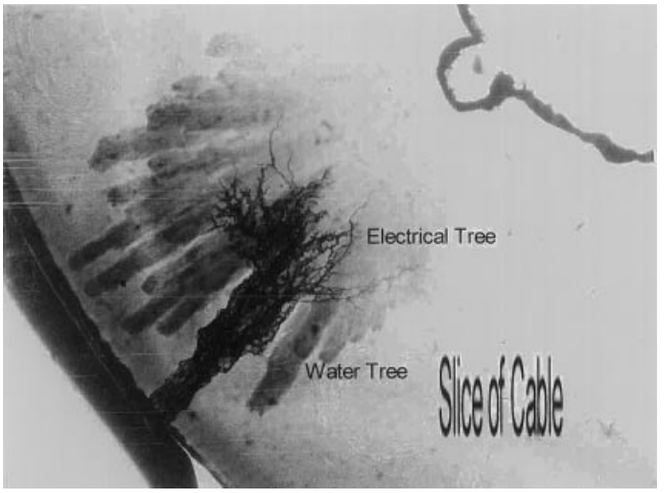

Figure 8. Conversion of a water tree to an electrical tree prior to breakdown.

4. The branches of an electrical tree grow until they bridge the dielectric across the electrodes, cause the short circuit, and give rise to electrical breakdown. For water treeing, breakdown does not occur even when the water tree completely bridges the dielectric across the electrodes. However, an electrical tree can start from the tip of a water tree, grow through the material, and cause the breakdown.

Prior to a breakdown, water trees always initiate an electrical tree, either in the bulk or from the electrodes. Electrical tree growth from a water tree—that is, the conversion of a water tree to an electrical tree prior to an electrical breakdown—is shown in Fig. 8. Thus, for dielectrics operating in dry as well as wet environments it is the electrical tree that is responsible for the breakdown.

INITIATION MECHANISMS OF ELECTRICAL TREEING

Earlier Work

Several mechanisms have been proposed to explain the degradation that occurs in dielectrics operating in high-voltage devices at electric fields much lower than their breakdown strength. Initial experiments on electrical treeing with sharp needles inserted into polymeric insulation reported low values of the tree inception voltage because inserting hot or cold needles into the polymer, held at or above room temperature, usually created voids at the needle tip. It was assumed that for electrical treeing, charge injection into the dielectric was not required, and tree inception was attributed to impact ionization, Maxwell stress, or Joule heating.

Tree Initiation Due to Impact Ionization. According to this mechanism, the free electrons in a void can gain sufficient energy from the applied electric field to cause material ionization upon impact on the walls of the void. The threshold energy required for pair creation (assuming equal effective masses for electrons and holes) by impact ionization across the band gap is given by

$$E_k = \tfrac{3}{2}E_g$$

where E_k is the kinetic energy and E_g is the band gap. Usually $E_k > 10$ eV, and this energy is sufficient to ionize most polymeric dielectrics. If $E_k < 10$ eV, the energetic electrons can form cation radicals that can capture thermal electrons. This leads to the formation of free radicals which may cause chain scission. The type of degradation associated with these processes depends on the dielectric material. For example, polyethylene will form microvoids by cross-linking. These microvoids could coalesce to give rise to larger voids in which partial discharges can start and cause electrical tree inception.

Tree Initiation Due to Mechanical Fatigue Caused by Maxwell Stress. The mechanical stress which can produce cracks in a dielectric parallel to the direction of the electric field is given by

$$S = \tfrac{1}{2}\epsilon_0\epsilon_r E^2$$

where S is the mechanical stress in the dielectric, ϵ_0 is the permittivity of free space, ϵ_r is the relative permittivity of the dielectric, and E is the applied electric field. Calculation with the above expression shows that even for electric fields as high as 1 MV/mm the Maxwell stress is much lower than the yield stress of most polymeric dielectrics at room temperature. The local force density in the dielectric could be enhanced in the presence of space charge, but the effect is still too weak (3).

Tree Initiation Due to Joule Heating and Thermal Decomposition. The temperature rise, ΔT, in a dielectric subjected to high voltage is

$$\Delta T = \pi V^2 f \epsilon_0 \epsilon_r \rho \tan\delta$$

where V is the applied voltage, f is the frequency of the applied voltage, ϵ_0 is the permittivity of free space, ϵ_r is the relative permittivity of the dielectric, ρ is the thermal resistivity, and tan δ is the dissipation factor. Even for very lossy dielectric materials having large tan δ, reasonable values of the applied voltage do not produce sufficient changes in the temperature to erode the material. However, if cavities exist in the material, then partial discharges can occur at relatively low voltage and even a small amount of the discharge energy could produce sufficient heat to raise the local temperature to several hundred degrees centigrade and erode the dielectric.

Recent Developments

Experimental studies on tree initiation in polymeric insulation have shown that for good contact between the electrode and the dielectric—that is, when voids do not exist at the electrode–dielectric interface—charge injection from the electrode into the polymer is required for tree inception. In this case, light having spectral range from near UV to near infrared, with the highest intensity usually in the visible range, is continuously emitted prior to tree inception (4). Since this light is caused by electrons injected into the dielectric, this phenomenon of light emission is called electroluminescence. The spectra of electroluminescence can be employed to distin-

guish the initiation phase from the propagation phase of electrical treeing. In a dielectric, charge carriers have low conductivity and mobility and a space charge forms near the injecting electrode. In homogeneous dielectrics, space charge injection is known to occur at fields almost 20% to 30% of the breakdown level and about one order of magnitude lower in inhomogeneous dielectrics.

Tree Initiation Due to Hot Electrons. The hot electron mechanism for tree initiation assumes that charges injected from the electrode into the dielectric can gain kinetic energies between 3.5 eV to 4.5 eV from the electric field. These energies correspond to bond dissociation energies of molecules encountered in many polymeric dielectrics. In model dielectrics, such as linear hydrocarbon n-$C_{37}H_{74}$, it was shown that electrons injected into the polymer at 700 kV/mm can achieve kinetic energy greater than 4 eV. Recent progress has shown that the energy loss rate for electrons having energies greater than 1.5 eV is controlled by acoustic phonons, and that the occurrence of hot electrons is strictly limited to fields larger than about 60% of the breakdown strength of the dielectric. As soon as an electrode injects charge into the polymeric insulation, space charge forms around the injecting electrode and reduces the local field. The field limited space charge (FLSC) model proposes (5) that the injected charge can only move into the dielectric once a critical field, E_c, is exceeded. The mobility of the carriers then increases drastically to those encountered in band transport in polymers. This is because the electrons can acquire sufficient kinetic energy from the electric field to remain above the mobility edge of the σ-electron conduction band. However, in practice, the σ-conduction band does not exist in a well-defined manner for the amorphous regions of semicrystalline polymers, such as polyethylene, and may not be oriented in the field direction in the crystalline regions. Thus, E_c could well be in excess of the breakdown strength of the polymer. Hot electrons in a dielectric can excite molecules upon impact, and these excited species could return to the lower energy levels by emitting light and cause electroluminescence. The hot electrons can also break polymer bonds; and after several bonds are broken to form a cavity, partial discharges can set in and cause tree inception. However, at present, it is not quite clear as to how much energy the injected charge can gain in the high-field region.

Tree Initiation Due to UV Emission Caused by Charge Recombination. Charge recombination can occur under polarity reversal caused by ac voltage when the charge of each polarity is injected into the polymeric insulation. During each half-cycle, the charges injected into shallow traps of the polymer form a space charge within milliseconds and modify the field at the injecting electrode. The penetration of the charge to the recombination centers in the polymer occurs under this space charge, which reaches a maximum in advance of the applied field. Electroluminescence is attributed (6) to the recombination of the injected charge with the deep trapped charge retained from the previous half-cycle. In semicrystalline polymers the recombination centers are located at the crystalline–amorphous boundaries. The intensity of electroluminescence increases with the applied voltage, and more light is emitted in the visible and near-infrared ranges than in the near-UV range. It is suggested that in commercial polymeric insulation containing chromophores, the light in the near-UV range can cause photo-degradation of the polymer and lead to electrical tree inception. Electroluminescence due to charge recombination can also occur under half rectified ac and impulse voltage, but at significantly higher fields.

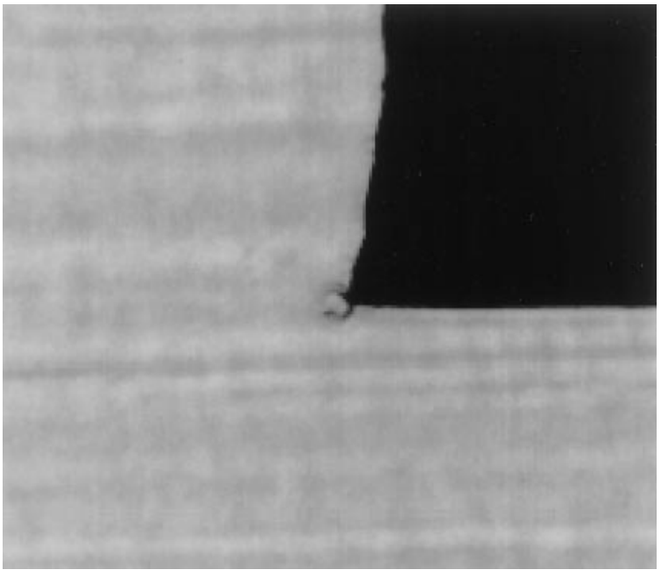

Figure 9. Degenerate region at the tip of a semicon tip in cross-linked polyethylene.

DEGENERATE REGION

The tree initiation mechanisms described above, acting singly or in combination, lead to tree inception and, depending on the operating conditions, a particular mechanism could be more dominant than the others. Irrespective of the initiation mechanism, the end result is the degradation of the material which leads to the formation of a degenerate region. In polymeric insulation, bonds are dissociated during the initiation phase, and a degenerate region with a small volume ($\sim 10^{-9}$ cm^3) appears. Figure 9 shows a degenerate region at an electric stress enhancement in polyethylene. The degenerate region was first observed in low-density polyethylene at liquid nitrogen temperature (7).

Analysis of the degenerate region in polyethylene has shown that it contains more CO and C=C groups and is more easily stained by methylene blue than the nondegraded polymer. Due to bond scission, free radicals are produced and these react with the oxygen present in the free volume to form CO groups; hence the degenerate region contains low-molecular-weight species. Microdischarges of <0.1 pC can occur in the degenerate region and form a void in which partial discharges can set in and cause tree propagation (8).

THRESHOLD VOLTAGE OF TREE INCEPTION

It was suggested that irreversible aging of polymeric insulation can start at local fields of 5 kV/mm to 20 kV/mm, lead to cavity formation, and, eventually, cause electrical treeing (9). However, long-term aging tests on 400 kV low-density polyethylene cable at 27 kV/mm for 9 months did not produce any

deterioration. Similar aging tests carried out on 500 kV cross-linked polyethylene cables did not show any reduction of the ac breakdown strength after 6 months of aging. Also, when low-density and cross-linked polyethylene specimens were subjected to accelerated aging at uniform fields up to 130 kV/mm, most low-density specimens survived 4.2 years at 80 kV/mm to 90 kV/mm, while all cross-linked polyethylene specimens survived 4.4 years at fields of 70 kV/mm to 80 kV/mm. Details on the above examples are furnished in references cited in Ref. 10. By aging high-voltage cable-grade polyethylene, it was shown that for uniform and divergent fields, cross-linked polyethylene specimens held below the electroluminescence inception voltage did not develop electrical trees, while those held above that level always developed trees, and the time to treeing depended on the applied voltage. Thus, it was concluded that the electroluminescence inception voltage is the threshold voltage at which the polymer starts to degrade (10). However, the true onset of tree inception is actually the presence of current pulses rather than the light pulses (8). Current pulses with a very small amplitude, usually between 40 fC to 0.3 pC, occur in polyethylene subjected to ac voltage (11). Such pulses are observed only on the positive half-cycle and are associated with the extraction of electrons from the polymer (see ELECTRICAL TREES IN SOLIDS).

TREE PROPAGATION

Electrical tree propagation is caused by partial discharges within the tree channels. Electrical degradation, thermal instability, mechanical failure, and chemical deterioration have been proposed as possible mechanisms for the extension of tree channels. Several propagation mechanisms have been described in detail in Ref. 12.

Tree Propagation Due to Electrical Degradation

According to this mechanism, the discharges enhance the electric field at the tip, causing localized breakdown which decomposes the material and thereby extends the channel. It has been argued that the gaseous decomposition products of the local breakdown could increase the pressure inside the channel and reduce the discharge activity. Thus, as shown in Fig. 5, electrical trees usually do not grow continuously but instead grow intermittently with bursts of propagation (section A), decaying to a standstill (section B), followed by further propagation activity (section C). The partial discharges also produce charged species which get trapped on the channel walls and inhibit any further discharges.

Another investigation on tree propagation (13) has revealed that neither partial discharge extinction nor tree growth propagation depends on the internal pressure inside the channel, but on the increase in the conductivity of the channel walls. The change in the conductivity causes the electrical field to concentrate at the tip, and a new propagation period follows. After the first branch has grown, tree propagation restarts as two new branches are added to the tip. The inactive period (section B of Fig. 5) has been assigned to tip splitting and is assumed to be caused by the extinction of partial discharges; however, for ac stress, partial discharges will still continue on the positive half-cycle. Once a number of branches have been formed, partial discharge activity could shift from one channel to another so that some branches are inactive while others, where the trapped charge has leaked away, will keep on growing. For bow-tie trees the lack of vent to release gaseous decomposition products to the external environment will cause cessation of tree propagation.

Recent work (14) has attributed electrical tree propagation to the deterministic breakdown mechanism operating in a chaotic regime at fields lower than that required for runaway breakdown. The shapes of the trees are related to the fluctuations of the chaotic field, and the trees grow in accordance with the prediction of the discharge avalanche model.

Tree Propagation Due to Thermal Instability

This mechanism (12) suggests that the local temperature in the vicinity of partial discharge activity increases and leads to thermal decomposition of the material. The conduction current can also increase, cause thermal instability, and lead to the formation of tree-like patterns.

Tree Propagation Due to Mechanical Fatigue

This mechanism (12) proposes that tree propagation results from electrofracture and depends on the amount of strain energy available and its spatial distribution. The mechanical stress due to intense electric field at the tip could exceed the yield stress of the material.

Tree Propagation Due to Chemical Deterioration

According to this mechanism (12), the high energy charge, reactive species, and UV radiation caused by partial discharges could chemically erode the channel tips and cause tree propagation.

Vented trees usually propagate through the weak parts of the dielectric; for example, in semicrystalline materials the propagation follows the amorphous crystalline boundaries. The final stages of tree growth exhibits an accelerating propagation of a tree branch to the opposite electrode. Unlike dielectric liquids, breakdown in solids does not occur instantaneously but could take up to an hour under normal operating voltage.

ELECTRICAL TREEING TESTS

Laboratory tests have been developed to evaluate the resistance of dielectrics, particularly polymeric insulation, to electrical treeing. Needles having known radii of curvature are embedded into the polymer to simulate stress concentration. Several samples have to be tested under various conditions and the data are statistically analyzed to obtain meaningful results. The American Society for Testing and Materials (ASTM) describes a standard test (D 3756-79) which can be used for comparing various insulating materials.

A more sensitive method is to determine the electroluminescence inception voltage and monitor the light emitted until tree inception. Higher values of the electroluminescence inception voltage does not necessarily imply that the material will have a higher tree inception voltage. Hence, it is imperative to determine tree inception time at a given voltage because the longer the time to tree inception the higher the resistance of the dielectric to electrical treeing (see ELECTRICAL TREES IN SOLIDS).

FACTORS AFFECTING ELECTRICAL TREEING

Effect of Voltage

One of the factors that affect electrical treeing is the voltage applied to the dielectric. Treeing occurs at lower values of ac and impulse voltage than dc voltage. Treeing also depends on the shape and frequency of ac and impulse voltage applied to the dielectric.

Treeing under dc Voltage

Tree Initiation Phase. For inhomogeneous dc fields, tree inception usually occurs at values much greater than the breakdown strength of the material. This is due to the homospace charge which moderates the stress enhancement at the point of injection (see ELECTRICAL TREES IN SOLIDS). If the dc field increases rapidly such that the space charge does not have sufficient time to form completely, as in the case of ramp rates $\geqslant 10^9$ kV/mm per second, then the tree inception field reduces but it still exceeds the breakdown field of the dielectric. This indicates that a threshold field is required for tree inception under dc voltage. However, electroluminescence does not occur when dielectrics are subjected to dc voltage, and this suggests that injection of charge of both polarities is required for light emission.

Tree Propagation Phase. Under dc stress, tree propagation can occur by means of avalanches taking place in one direction only. Electrons injected, or extracted, during dc ramp will initiate a sequence of avalanches and generate a first channel. Any heterocharge deposited on the walls of the channel will be swept out and neutralized by the electrode, thereby transferring the maximum stress to a region around the channel tip. Repetition of the avalanche erosion will cause tree propagation with each new channel tip acting as a potential branch point. In many polymers, tree propagation is reported (15) to occur faster under positive dc than under negative dc, and this effect has been attributed to the difference in the field modification at the injecting electrode by the space charge. If the dc voltage is switched off and then turned on after only a few minutes, then it does not have any significant influence on the propagation rate of treeing. However, if the voltage is switched on after several hours, more intense discharge activity is noticeable immediately after the reapplication of the voltage, and breakdown occurs if the tree was well-developed. This is because the diffusion of gases and subsequent pressure release would cause avalanches at the tips and increase tree propagation.

Treeing under ac Voltage

Tree Initiation Phase. Under ac stress when positive and negative charges are injected and extracted on alternate half-cycles, tree inception occurs much below the breakdown value. Some portion of the injected charge is retained in deep traps during the subsequent half-cycle, and recombination at luminescent centers gives rise to electroluminescence. Since the intensity of electroluminescence depends on the amount of charge injected into the polymer, the light intensity changes with the voltage applied to the polymer. Figure 10 shows the variation of electroluminescence intensity with time for various voltages applied to cross-linked polyethylene insulation prior to electrical treeing. When the voltage is increased or decreased, the intensity immediately adjusts to a new level and remains almost constant at that level.

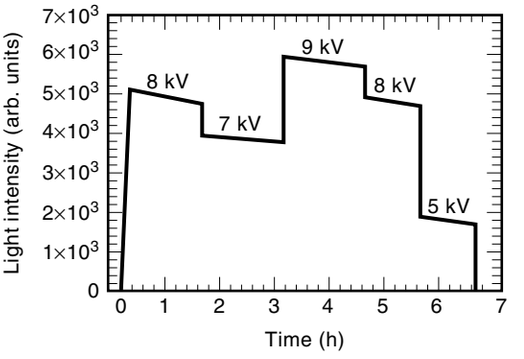

Figure 10. Electroluminescence intensity in polyethylene immediately adjusts to a new level when the voltage is increased or decreased.

Tree Propagation Phase. In polyethylene with ac electric fields at 50 Hz, usually branch-type trees are formed below 5.4×10^2 kV/mm, bush-type trees are formed between 5.4×10^2 kV/mm, and 6×10^2 kV/mm, and bush-branch trees are formed above 6×10^2 kV/mm, and these values reduce as the frequency increases. The change in tree shape from a branch-type to a bush-type tree has been correlated with the change in the propagation rate (see Fig. 5 of ELECTRICAL TREES IN SOLIDS). In laboratory tests, the type of tree that develops depends on the gap distance between needle electrodes inserted into the polymer (16). Figure 11 shows the propagation regimes and the types of trees that develop in cross-linked polyethylene. Two different propagation regimes, denoted as Type I and II, exist for each type of tree. For the Type I regime, partial discharge activity increases, unique types of microchannels are produced, and the tree propagation rate is constant. In the Type II regime, the partial discharge activity is irregular, channels with different geometrical features are produced, and the tree propagation is also irregular. During tree propagation under ac voltage, current pulses on both half-cycles occur during channel formation and are followed by the disappearance of the negative half-cycle pulses as the channel growth is terminated. In epoxy resin, discharge phase-angle relationships between needle-like channel and disk-type voids have been used to characterize the crossover from void discharge to channel formation.

Treeing under Impulse Voltage

Tree Initiation Phase. For positive or negative impulses, having rise or fall time of a few to several hundred microseconds, the probability of electroluminescence emission is independent of the rise time but increases with the fall time and the impulse amplitude. During repeated unipolar impulses, the electroluminescence pulses are grouped within two distinct time periods between which there is no electroluminescence activity. Figure 12 shows the cumulative probability of the electroluminescence pulses for 15 kV negative impulses applied to cross-linked polyethylene. The graph shows that the light pulses only occur during times t_1 and t_2, when the local field in the polymer is above the electroluminescence inception level.

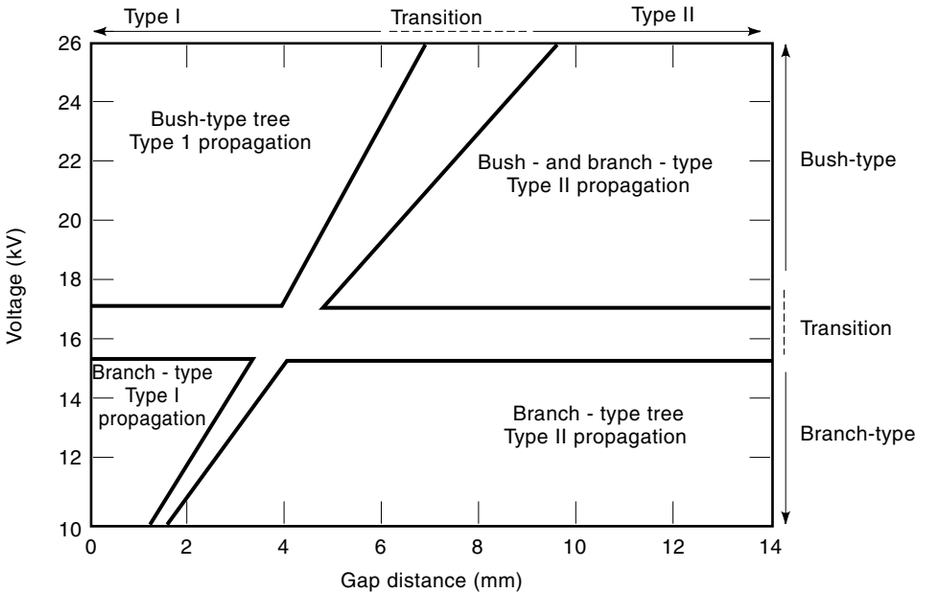

Figure 11. Propagation regimes and the type of tree that develops depend on the gap distance between the needle electrodes in cross-linked polyethylene.

When positive and negative impulses are applied alternately to polyethylene, more electroluminescence pulses are emitted during the negative impulse than during the positive impulse, and the highest number of light pulses occur during the increasing portion of the negative impulse. This is because electron injection is more efficient than hole injection in polyethylene. Figure 13 shows the electroluminescence pulses emitted when 10 positive and negative impulses were consecutively applied to polyethylene. Also, more electroluminescence pulses are emitted from the aged polymer, which has more trapped charge species than the unaged polymer. This could suggest that the charge injected during impulse voltage into the polymer recombines with the trapped charge and emits more light from the aged polymer than from the unaged polymer.

Tree Propagation Phase. For repeated impulses of the same polarity, tree propagation depends on the time allowed between pulses so that the space charge could dissipate from the channel tips. If sufficient time has elapsed, then for a new impulse all tips may act as potential propagation sites. Several hours could be required for this to happen, and prior to that, repeat impulses of the same polarity will cause propagation from only a few tips where the space charge has dissipated. However, for polarity reversal the extraction of heterocharges will cause the space charge to activate all tips, and a branch type tree will develop.

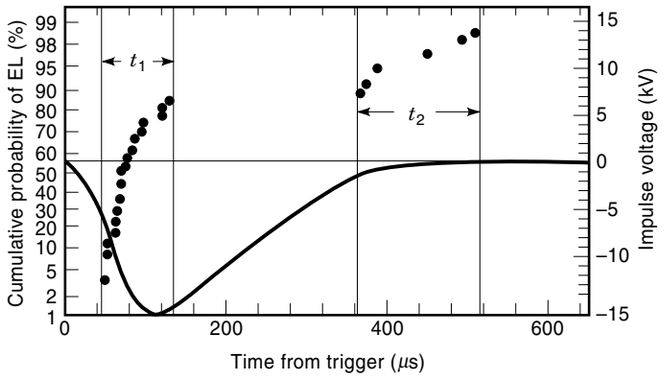

Figure 12. Electroluminescence (EL) pulses in cross-linked polyethylene are grouped within two distinct time periods during impulse voltage.

Effect of Gas

Tree Initiation Phase. Gases can be present at the electrode-dielectric interface or dissolved in the material. The electrical double layer formed at the interface governs the charge transfer across the interface. According to the band theory, the surface states of a dielectric material depend on the type of gas present at the interface. The number of surface states will be considerably smaller in vacuum than when a gas is present. The presence of electronegative gases, such as O_2 and SF_6, will give rise to acceptor-type states at the surface of the polymer. A depletion region is formed in the polymer for vacuum interface, and an inversion region for electronegative gas is present at the interface. The inversion region is most favorable for charge injection. Hence, electronegative gases produce charge injection across the interface at lower applied fields than inert gases. This is why electroluminescence in electronegative gas-impregnated polyethylene occurs at lower voltages than does electroluminescence in the degassed polymer.

Recent experiments on polyethylene, polypropylene, polyvinyl chloride, and polytetrafluoroethylene (17) have revealed that for low electric fields of 2 kV/mm to 20 kV/mm, electroluminescence predominantly occurs at the electrode–polymer interface rather than in the bulk of the polymer. The radiative recombination of electrons and holes trapped at the surface states of the polymer cause light emission in the visible and near-infrared ranges. Also, the intensity of electroluminescence depends on the density of the surface states of the polymer.

In the polymeric insulation of underground high-voltage cables, chromophores (such as carbonyl and hydroperoxide

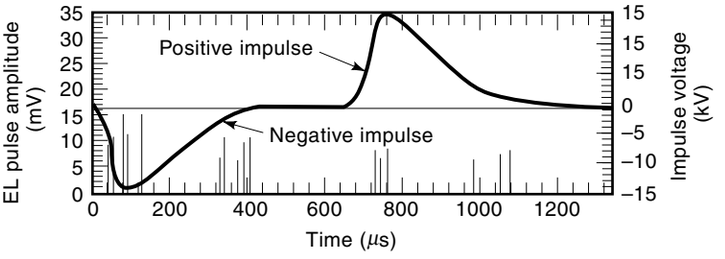

Figure 13. More electroluminescence (EL) pulses are emitted from cross-linked polyethylene during the negative than the positive impulse.

groups), catalyst residues, and oxygen substrate complexes are introduced into the polymer during the various stages of material processing and cable manufacture. When electroluminescence occurs, the chromophores absorb the photoenergy and some of their electrons in the ground state are raised to higher energy states. Since these latter states are unstable, they discharge excitation energy by various photophysical and photochemical processes. If the excitation energy is not completely used in the photophysical process, the excess energy will lead to a photochemical process—that is, dissociation of polymer bonds. UV light causes the formation of free radicals in hydrogen containing polymers. The rate of formation and specific concentration of the radicals increases with increasing oxygen content in the presence of UV light. The possible photochemical reactions (6) in cross-linked polyethylene containing the normal and decreased amounts of oxygen in its free volume are shown in Fig. 14.

The chromophores absorb the UV light and become excited. The excited chromophores can cleave the C=C bonds and give rise to free radicals. The types of reactions that now occur depend upon the concentration of oxygen present in the polymer. In degassed and inert-gas-impregnated polyethylene, having a decreased concentration of oxygen, the free radicals will combine with each other to give inactive products. On the other hand, in normal specimens the free radicals will react with the oxygen molecules to produce peroxy ($ROO^{\cdot}$) radicals. The peroxy will abstract hydrogen from another molecule to form hydroperoxides (ROOH). Also, oxygen, being a ground-state triplet, will quench some of the excited states, and this would result in the formation of singlet oxygen ($^1O_2$). The UV light and the collision of the injected charge with oxygen molecule can result in the formation of singlets. This oxygen singlet is very reactive because it attacks the olefinic sites and gives rise to hydroperoxides. The hydroperoxides can undergo homolysis to form alkoxyl ($RO^{\cdot}$) radicals. These radicals

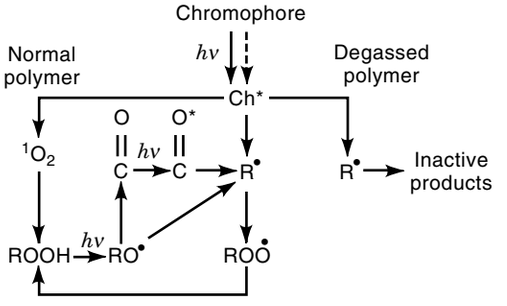

Figure 14. Photochemical reactions in polyethylene containing normal and decreased amounts of oxygen in its free volume.

can react with other polymer molecules to give free radicals ($R^{\cdot}$) either directly or through the formation of ketonic carbonyl (C=O) groups. Thus, a chain reaction is started which degrades the polymer very rapidly. This is why the tree inception voltage of polyethylene decreases as the concentration of oxygen in the free volume of the polymer increases (18).

Recent results on low-density polyethylene impregnated with an inert gas, such as helium and argon, did not show an increase in the tree inception voltage as compared to the nondegassed polymer containing oxygen in its free volume. Thus, it was concluded that the low tree inception voltage was caused by Penning process in the free volume, and that hot electrons rather than the recombination mechanism are responsible for light emission and tree inception. According to this model, shown in Fig. 15, the electrons injected into the polymeric insulation are accelerated in the free volume of the polymer by the electric field and can achieve energies up to 20 eV (19). This requires the free volume in the polymer to be several tens to hundreds of nanometers in size. The hot electrons bombard the polymer molecules and cause excitation and bond scission. Electroluminescence is emitted when the excited molecules return to their ground state. Bond scission leads to the formation of free radicals, and after several bonds are broken a cavity is formed in which partial discharges can set in and cause tree propagation.

Tree Propagation Phase. Since some gases have higher partial discharge inception voltage than others, the tree propagation rate is affected by the type of gas present in the channels. In polymers, partial discharges will produce oxides of nitrogen and sulfur which then chemically degrade the insulation. However, oxygen gas can be most damaging because it reacts with the polymer radicals formed by partial discharge and promotes bond scission and channel formation. The UV light produced by partial discharges can also photodegrade the polymer, and dielectrics susceptible to photodegradation will exhibit larger propagation rates during electrical treeing.

Volatile and nonvolatile degradation products formed during partial discharges can influence discharge patterns. The nonvolatile products could influence the voltage drop along the tree channel. In polyethylene and polypropylene, dehydration of the macromolecular chain produces large quantities of hydrogen, while reactions between hydrogen and residual air produce small quantities of carbon dioxide and water. Acrylic and epoxy resins contain oxygen in the polymer structure and generate large quantities of water and very little hydrogen. The walls of a tree in such materials are lined with high-molecular-weight species produced by the double bonds.

Effect of Temperature

Tree Initiation Phase. In polymeric insulation such as low-density polyethylene and cross-linked polyethylene, the elec-

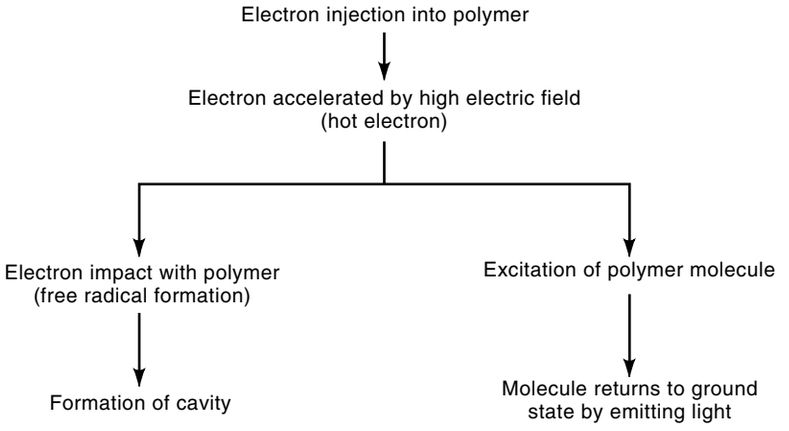

Figure 15. Polymer degradation with hot electrons with energies up to 20 eV.

troluminescence inception voltage increases with the temperature. This is because at high temperature, phonon relaxation increases, the detrapping efficiency also increases, and this decreases the rate of recombination of charges injected into the material. However, at high temperature, the time to tree inception decreases because of the increase in the efficiency of photodegradation which causes rapid degradation of the insulation. Since the quantum efficiency of light emission increases with the decrease in temperature, the intensity of electroluminescence in polyethylene at cryogenic temperature (77 K) is much higher than that at room temperature.

For hot electrons, the decrease in the time to tree inception at high temperature has been attributed to the decrease in the local breakdown strength of polyethylene due to an increase in the size of the free volume. Thus, the electrons will travel over a longer path length, achieve a higher kinetic energy before collision, break more bonds, and cause tree inception sooner. At cryogenic temperatures, polyethylene is rigid below the glass transition temperature and the amorphous regions have a higher tensile strength. Since the free volume is less than at room temperature, higher electric fields are required for the injected charge to acquire sufficient energy to break the polymer bonds and cause tree inception. For polystyrene and polyvinyl chloride, rapid tree inception at high temperature is assumed to be due to the changes in the mechanical properties of the materials.

The degenerate region at the stress enhancement point in the polymer grows very rapidly and reaches its maximum size within a few hours. Figure 16 shows that the propagation rate is accelerated and the size of the degenerate region is larger at high temperature than at room temperature. Even after the degenerate region has stopped growing, it changes its color from light brown to dark brown. This suggests that the formation of low-molecular-weight products and the increase of free radicals and oxidation continues as long as the voltage is applied to the dielectric.

Tree Propagation Phase. At high temperatures, the propagation rate of electrical treeing due to partial discharges also increases. This is because the high temperature will cause the adsorbed charge to diffuse away from the channel walls and thus reduce the counter field to discharge inception. Thus, larger partial discharges can occur and increase tree propagation. In polyethylene, at temperatures $\geq$80°C only branch-type treeing occurs because at high temperature the gases produced by partial discharges diffuse out rapidly and the extent of degradation at the channel tip is increased. On the other hand, at cryogenic temperatures (77 K), the trees propagate slowly and are rather compact because the gas pressure in the tree channels is not easily released by diffusion. Hence, treeing is more likely to occur due to mechanical cracking with some contribution from the electrostatic forces.

Morphology

For electrical tree inception the formation of a channel by charge injected to and from the electrode is necessary. The time, t_I, required to develop a channel-forming rupture depends on the amount of energy C_t transferred to the material and is given by

$$t_I f(G_n - G_{\text{th}}) = C_t$$

where G_n is the energy gained by the injected charge in the local field, G_{th} is the threshold energy for damage production, f is the frequency of the applied voltage, and C_t is a material property (see Fig. 4 of ELECTRICAL TREES IN SOLIDS).

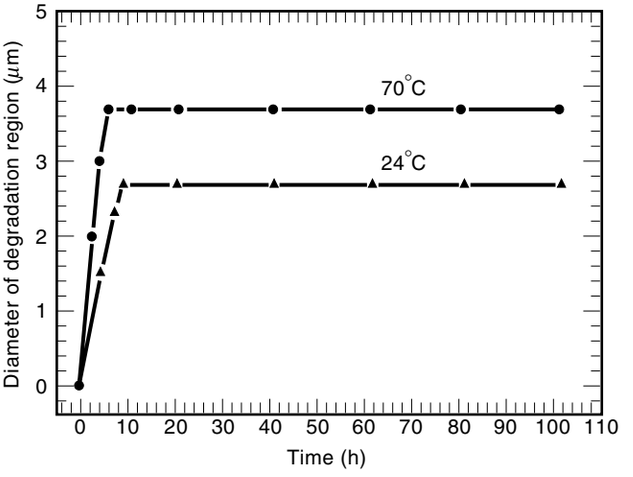

Figure 16. The growth of the degenerate region initially increases very rapidly when ac voltage is applied to polyethylene at different temperatures.

The value of C_t depends on the tensile strength of the material, hence materials with lower tensile strength have shorter times to tree inception. Semicrystalline materials such as cross-linked polyethylene anneal rapidly between 70°C and 90°C and change weight within a few days in this temperature range. Heat treatment of the polymer causing partial melting and recrystallization at a slow cooling rate increases its crystallinity and density. The increase in the crystallinity decreases the free volume in the adjacent amorphous regions and thus increases the tree inception voltage as well as the breakdown strength. If free volume defects are aligned to metal asperities, then they would act as nucleation sites for microcracks. In epoxy resins and polyesters, cracks could appear during inadequate curing and thus lower the tree inception voltage.

In semicrystalline polymers, the tree inception voltage due to impulse voltage increases with the spherulite size. Above the glass transition temperature, the length of trees increases with the increase in temperature and the decrease in the size of the spherulites. During tree propagation, channels will form easily in the amorphous regions having lower yield stress. Since in a polymer the bonds have to be broken for trees to propagate, the bonds under tensile stress will be broken more easily than the unstressed ones. Thus tree propagation is accelerated in a plane perpendicular to the direction of tensile stress. Microcracks will form in the plane perpendicular to the stress direction if the tensile stress is sufficiently high, and tree propagation will be accelerated in the direction of the stress.

TREE RETARDATION

Recent advances in processing and manufacturing techniques have helped to reduce electrical treeing in underground high-voltage cables. Cleaner materials and the triple extrusion process have significantly reduced the contamination level, produced smoother interfaces, and decreased the possibility of having semiconductor protrusions in the insulation. The dry-curing method which uses dry nitrogen instead of steam for cross-linking has reduced the number and size of microcavities. However, these measures to prevent treeing have a practical limitation in that an ideal defect-free dielectric cannot be realized on a commercial scale. One practical approach to make the cable more resistive to electrical treeing is to incorporate additives, known as tree retardants, into the insulation. These additives can play many roles; for example, they can grade the local field enhancement, fill microcavities, and interfere with chemical reactions.

Field Grading

The idea behind this method is to introduce additives which are mobile in the polymer matrix, so that they could move to the regions of stress enhancement and grade the local field. For example, Treben 100, a thermoplastic, contains dodecanol which can migrate to the points of electrical stress enhancement, grade the stress, and retard tree propagation. Acetophenone, a by-product of cross-linking, is a diketone which can also grade the field and retard treeing. However, like other cross-linking by-products, it is fugitive because of its high vapor pressure and exudes from the polymer.

Voltage Stabilizers

Additives that can suppress partial discharges can retard tree propagation as well as prevent tree inception in voids. Aromatic organic compounds have been used to form a semiconducting coating so that discharges do not take place along the walls of voids or tree channels. Additives that can trap electrons injected into the insulation have also been incorporated into the polymer. Ferrocene, a scavenger of electrons, can capture and deactivate the injected electrons; however, it is very unstable in the presence of oxygen and dicumyl peroxide, and attempts to stabilize it with antioxidants have been unsuccessful. Ortho-nitrotoluene has been used to suppress tree propagation because it traps the high-energy electrons, forms a resonance structure, and later releases the electron in a deactivated state. Voltage stabilizers such as diphenyl-*p*-phenylenediamene and organic semiconductors have also been used so that partial discharge extinction occurs as soon as the surface conductivity of the cavity walls increases above 10^{-12} S. Grafted materials containing polystyrene and polysulfone have also been used with some success. Voltage stabilizers should be uniformly distributed in the polymers or they could enhance breakdown at nominally uniform fields by producing stress-enhancing filamentary tracks, especially in semicrystalline materials where the additive is confined to the amorphous part.

Fillers

Treeing can also be inhibited by the presence of certain finely divided inorganic fillers. Minerals such as calcined clay, mica, and titanium oxide are most often incorporated as fillers in ethylene propylene rubber (EPR). The selection of minerals, particle size and shape, and surface treatment are quite crucial for inhibiting treeing. Styrene and ethylene copolymers, stannate, and titanyl sulfate have been added to the polymer to retard electrical treeing. Semiconducting organic liquids which migrate into the channels and form a coating on the channel walls to inhibit discharges have also been used. Aromatic derivatives such as phenols appear to be most effective. However, the main problem with mobile additives is that they diffuse out of the insulation during service.

Antioxidants

The addition of phenolic and amine antioxidants reduces the propensity of oxidation especially during extrusion and cross-linking of cable insulation when temperatures of 175°C or higher may be reached. Some of these antioxidants will decompose during extrusion, and the degraded antioxidant will be present in the extrudate along with the original component. Antioxidants can serve as voltage stabilizers and play a significant role in increasing the time to tree inception. On the other hand, degraded antioxidant products could act as contaminants, if their solubility is less than that of their precursor. To prevent deleterious antioxidant clusters from forming in the material, it is essential that the antioxidant is uniformly dispersed throughout the polymeric insulation. Clusters of antioxidant could facilitate field emission and cause the polymer at the polymer–antioxidant interface to be more susceptible to chain rupture because of the high concentration of polymer radicals that the antioxidant causes to form at the interface. This would ultimately lead to degradation and microvoid formation. Thus above critical concentra-

tion, clusters of antioxidant could have exactly the opposite effect because they could serve to promote rather than to prevent treeing as exhibited by well-dispersed antioxidants. This is why Irganox has practically replaced Santanox, which has a high melting point and poor dispersion in polyethylene. At levels above a critical concentration, the inhibition efficiency of antioxidants is lowered because they react so rapidly with oxygen that the probability of chain cleavage is increased. Amine antioxidants with a high polarizability and capability of field dissociation modify the local stress through an increase in conductivity and thereby increase the resistance to electrical treeing. Grafted materials containing polystyrene and polysulfone have also been used with some success.

UV Stabilizers

Antioxidants, usually added to the polymeric insulation, cannot retard the photodegradation due to UV emission caused by electroluminescence. This is because the antioxidants degrade under the action of UV light. However, light stabilization for a polymeric insulation can be obtained by adding UV stabilizers. Such stabilizers absorb the UV light and prevent the harmful radiation from reaching the chromophoric groups in the polymer. One of the most effective stabilizers is carbon black, which has the ability to filter UV radiation, but adding carbon black in any significant amount makes the polymer very lossy. Benzotriazole (Tinuvin 328), which has an absorption range from 270 nm to 400 nm, has been used as a photostabilizer in polyethylene, but Tinuvin is generally rejected by the crystalline regions of the polymer and accumulates in the amorphous parts. Photostabilizers added to the polymer can absorb the UV light as well as quench the excited states, decompose the hydroperoxides, and scavenge free radicals, and thus they are able to retard polymeric degradation. Figure 17 shows the temporal behavior of electroluminescence from polyethylene containing 700 ppm of phenolic antioxidant and a combination of Tinuvin 622 and Chimasorb 81, a hindered amine light stabilizer. Under accelerated aging, the photostabilizer increased the time to tree inception by almost two orders of magnitude. Also, during accelerated aging tests, full size distribution class cables containing photostabilizers have outlived conventional cables that have an antioxidant package in their polymeric insulation.

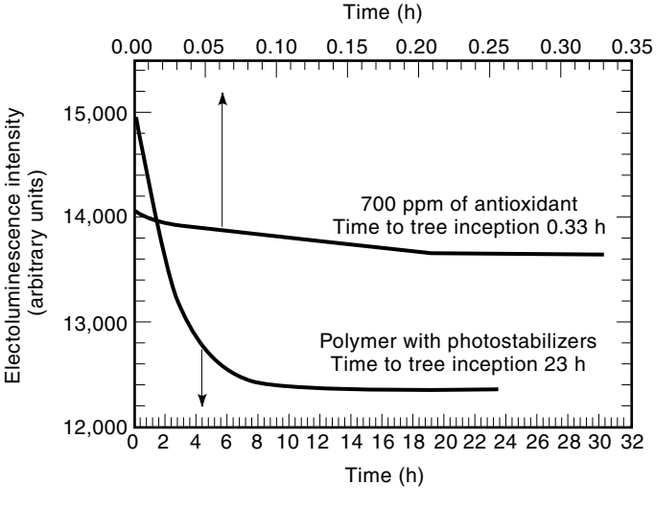

Figure 17. Comparison of the time to tree initiation in cross-linked polyethylene containing antioxidants and photostabilizers.

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