Breakdown of Solid Insulating Materials

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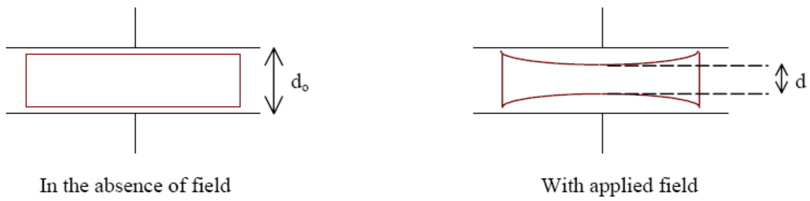
- In solid dielectrics, highly purified and free of imperfections, the breakdown strength is high of the order of 10 MV/cm
- The highest breakdown strength obtained under carefully controlled conditions is known as the "intrinsic strength" of the dielectric. However, intrinsic strength is rarely reached even under experimental conditions. Intrinsic breakdown is accomplished in times of the order of 10^{-8} sec and has therefore been postulated to be electronic in nature. Stresses required for intrinsic breakdown are of the order of 106 V/cm.

- Dielectrics usually fail at stresses well below the intrinsic strength due usually to one of the following causes.
  (a) Electro-mechanical breakdown
  (b) Surface breakdown (tracking and erosion)
  (c) Thermal breakdown
  (d) Electro-chemical breakdown
  (e) Chemical deterioration
  (f) Breakdown due to internal discharges

Electro-mechanical breakdown

- Substances which can deform appreciably without fracture may collapse when the electrostatic compression forces on the test specimen exceed its mechanical compressive strength.
- When an electric field is applied to a dielectric between two electrodes, a mechanical force will be exerted on the dielectric due to the force of attraction between the surface charges. The pressure exerted when the field reached about 10^6 C/cm may be several kN / m^2.
- This compression decreases the dielectric thickness thus increasing the effective stress



Compressive force $P_c = ½ D E = ½ \varepsilon_o \varepsilon_r V^2/d^2$, From Hooke's Law for large strains, $P_c = Y \ln (d_o/d)$

At equilibrium, equating forces gives the equation,

$½ \varepsilon_o \varepsilon_r V^2/d^2 = Y \ln (d_o/d)$

$V^2 = \{d^2 * \ln (d_o/d)\}/ \varepsilon_o \varepsilon_r$

Where d_o is the initial thickness of the dielectric material and d represents the thickness under applied voltage V.

- By differentiating with respect to d, it is seen that the system becomes unstable when
  $2V (dV/dd) = K [2d \ln (d_o/d) – d^2 (d/d_o) (d_0/d^2)] = 0$
  $[2d \ln (d_o/d)] = d$
  $\ln (d_o/d) > ½$ or $d < 0.6 d_o$.
  Thus when the field is increased, the thickness of the material decreases.
- At the field when $d < 0.6 d_o$, any further increase in the field would cause the mechanical collapse of the dielectric.
  The apparent stress (V/d_o) at which this collapse occurs is thus given by the equation
  $E_a = \{0.6 * Y / \varepsilon_o \varepsilon_r \}^{1/2}$

Thermal Breakdown

- Heat is generated continuously in electrically stressed insulation by dielectric losses, which is transferred to the surrounding medium by conduction through the solid dielectric and by radiation from its outer surfaces.
- Heat Generated = Heat Absorbed + Heat Lost
- The absorbed heat increases the temperature of the material.
- If the heat generated exceeds the heat lost to the surroundings, the temperature of the insulation increases.

- The power dissipated in the dielectric can be calculated as follows:
- Uniform direct stress

  Power dissipated/volume = E^2 / ρ , Watts / m^3

where E = uniform direct stress V/m

and ρ = resistivity of insulation in Ohm-m

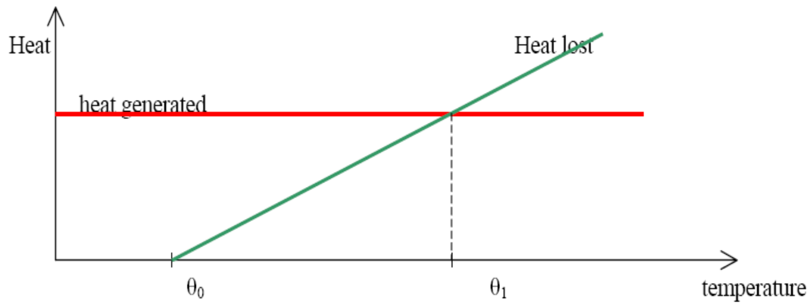
- Uniform alternating stress

  Power dissipated $P = V I \cos\phi = V (V \omega C) \tan\delta$,
  where V = applied voltage V
  C = dielectric capacitance in farads = $\varepsilon A/d$

  Therefore $P = V^2 \omega (\varepsilon A/d) \tan\delta$,
  $= (V^2 / d^2) \omega (\varepsilon A d) \tan\delta$, Watts
  Power dissipated/volume = $E^2 \omega \varepsilon \tan\delta$, Watts / m^3
  Thus, heat generated per unit volume varies as square of the applied field stress.

- The simplest case is where the loss of heat by cooling is linearly related to the temperature rise above surroundings, and the heat generated is independent of temperature. (i.e. the resistivity and the loss angle do not vary with temperature)..

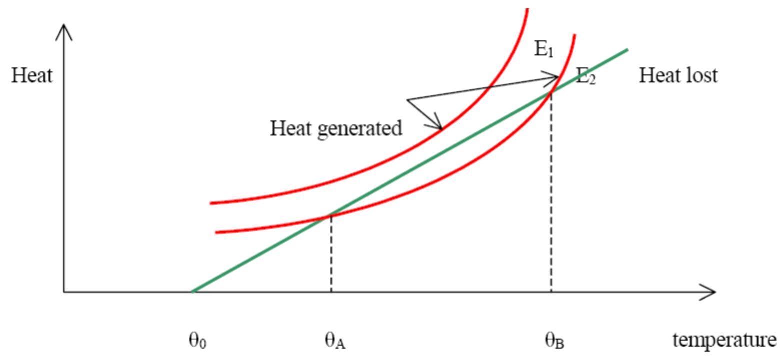
- The heat lost to surroundings is given by, K (T-Ta), where Ta is the ambient temperature.
- In practice, although the heat lost may be considered somewhat linear, the heat generated increases rapidly with temperature, and at certain values of electric field no stable state exists where the heat lost is equal to the heat generated so that the material breaks down thermally.



Thermal breakdown

Heat lost = k (θ-θ_0), where θ is the ambient temperature. Equilibrium will be reached at a temperature θ_1 where the heat generated is equal to the heat lost to the surroundings, as shown above

- In practice, although the heat lost may be considered somewhat linear, the heat generated increases rapidly with temperature, and at certain values of electric field no stable state exists where the heat lost is equal to the heat generated so that the material breaks down thermally. The rapid increase is due to the fact that with rise in temperature, the loss angle of the dielectric increases in accordance with an exponential law (loss $\propto e^{-A/T}$, where T is the absolute temperature).



The above figure shows the variation of heat generated by a device for 2 different applied fields and the heat lost from the device with temperature. For the field E_2, a stable temperature A exists (provided the temperature is not allowed to reach B). For the field E_1, the heat generated is always greater than the heat lost so that the temperature would keep increasing until breakdown occurs.

- The maximum voltage that a given insulating material can withstand cannot be increased indefinitely simply by increasing its thickness. Owing to thermal effects, there is an upper limit of voltage V, beyond which it is not possible to go without thermal instability.
- This is because with thick insulation, the internal temperature is little affected by the surface conditions.
- Usually, in the practical use of insulating materials, V is a limiting factor only for high- temperature operation, or at high frequency failures

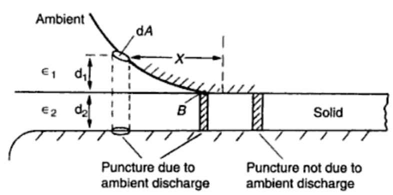
Surface Breakdown

- In practical insulation systems the solid material is stressed in conjunction with one or more other materials. If one of the materials is gas or liquid, then the measured breakdown voltage will be influenced more by the weak medium than by the solid.
- Surface flashover is a breakdown of the medium in which the solid is immersed. The role of the solid dielectric is only to distort the field so that the electric strength of the gas is exceeded.

- Some of the main surface breakdown phenomenon are:
  1. Breakdown due to internal Discharges
  2. Pollution Flashover
  3. Tracking
  4. Erosion

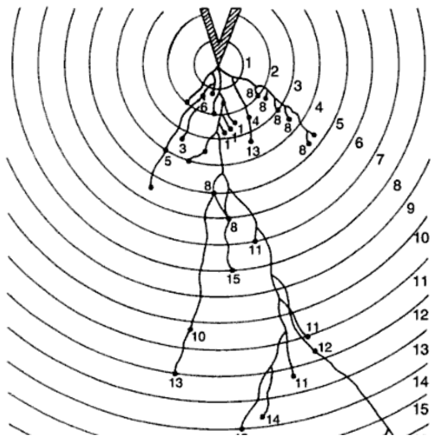
Edge Breakdown & Treeing

- A cross section of a simplified example is shown in figure below, which represents testing of a dielectric slab between sphere-plane electrodes. Ignoring the field distribution, i.e., assuming a homogeneous field, if we consider an elementary area dA spanning the electrodes at a distance x as shown, a fraction V_1 of the applied voltage appears across the ambient given by, $V_1 = V d_1 / (d_1 + (\varepsilon_1/\varepsilon_2)\, d2)$, where d_1 and d_2 represent the thickness of media 1 and 2.



Breakdown of solid specimen due to ambient discharge-edge effect

- The stress in the gaseous part of the system increases as d_1 is decreased, and is very high for very small values of d_1
- This effect is known as 'edge effect', i.e, intensification of the field at the boundary or the edge of the interface between solid and liquid dielectric.
- Breakdown in general is not accomplished by the formation of a single channel, but assumes a tree-like structure. The time required for this type of breakdown under alternating voltage will vary from few seconds to a few minutes.
- The tree pattern is not limited specifically to edge effect but may be observed in other dielectric failure mechanisms where fields are non –uniform.



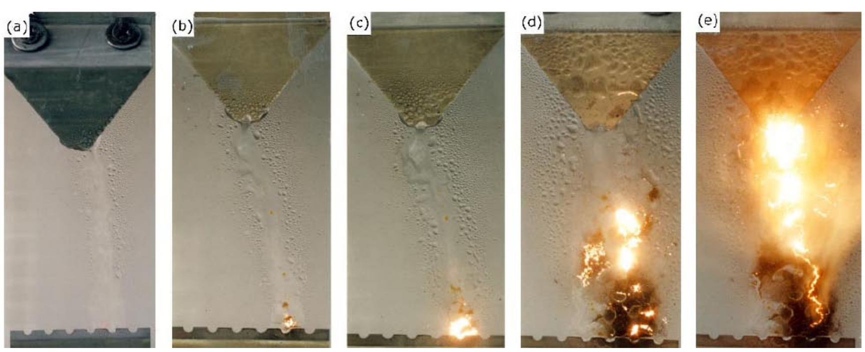
Tree like Breakdown Channels in Plexi-Glass upon application of impulse voltage

Tracking

- Tracking is the formation of a permanent conducting path across a surface of the insulation, and in most cases the conduction (carbon path) results from degradation of the insulation itself leading to a bridge between the electrodes.
- The insulating material must be organic in nature for tracking to occur.

Erosion

- In a surface discharge, if the products of decomposition are volatile and there is no residual conducting carbon on the surface, the process is simply one of pitting. This is erosion, which again occurs in organic materials.
- If surface discharges are likely to occur, it is preferable to use materials with erosion properties rather than tracking properties, as tracking makes insulation immediately completely ineffective, whereas erosion only weakens the material but allows operation until replacement can be made later.



Tracking process. (a) The contaminant flows down the sample surface; (b) the discharge, i.e. dry-band arcing, occurs;
(c) scintillation, i.e. ignition, initiates tracking; (d) track, i.e. conducting carbide path, forms and propagates; and (e) the track grows until the sample fails.

Photo of severe spark Erosion Damage.

Erosion Damage on 11 kV Stator Coil

Pollution Flashover

- This refers to the surface flashover which generally happens in the case of polluted outdoor insulators and bushings.
  The three essential components of the surface flashover phenomena are
  (a) Presence of a conducting film across the surface of the insulation
  (b) A mechanism whereby the leakage current through the conducting film is interrupted
  with the production of sparks,
  (c) Degradation of the insulation caused by the sparks.

- The conducting film is usually moisture from the atmosphere absorbed by some form of contamination. Moisture is not essential as a conducting path can also arise from metal dust due to wear and tear of moving parts. Sparks are drawn between moisture films, separated by drying of the surface due to heating effect of leakage current, which act as extensions to the electrodes.
- {For a discharge to occur, there must be a voltage at least equal to the Paschen minimum for the particular state of the gas. For example, Paschen minimum in air at N.T.P it is 380 V, whereas tracking can occur at well below 100 V. It does not depend on gaseous breakdown.]

- Degradation of the insulation is almost exclusively the result of heat from the sparks, and this heat either carbonises if tracking is to occur, or volatilises if erosion is to occur. Carbonization results in a permanent extension of the electrodes and usually takes the form of a dendritic growth.
- Increase of creepage path during design will prevent tracking, or coating with materials which prevent formation of conducting films will help to increase the surface breakdown strength.

Contaminated insulator showing leakage current marks on its surface.

Electro-chemical Breakdown

- Since no insulant is completely free of ions, a leakage current will flow when an electric field is applied. The ions may arise from dissociation of impurities or from slight ionisation of the insulating material itself. When these ions reach the electrodes, reactions occur in accordance with Faraday's law of electrolysis, but on a much smaller scale.
- The reactions are much slower than in normal electrolytic processes due to the much smaller currents. The products of the reactions may be electrically and chemically harmful because the insulation and electrodes may be attacked, and because harmful gases may be evolved.

- Typically a 1 µF paper capacitor operating at 1 kV at room temperature would require 2 to 3 years to generate 1 cm^3 hydrogen.
- At elevated temperatures, the products of electrolysis would be formed much more rapidly. Also since impurities give rise to an increase in the ion concentration, care must be taken to prevent contamination during manufacture.
- The rate of electrolysis is much greater with direct stress than with alternating stress. This is due to the fact that the reactions may be wholly or partially reversed when the polarity changes and the extent of reaction depends on the reaction rate and the time for diffusion of the reaction products away from the electrodes as well as on the nature of the reaction products.

- However at power frequency, electrochemical effects can be serious and are often responsible for long-term failure of insulation. The most frequent source of ions is ionizable impurities in the insulation. Thus contamination of insulation during manufacture and during assembly into equipment must be avoided with great care.
- The long term lives of capacitors containing chlorinated impregnants under direct stress may be greatly extended by adding small quantities of certain stabilizers, which are hydrogen acceptors and act as depolarizers at the cathode.
- The extension of the life caused by the stabilizers is proportional to the amount of stabilizer added. For example, with 2% of the stabilizer Azobenzene, mean life may be extended 50 times.

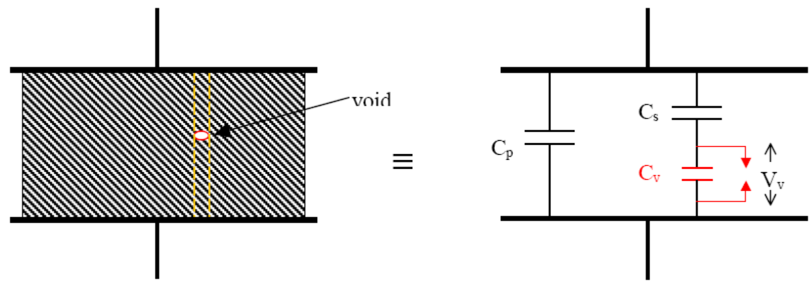
- Progressive chemical degradation of insulating materials can occur in the absence of electric stress from a number of causes.
- Chemical Instability

  Many insulating materials, especially organic materials, show chemical instability. Such chemical changes may result from spontaneous breakdown of the structure of the material. Under normal operating conditions, this process is very slow, but the process is strongly temperature dependant.
- The logarithm of the life t of paper insulation can be expressed as an inverse function of the absolute temperature

  $\log_{10} T = (A/\theta) + B$ where A & B are constants
- In the presence of oxygen or moisture, the life of the insulation decreases much more rapidly. With increase in amount of moisture present, B decreases so that the life of the paper also decreases. With about 0.1% moisture present, B decreases by as much as 0.8, so that t decreases by a factor of about 6. This means that presence of about 0.1% moisture reduces the life of the insulation by as much as 6 times.

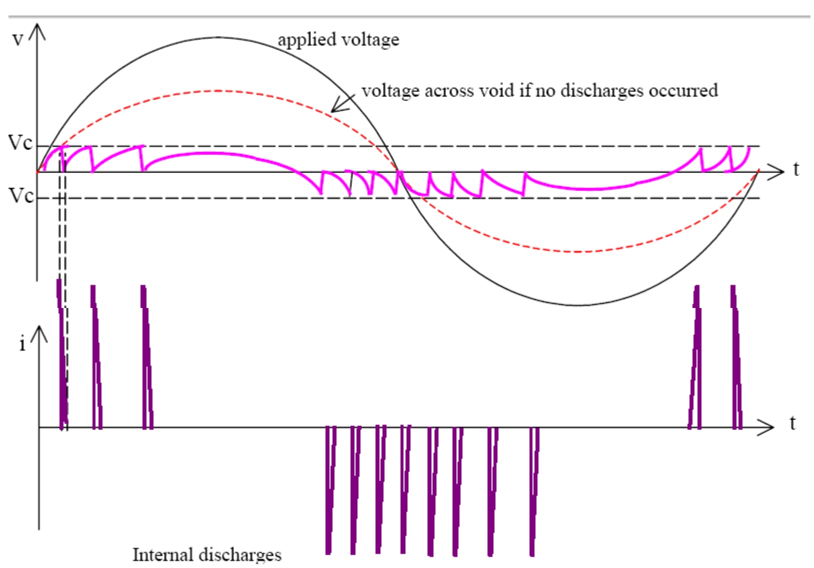
Breakdown due to Internal Discharges

- Solid insulating materials sometimes contain voids or cavities in the medium or boundaries between the dielectric and the electrodes.
- These voids have a dielectric constant of unity and a lower dielectric strength. Hence the electric field strength in the voids is higher than that across the dielectric.
- Thus even under normal working voltages, the field in the voids may exceed their breakdown value and breakdown may occur.
- The mechanism can be explained by considering the following equivalent circuit of the dielectric with the void, shown in the next slide



Equivalent circuit of dielectric with void

When the voltage V_v across the void exceeds the critical voltage V_c, a discharge is initiated and the voltage collapses. The discharge extinguishes very rapidly (say 0.1µs). The voltage across the void again builds up and the discharges recur. The number and frequency of the discharges will depend on the applied voltage. The voltage and current waveforms (exaggerated for clarity) are shown in next slide



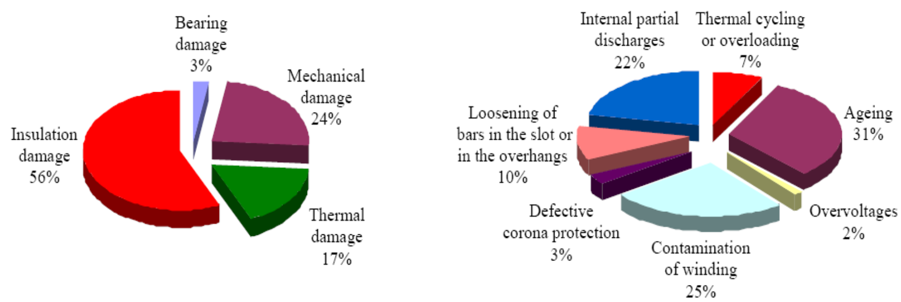
- In each of the discharges, there will be heat dissipated in the voids which will cause carbonization of the surface of the voids and erosion of the material. The gradual erosion of the material and consequent reduction in the thickness of the insulating material eventually leads to breakdown.
- Breakdown by this process is slow and may occur in a few days or may take a few years.
- **Deterioration due to internal discharges**
- In organic liquid-solid dielectrics, internal discharges produce gradual deterioration because of
- (a) disintegration of the solid dielectric under the bombardment of electrons set free by the discharges
- (b) chemical action on the dielectric of the products of ionization of the gas
- (c) high temperatures in the region of the discharges.

- All voids in the dielectric can be removed by careful impregnation and this results in an increase in the discharge inception stress E_i. The final value E_i then depends on electrical processes which lead to gas formation.
- In oil impregnated paper these are

(a) decomposition of moisture in paper

(b) local electrical breakdown of the oil.

- The stress at which gas is evolved from paper containing appreciable quantities of moisture can be less than 10 V/m, but increases continuously with increasing dryness and can be higher than 100 V/m when the paper is thoroughly dry.
- Except in very dry conditions, the gas first formed arises from electrochemical decomposition of water held in the paper. Permanent damage can be caused by the discharges and this manifests itself in an increase of loss angle due to the formation of ions by the discharges. Also, due to the discharges, widespread carbonization occurs.



Damages of hydrogenerators (left) and root causes of insulation damages (right) [5]

Failures are predominantly due Insulation Failure!