

# Breakdown of Liquid and Solid Insulation

## 2.1 Breakdown in Liquids

In highly purified liquid dielectrics, breakdown is controlled by phenomena similar to those for gasses and the electric strength is high (of the order of 1 MV/cm).

Unfortunately, liquids are easily contaminated, and may contain solids, other liquids in suspension and dissolved gasses. The effect of these impurities is relatively small for short duration pulses (10  $\mu$ s).

However, if the voltage is applied continuously, the solid impurities line up at right angles to equipotentials, and distort the field so that breakdown occurs at relatively low voltage. The line up of particles is a fairly slow process, and is unlikely to affect the strength on voltages lasting for less than 1 ms.

Under the action of the electric field, dissolved gasses may come out of solution, forming a bubble. The gas in the bubble has a lower strength than the liquid, so that more gas is produced and the bubble grows, ultimately causing breakdown. Because, of the tendency to become contaminated, liquids are not usually used alone above 100 kV/cm in continuously energised equipment, however, they are used at much higher stresses (up to 1 MV/cm) in conjunction with solids, which can be made to act as barriers, preventing the line-up of solid impurities and localising of any bubbles which may form. The main function of the liquid in such arrangements is to fill up the voids.

### 2.1.1 Breakdown of Commercial liquids

When a difference of potential is applied to a pair of electrodes immersed in an insulating liquid, a small conduction current is first observed. If the voltage is raised continuously, at a critical voltage a spark passes between the electrodes. The passage of a spark through a liquid involves the following.

- (a) flow of a relatively large quantity of electricity, determined by the characteristics of the circuit,
- (b) a bright luminous path from electrode to electrode,
- (c) the evolution of bubbles of gas and the formation of solid products of decomposition (if the liquid is of requisite chemical nature)
- (d) formation of small pits on the electrodes,
- (e) an impulsive pressure through the liquid with an accompanying explosive sound.

Tests on highly purified transformer oil show that

- (a) breakdown strength has a small but definite dependence on electrode material,
- (b) breakdown strength decreases with increase in electrode spacing,
- (c) breakdown strength is independent of hydrostatic pressure for degassed oil, but increases with pressure if oil contains gases like nitrogen or oxygen in solution.

In the case of commercial insulating liquid, which may not be subjected to very elaborate purifying treatment, the breakdown strength will depend more upon the nature of impurities it contains than upon the nature of the liquid itself.

These impurities which lead to the breakdown of commercial liquids below their intrinsic strength, can be divided into the following 3 categories.

- (a) Impurities which have a breakdown strength lower than that of the liquid itself (ex: bubbles of gas). Breakdown of the impurities may trigger off the total breakdown of the liquid.
- (b) Impurities which are unstable in the electric field (ex: globules of water). Instability of the impurity can result in a low resistance bridge across the electrodes and in total breakdown.
- (c) Impurities which result in local enhancement of electric field in a liquid (ex: conducting particles). The enhanced field may cause local breakdown and therefore initiate complete breakdown.

These will be considered in turn in the following sections.

### 2.1.2 Breakdown due to gaseous inclusions

Gas or vapour bubbles may exist in impure liquid dielectrics, either formed from dissolved gasses, temperature and pressure variations, or other causes.

The electric field  $E_b$  in a gas bubble which is immersed in a liquid of permittivity  $\epsilon_1$  is given by

$$E_b = \frac{3\epsilon_1}{2\epsilon_1 + 1} E_0$$

where  $E_0$  is the field in the liquid in the absence of the bubble.

The electrostatic forces on the bubble cause it to get elongated in the direction of the electric field. The elongation continues, when sufficient electric field is applied, and at a critical length the gas inside the bubble (which has a lower breakdown strength) breaks down. This discharge causes decomposition of the liquid molecules and leads to total breakdown.

### 2.1.3 Breakdown due to liquid globules

If an insulating liquid contains in suspension a globule of another liquid, then breakdown can result from instability of the globule in the electric field.

Consider a spherical globule of liquid of permittivity  $\epsilon_2$  immersed in a liquid dielectric of permittivity  $\epsilon_1$ . When it is subjected to an electric field between parallel electrodes, the field inside the globule would be given by

$$E = \frac{3\epsilon_1}{2\epsilon_1 + \epsilon_2} E_0$$

where  $E_0$  is the field in the liquid in the absence of the globule.

The electrostatic forces cause the globule to elongate and take the shape of a prolate spheroid (i.e. an elongated spheroid). As the field is increased, the globule elongates so that the ratio  $\gamma$  of the longer to the shorter diameter of the spheroid increases. For the same field  $E$ , the ratio  $\gamma$  is a function of  $\epsilon_2/\epsilon_1$ .

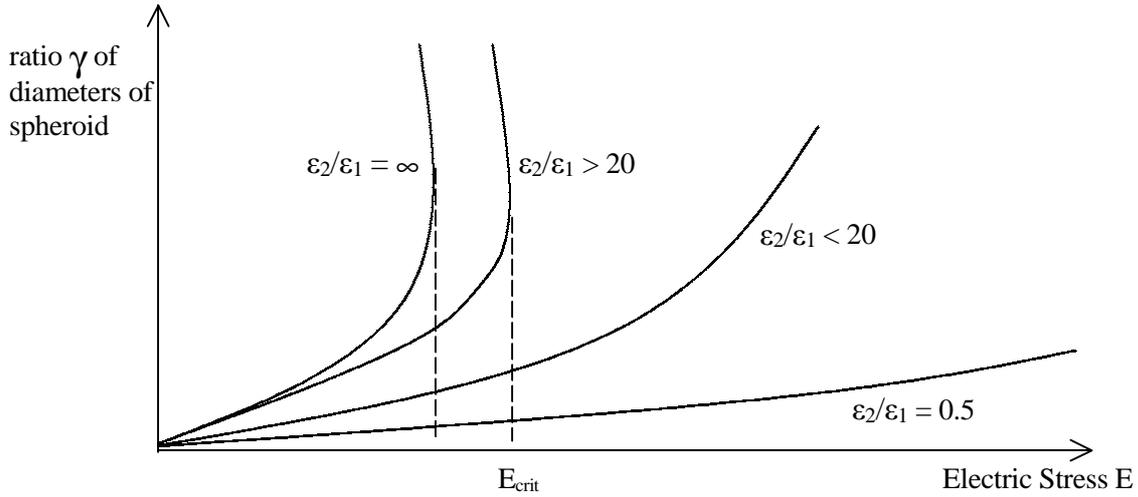


Figure 2.1 - Variation of ratio of diameters of spheroid

When  $\epsilon_2 \gg \epsilon_1$  (generally when  $\epsilon_2/\epsilon_1 > 20$ ), and the field exceeds a critical value, no stable shape exists, and the globule keeps on elongating eventually causing bridging of the electrodes, and breakdown of the gap. When  $\epsilon_2/\epsilon_1 \gg 20$ , the critical field at which the globule becomes unstable no longer depends on the ratio, and is given by  $E_{crit}$ .

$$E_{crit} = 1.542 \left( \frac{\sigma}{R \epsilon_1} \right)^{1/2} \text{ kV/cm}$$

where  $\sigma$  = surface tension of the globule (N/m)  
 $\epsilon_1$  = relative permittivity of the insulating liquid  
 $R$  = initial radius of globule (m).

**Example 2.1**

For a droplet of water ( $R = 1 \mu\text{m}$ ,  $\epsilon_2 = 90$ ) in an insulating oil ( $\epsilon_1 = 2$ );  $\epsilon_2 \gg \epsilon_1$ .  
 Also  $\sigma = 0.043 \text{ N/m}$ .

$$\begin{aligned} \text{Thus } E_{crit} &= 1.542 (0.043/10^{-6} \times 2)^{1/2} \text{ kV/cm} = 226 \text{ kV/cm.} \\ &= 0.226 \text{ MV/cm} \end{aligned}$$

Thus we see that a droplet of water even as small as  $1 \mu\text{m}$  in radius (quite unobservable) can greatly reduce the breakdown strength of the liquid dielectric. In fact, a globule of water of radius of only  $0.05 \mu\text{m}$ , which is quite unobservable, will be disrupted at a value of about  $1 \text{ MV/cm}$  which is the breakdown strength of the pure liquid. Thus even submicroscopic sources of water, such as condensed breakdown products, or hygroscopic solid impurities, may greatly influence breakdown conditions. A globule which is unstable at an applied value of field elongates rapidly, and then electrode gap breakdown channels develop at the end of the globule. Propagation of the channels result in total breakdown.

**2.1.4 Breakdown due to solid particles**

In commercial liquids, solid impurities cannot be avoided and will be present as fibres or as dispersed solid particles. If the impurity is considered to be a spherical particle of permittivity  $\epsilon_2$  and is present in a liquid dielectric of permittivity  $\epsilon_1$ , it will experience a force

$$\frac{(\epsilon_2 - \epsilon_1)}{\epsilon_2 + 2\epsilon_1} \Delta E^2$$

where  $E$  = applied field,  $r$  = radius of particle.

Generally  $\epsilon_2 > \epsilon_1$ , so that the force would move the particle towards the regions of stronger field. Particles will continue to move in this way and will line up in the direction of the field. A stable chain of particles would be produced, which at a critical length may cause breakdown.

Because of the tendency to become contaminated, liquids are seldom used alone above 100 kV/cm in continuously energised equipment. However they may be used up to 1 MV/cm in conjunction with solids which can be made to act as barriers, preventing the line-up of solid impurities and localising bubbles which may form.

### 2.1.5 Purification of a liquid for testing

#### (a) Removal of dust

Small dust particles can become charged and cause local stresses which can initiate breakdown. They can also coalesce to form conducting bridges between electrodes. Careful filtration can remove dust particles greater in size than 1  $\mu\text{m}$ . The strength of the liquid then increases and greater stability is achieved.

#### (b) Removal of dissolved gasses

Liquid insulation will normally contain dissolved gas in small but significant amounts. Some gases such as Nitrogen and Hydrogen do not appear to upset the electrical properties to a great extent, but oxygen and carbon dioxide can cause the strength to change significantly. Thus it necessary to control the amount of gases present. This is done by distillation and degassing.

#### (c) Removal of ionic impurities

Ionic impurities in the liquid (particularly residual water which easily dissociates) leads to abnormal conductivity and heating of the liquid. Water can be removed by drying agents, vacuum drying, and by freezing out in low temperature distillation.

For measurements on liquid dielectrics, where test cells are small, electrode preparation is much more critical than it is for measurements on gases or solids. Not only is the surface smoothness important, but surface films, particularly oxides can have a marked influence on the strength.

## 2.2 Breakdown of Solid Insulating Materials

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. Dielectrics usually fail at stresses well below the intrinsic strength due usually to one of the following causes.

- (a) electro-mechanical breakdown
- (b) breakdown due to internal discharges
- (c) surface breakdown (tracking and erosion)
- (d) thermal breakdown
- (e) electro-chemical breakdown
- (f) chemical deterioration

These will now be considered in the following sections.

### 2.2.1 Electro-mechanical breakdown

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. This compression decreases the dielectric thickness thus increasing the effective stress. This is shown in figure 2.2.



Figure 2.2 - Process of breakdown

Compressive force  $P_c = \frac{1}{2} D E = \frac{1}{2} \epsilon_0 \epsilon_r V^2/d^2$ ,  
 and From Hooke's Law for large strains,  $P_c = Y \ln (d_0/d)$

At equilibrium, equating forces gives the equation,

$$V^2 = \frac{2 Y}{\epsilon_0 \epsilon_r} d^2 \ln \frac{d_0}{d}$$

By differentiating with respect to d, it is seen that the system becomes unstable when  $\ln (d_0/d) > \frac{1}{2}$  or  $d < 0.6 d_0$ .

Thus when the field is increased, the thickness of the material decreases. At the field when  $d < 0.6 d_0$ , any further increase in the field would cause the mechanical collapse of the dielectric. The apparent stress ( $V/d_0$ ) at which this collapse occurs is thus given by the equation

$$E_a = 0.6 \left[ \frac{Y}{\epsilon_0 \epsilon_r} \right]^{\frac{1}{2}}$$

**2.2.2 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 figure 2.3.

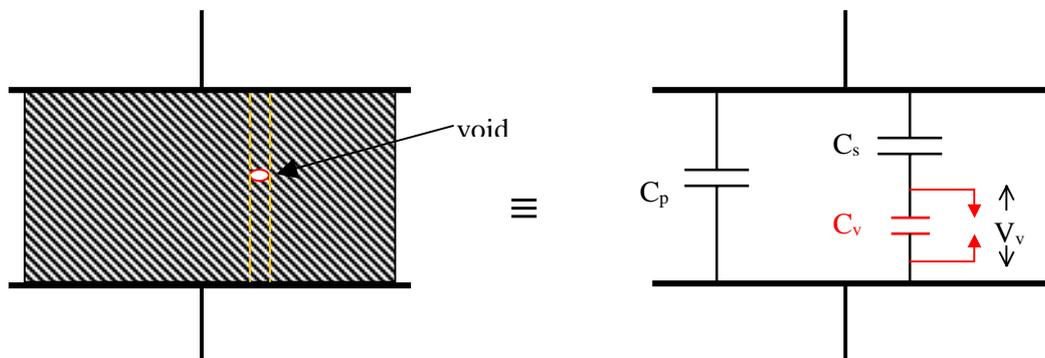


Figure 2.3 - Equivalent circuit of dielectric with void

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  $0.1 \mu s$ ). 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 figure 2.4.

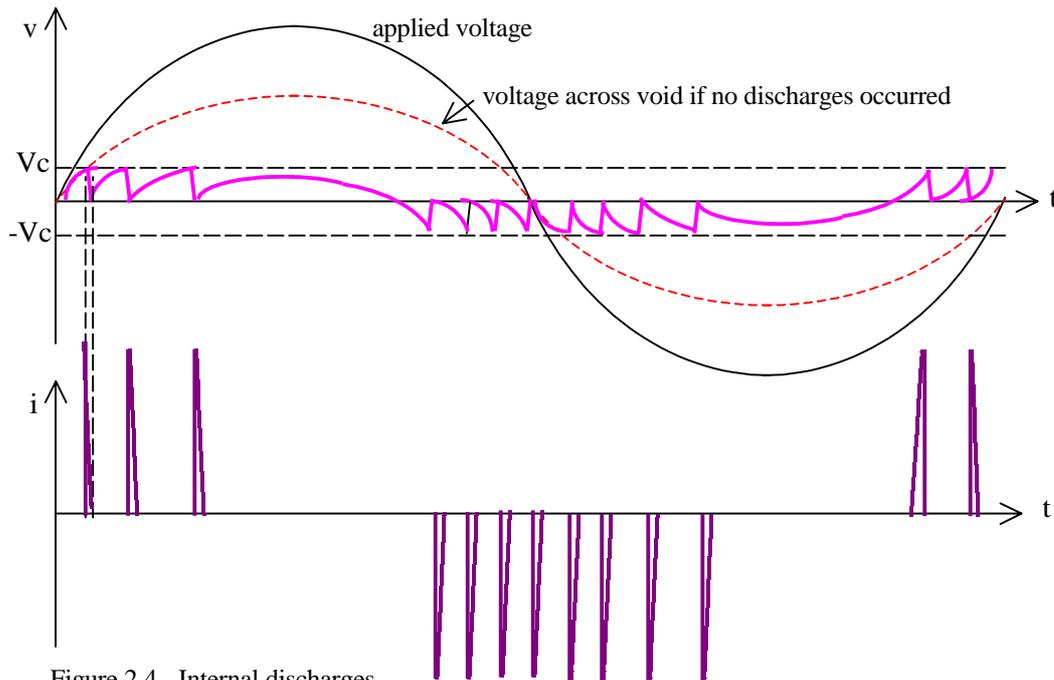


Figure 2.4 - Internal discharges

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  $10 \text{ V}/\mu\text{m}$ , but increases continuously with increasing dryness and can be higher than  $100 \text{ V}/\mu\text{m}$  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.

When a gas bubble is formed in an oil-paper dielectric at the discharge inception stress  $E_i$ , discharges in the bubble decompose the molecules of the oil, resulting in further gas formation and a rapid growth of the bubble. As long as the bubble remains in the dielectric, the inception stress  $E_i$  is low, often lower than the rated stress, but resting the dielectric long enough for the gas to dissolve in the oil restores the initial high discharge inception stress. Although on resting  $E_i$  improves, permanent damage has been caused by the discharges and this manifests itself in an increase of loss angle and is due to the formation of ions by the discharges. Also, due to the discharges, widespread carbonization occur.

### 2.2.3 Surface Breakdown

#### Surface flashover

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.

If a piece of solid insulation is inserted in a gas so that the solid surface is perpendicular to the equipotentials at all points, then the voltage gradient is not affected by the solid insulation. An example of this is a cylindrical insulator placed in the direction of a uniform field. Field intensification results if solid insulation departs even in detail from the cylindrical shape. In particular if the edges are chipped, or if the ends of the cylinder are not quite perpendicular to the axis, then an air gap exists next to the electrode, and the stress can reach up to  $\epsilon_r$  times the mean stress in the gap. [ $\epsilon_r$  is the dielectric constant of the cylinder]. Discharge may therefore occur at a voltage approaching  $1/\epsilon_r$  times the breakdown voltage in the absence of the cylinder, and these discharges can precipitate a breakdown.

The three essential components of the surface flashover phenomena are

- (a) the 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 must be 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, but in most practical cases, moisture films can eliminate the designed creepage path.

#### 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.

### 2.2.4 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. 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

$$\text{Power dissipated/volume} = \xi^2 / \rho \quad \text{W/m}^3 \quad \text{where} \quad \begin{array}{l} \xi = \text{uniform direct stress} \quad \text{V/m} \\ \rho = \text{resistivity of insulation} \quad \Omega \text{ m} \end{array}$$

#### Uniform alternating stress

$$\begin{array}{l} \text{Power dissipated } P = V \cdot I \cos \phi \quad \text{where } V = \text{applied voltage} \quad \text{V} \\ = V \cdot VC\omega \tan \delta \quad \omega = \text{supply frequency} \quad \text{Hz} \end{array}$$

$$\begin{array}{l} \text{Capacitance } C = A \epsilon_r \epsilon_0 / d \quad C = \text{dielectric capacitance} \quad \text{F} \\ \delta = \text{loss angle} \quad \text{rad} \\ \epsilon = \text{dielectric constant} \end{array}$$

$$\text{Therefore } P = V^2 (A \epsilon_r \epsilon_0 / d) \omega \tan \delta \quad \xi = \text{alternating stress} \quad \text{V/m}$$

Re-arranging terms gives the result

$$P = (V/d)^2 \cdot \epsilon_r \epsilon_0 \cdot 2 \pi f \cdot \tan \delta \cdot A \cdot d$$

Since  $A \cdot d$  is the volume of the dielectric, and  $V/d$  is the uniform applied stress,

$$\begin{aligned} \text{Power dissipated/volume} &= \xi^2 \epsilon_r \epsilon_0 2 \pi f \tan \delta \quad \text{W/m}^3 \\ &= 2 \pi \times 8.854 \times 10^{-12} \xi^2 \epsilon_r f \tan \delta \quad \text{W/m}^3 \\ &= 5.563 \times 10^{-11} \xi^2 \epsilon_r f \tan \delta \times 10^{10} \quad \text{W/m}^3 \quad \text{if } \xi \text{ is in kV/cm} \end{aligned}$$

$$\text{Power dissipated/volume} = 0.556 \xi^2 f \epsilon_r \tan \delta \quad \text{W/m}^3 \quad \text{with } \xi \text{ in kV/cm}$$

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).

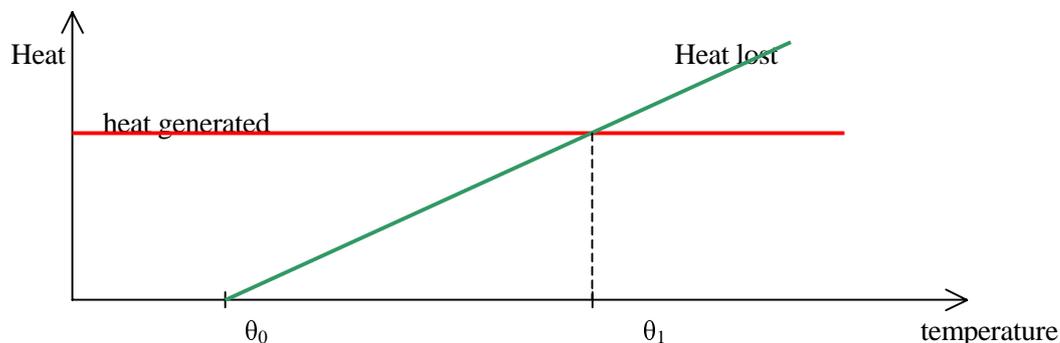


Figure 2.5 Thermal breakdown

$$\text{Heat lost} = k (\theta - \theta_0), \quad \text{where } \theta = \text{ambient temperature}$$

Equilibrium will be reached at a temperature  $\theta_1$  where the heat generated is equal to the heat lost to the surroundings, as shown in figure 2.5.

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 ( $\text{loss} \propto e^{-A/T}$ , where  $T$  is the absolute temperature).

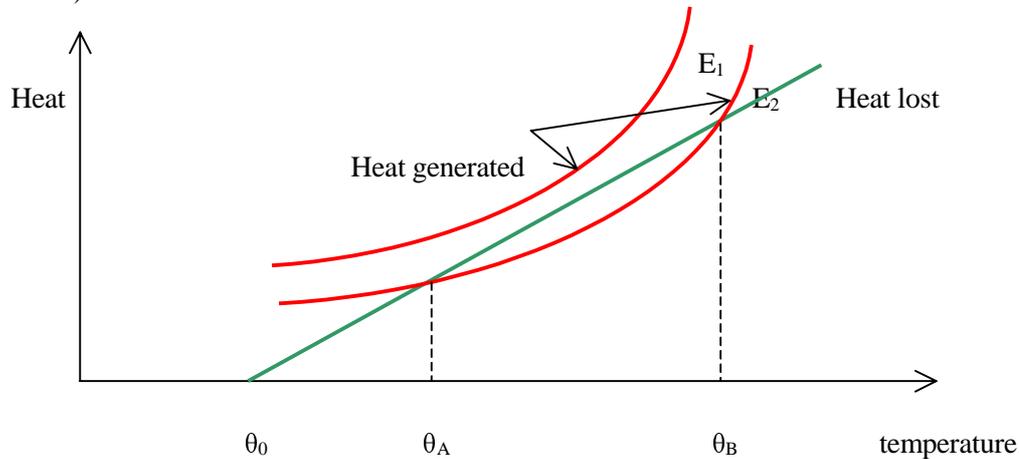


Figure 2.6 Thermal breakdown

Figure 2.6 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  $\theta_A$  exists (provided the temperature is not allowed to reach  $\theta_B$ ). 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 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  $V_\theta$ , 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,  $V_\theta$  is a limiting factor only for high-temperature operation, or at high frequency failures.

### 2.2.5 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 ionisations 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 insulation and the electrode metal may be attacked, gas may be evolved or substance may be deposited on the electrodes. The products of the electrode reaction may be chemically or electrically harmful and in some cases can lead to rapid failure of the insulation. 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  $1 \mu\text{F}$  paper capacitor operating at 1 kV at room temperature would require 2 to 3 years to generate  $1 \text{ cm}^3$  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. Also, contamination in polar insulating materials should be avoided with still greater care because of the greater degree of dissociation of ionic substance in solution.

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. Hydrogen ions discharged at the cathode readily react with the stabilizer rather than with the impregnant, a more difficult chemical process. In the absence of the stabilizer, the hydrogen reacts with the chlorine of the impregnant to produce hydrochloric acid, and rapid deterioration occurs due to attack of the acid on the electrodes and cellulose. 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.

### 2.2.6 Chemical Deterioration

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  $\theta$ .

$$\log_{10} t = A/\theta + B \quad \text{where A \& B are constants}$$

If  $t$  is expressed in weeks, for vacuum dried paper immersed in oil in contact with Nitrogen, the constants have values  $A = 7000$  and  $B = -16.0$ .

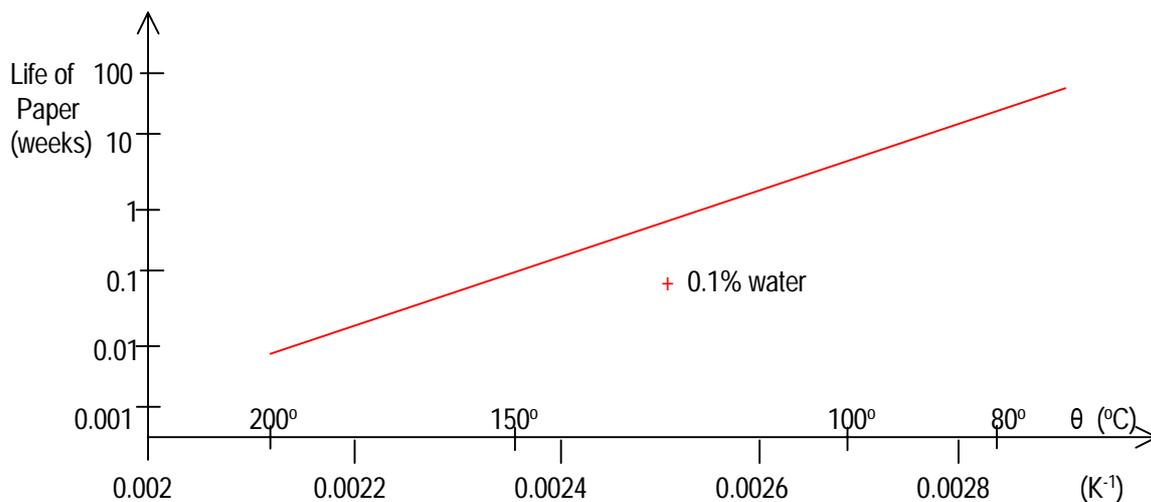


Figure 2.7 - Dependence of life of paper on temperature

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. Figure 2.7 shows the variation.

### **Oxidation**

In the presence of air or oxygen, especially ozone, materials such as rubber and polyethylene undergo oxidation giving rise to surface cracks, particularly if stretched and exposed to light. Polythene also oxidises in strong day light unless protected by an opaque filler.

### **Hydrolysis**

When moisture or water vapour is present on the surface of a solid dielectric, hydrolysis occurs and the materials lose their electrical and mechanical properties. Electrical properties of materials such as paper, cotton tape, and other cellulose materials deteriorate very rapidly due to hydrolysis. Polyethylene film may lose its mechanical strength in a few days if kept at 100 % relative humidity.

### **Other processes**

Progressive chemical degradation of insulating materials can also occur due to a variety of processes such as, incompatibility of materials (ex: rubber ages more rapidly at elevated temperatures in the presence of copper, and cellulose degrades much more rapidly in the presence of traces of acidic substances), and leaching (washing out of a soluble constituent) of chemically active substances (ex: glass fabrics made from glasses of high sodium content lose their strength rapidly due to leaching of sodium to the surface of the fibres and the subsequent chemical attack of the strong alkali on the glass surface).

## **2.3 Breakdown of Composite Insulation**

Almost no complete electrical insulation consists of one insulating phase. Usually more than one insulating material will be involved, either in series, parallel or both.

The simplest form of composite insulation system consists of 2 layers of the same material. In this case advantage is taken of the fact that two thin sheets have a higher electric strength than a single sheet of the same total thickness.

In other cases, composite dielectrics occur either due to design considerations (ex: paper with an impregnating liquid) or due to practical difficulties of fabrication (ex: air in parallel with solid insulation).

In certain cases, the behaviour of the composite insulation could be predicted from the behaviour of the components. But in most cases, the system as whole has to be considered. The following considerations determine the performance of the system as a whole.

- (i) The stress distribution at different parts of the insulation system is distorted due to the component dielectric constants and conductivities,
- (ii) the breakdown characteristics at the surface are affected by the insulation boundaries of various components,
- (iii) the internal or partial discharge products of one component invariably affect the other components in the system, and
- (iv) the chemical ageing products of one component also affect the performance of other components in the system.

### 2.3.1 Matching dielectric constants

When composite insulation has components with different dielectric constants, utilisation of the materials may be impaired. This is especially true in the oil/transformerboard dielectric. This is because the oil has a lower dielectric constant and lower dielectric strength compared to that of transformerboard.

Since the dielectrics are in series,

$$\frac{V_1}{V_2} = \frac{C_2}{C_1} = \frac{A \epsilon_2}{d_2} \cdot \frac{d_1}{A \epsilon_1} = \frac{\epsilon_2 d_1}{\epsilon_1 d_2}$$

$$V = V_1 + V_2$$

$$\frac{V_1}{V} = \frac{V_1}{V_1 + V_2} = \frac{\epsilon_2 d_1}{\epsilon_1 d_2 + \epsilon_2 d_1}$$

$$\xi_1 = \frac{V_1}{d_1} = \frac{\epsilon_2}{\epsilon_1 d_2 + \epsilon_2 d_1} \cdot V$$

$$\xi_2 = \frac{V_2}{d_2} = \frac{\epsilon_1}{\epsilon_1 d_2 + \epsilon_2 d_1} \cdot V$$

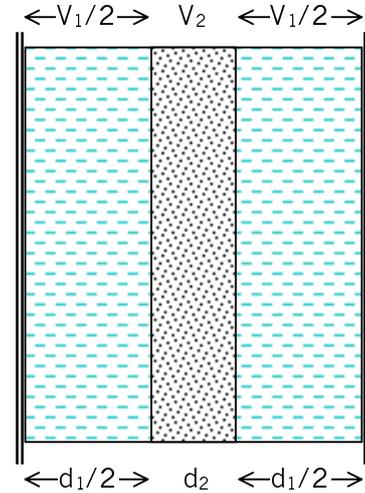


Figure 2.8 - Composite Dielectric

#### Example

A transformer oil having a dielectric constant of 2.2 and a dielectric strength of 25 kV/mm, is used as an insulation in a of spacing 8 mm. Determine the maximum applicable voltage. A barrier of thickness 3 mm of transformerboard with a higher dielectric strength of 50 kV/mm (dielectric constant 4.4) is used in this space to increase the strength. Does the transformerboard serve this purpose in this case ?

With only transformer oil, the maximum applicable voltage is given by

$$V = 25 \times 8 = 400 \text{ kV}$$

If a barrier of thickness 3 mm is placed in the space with the oil, the maximum applicable voltage is given by

$$50 = \frac{4.4}{2.2 \times 2 + 4.4 \times 6} \times V$$

$$V = \frac{50 \times 14}{2} = 350 \text{ kV}$$

It can be seen that the maximum applicable voltage in fact reduces below that of only oil.

It is thus important, when barriers have to be used, to match the permittivities of the component insulations. Thus great gains could be achieved if a transformerboard with a dielectric constant of 2.6 could be used instead of one with 4.4.