Chapter 6

Breakdown in solid and liquid dielectrics

6.1 Breakdown in solids

Solid insulation forms an integral part of high voltage structures. The solid materials provide the mechanical support for conducting parts and at the same time insulate the conductors from one another. Frequently practical insulation structures consist of combinations of solids with liquid and/or gaseous media. Therefore, the knowledge of failure mechanisms of solid dielectrics under electric stress is of great importance.

In gases the transport of electricity is limited to positive and negative charge carriers, and the destruction of insulating properties involves a rapid growth of current through the formation of electron avalanches. The mechanism of electrical failure in gases is now understood reasonably clearly. This is not the case for solid insulation. Although numerous investigators have studied the breakdown of solids for nearly a century now, and a number of detailed theories have been put forward which aimed to explain quantitatively the breakdown processes in solids, the state of knowledge in this area is still very crude and inconclusive.

Electrical conduction studies in solids are obscured by the fact that the transport phenomena besides electronic and ionic carriers include also currents due to the slower polarization processes such as slow moving dipoles (orientation polarization) and interfacial polarization (see Chapter 7, Section 7.1). Electrical methods are unable to distinguish between the conduction currents and the currents due to polarization having a longer time constant than the duration of a particular experiment. At low stresses and normal temperatures conduction by free electrons and ions in solids is exceptional. Examples in which the conduction is believed to be of the simple electrolytic type at room temperature and above are glasses. In this case the conduction–temperature relation is found to be of the form

$$\sigma = A \exp \left[-\frac{u}{kT} \right]$$

where A and u are empirical constants. Ceramics also develop a significant conductivity at higher temperatures that may be electronic or ionic.

As the stress in solids is increased and approaches the breakdown stress, the current is found to increase exponentially, but does not vary so markedly with time for steady voltage.[1]* This increased current at high stresses is generally believed to result from the injection of carriers from an electrode or from electron multiplication in the bulk of the material or both. In addition, if impurities or structural defects are present they may cause local allowed energy levels (traps) in the forbidden band, and electrons may pass through the insulator by jumping from one trap to another (hopping effect).

From the electrodes the electrons are believed to be ejected by either the 'Schottky's emission effect' or the 'field emission effect' (tunnelling) discussed already in Chapter 5. Once injected into the material the electron multiplication is thought to be analogous to that in a gas discharge. Under certain strictly controlled experimental conditions the breakdown of solids may therefore be accomplished by a process similar to gas breakdown. Under normal industrial conditions, however, the same solid materials are found to exhibit a wide range of dielectric strength, depending upon the conditions of the environment and the method of testing. The measured breakdown voltage is influenced by a large number of external factors such as temperature, humidity, duration of test, whether a.c., d.c., or impulse voltage is applied, pressure applied to the electrodes, discharges in the ambient medium, discharges in cavities and many other factors. The fundamental mechanisms of breakdown in solids are understood much less clearly than those in gases; nevertheless, several distinct mechanisms have been identified and treated theoretically.[2−4]

In this section the presently accepted breakdown mechanisms will be discussed briefly in a qualitative manner. No conduction mechanism will be discussed here and the reader is referred to reference 6. Broadly speaking the mechanism of failure and the breakdown strength changes with the time of voltage application and for discussion purposes it is convenient to divide the time scale of voltage application into regions in which different mechanisms operate, as shown in Fig 6.1.
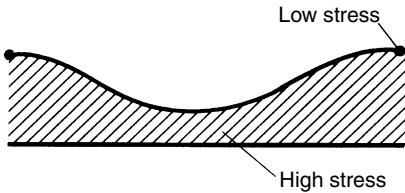
6.1.1 Intrinsic breakdown

If the material under test is pure and homogeneous, the temperature and environmental conditions are carefully controlled, and the sample is so stressed that there are no external discharges. With undervoltages applied for a short time the electric strength increases up to an upper limit which is called the intrinsic electric strength. The intrinsic strength is a property of the material and temperature only. Experimentally the intrinsic strength is rarely reached, but numerous attempts have been made to measure it for various materials. To achieve the highest strength the sample is so designed that there is a high

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* Superscript numbers are to references at the end of the chapter.
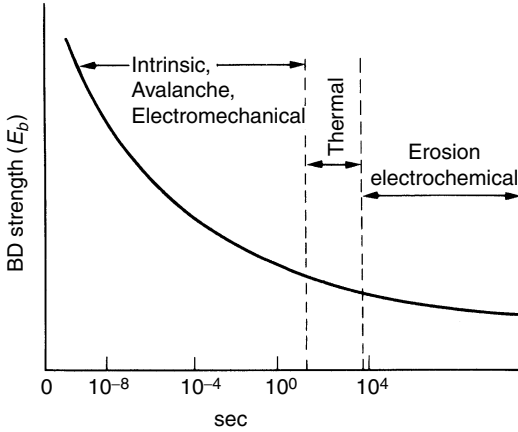
**Figure 6.1** *Mechanisms of failure and variation of breakdown strength in solids with time of stressing*

Figure 6.2 *Electrode arrangement used for measuring intrinsic breakdown in solids*

stress in the centre of the solid under test and too low stress at the edges which cause discharge in the medium as shown in Fig. 6.2.

The intrinsic breakdown is accomplished in times of the order of 10^{-8} sec and has therefore been postulated to be electronic in nature. The stresses required for an intrinsic breakdown are well in excess of 10^6 V/cm. The intrinsic strength is generally assumed to be reached when electrons in the insulator gain sufficient energy from the applied field to cross the forbidden energy gap from the valence to the conduction band. The criterion condition is formulated by solving an equation for the energy balance between the gain of energy by conduction electrons from the applied field and its loss to the lattice. Several models have been proposed in an attempt to predict the critical value of the field which causes intrinsic breakdown, but no completely satisfactory solution has yet been obtained. The models used by various workers differ from each other in the proposed mechanisms of energy transfer from conduction electrons to the lattice, and also by the assumptions made concerning the

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distribution of conduction electrons. In pure homogeneous dielectric materials the conduction and the valence bands are separated by a large energy gap, and at room temperature the electrons cannot acquire sufficient thermal energy to make transitions from valence to conduction band. The conductivity in perfect dielectrics should therefore be zero. In practice, however, all crystals contain some imperfections in their structures due to missing atoms, and more frequently due to the presence of foreign atoms (impurities). The impurity atoms may act as traps for free electrons in energy levels that lie just below the conduction band, as illustrated schematically in Fig. 6.3.
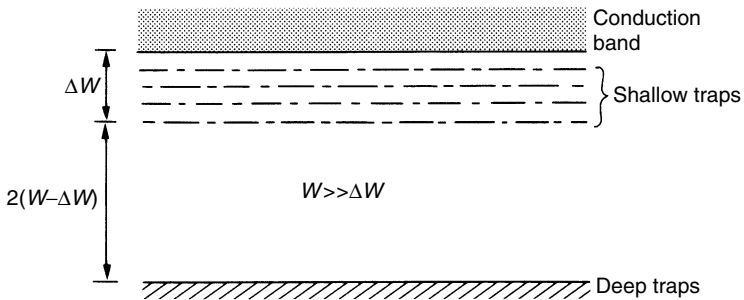
Figure 6.3 *Schematic energy level diagram for an amorphous dielectric*

At low temperatures the trap levels will be mostly filled with electrons caught there as the crystal was cooled down during its manufacture. At room temperature some of the trapped electrons will be excited thermally into the conduction band, because of the small energy gap between the trapping levels and the conduction level. An amorphous crystal will therefore have some free conduction electrons.

When a field is applied to a crystal the conduction electrons gain energy from it, and due to collisions between them the energy is shared by all electrons. For a stable condition this energy must be somehow dissipated. If there are relatively few electrons such as in pure crystals, most of the energy will be transferred to the lattice by electron–lattice interaction. In steady state conditions the electron temperature (T_e) will be nearly equal to the lattice temperature (T).

In amorphous dielectrics the electron interactions predominate, the field raises the energy of the electrons more rapidly than they can transfer it to the lattice, and the electron temperature T_e will exceed the lattice temperature T. The effect of the increased electron temperature will be a rise in the number of trapped electrons reaching the conduction band. This increases the material's conduction and as the electron temperature continues to increase a complete breakdown is eventually reached known as 'high-temperature breakdown'.

Neglecting for the moment the details of the mechanism of energy transfer and assuming electronic conduction in solids, for an applied field E the rate of energy gained by electrons from the field will be a function of the field strength E and the lattice temperature T. The rate at which this energy is transferred to the lattice will depend only on T. In addition, both rates will depend on parameters describing the conduction electrons. If we denote these parameters collectively by α, then for the steady state conditions the energy equation for conduction electrons may be written as

$$A(E, T, \alpha) = B(T, \alpha) \qquad (6.1)$$

where the l.h.s. represents the rate of energy gain by electrons from the field, and the r.h.s., the rate of energy transfer from electrons to lattice. Equation (6.1) can be physically satisfied for values of E below a certain critical value E_c, and this value has been considered by several workers as the intrinsic critical field. The value of E_c can be found by identifying correctly the parameters α describing the conduction electrons and then solving eqn (6.1) for the critical field strength E_c.

For a pure homogeneous dielectric Fröhlich developed the so-called 'high energy' breakdown criterion, based on the assumption that the dielectric is destroyed by an infinitely large multiplication of electrons in the conduction band. In this model the critical field strength (E_c) in the energy balance eqn (6.1) is obtained by first identifying the parameter α with the electron energy (W_e) such that the balance equation is satisfied and then calculating the critical field strength.

The functional relationship between the parameters in eqn (6.1) is shown schematically in Fig. 6.4, which shows the average rate of energy gain from the field for various field strengths and the rate of energy loss to the lattice.

For the critical field criterion, eqn (6.1) becomes

$$A(E_c, T, I) = B(T, I) \qquad (6.2)$$

where I is the ionization energy corresponding to the transition of an electron from a valence band to a conduction band. From Fig. 6.4 it is seen that for an electron to remain accelerated and thus lead to instability at any given field it should find itself with an energy which brings it above the curve B so that it gains energy more rapidly than it loses. Equation (6.2) enables us to determine the critical field strength E_c that is required to cause collision ionization from valence to conduction band. For field strength exceeding E_c the electrons gain energy more rapidly from the field than they lose to the lattice and breakdown will result. The above mechanism applies to pure solids in which the equilibrium is controlled by collisions between electrons and the lattice vibrations.

Fröhlich and Paranjape[5] have extended this model to amorphous materials in which the concentration of conduction (or trapped) electrons is high enough
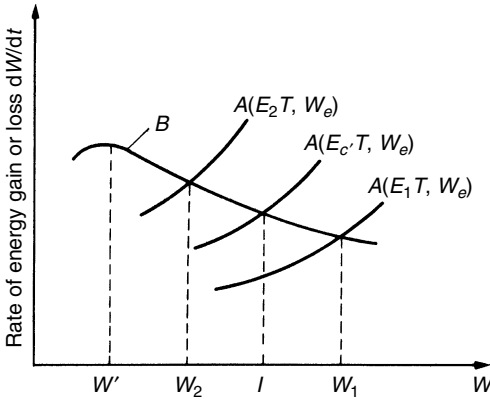
Figure 6.4 *The average rate of energy gain $A(E, T, W_e)$ from an applied field for various field strengths and the average rate of energy loss to lattice $B(W_L, T)$*

to make electron–electron collisions the dominant factor. In this case it is necessary to calculate the electron temperature T_e which will be higher than the lattice temperature T.

The energy balance eqn (6.1) will then take the form

$$A(E, T_e, T) = B(T_e, T). \tag{6.3}$$

This relationship is plotted schematically in Fig. 6.5 in which the family of curves plotted for various values of E represents the l.h.s. of the equation and
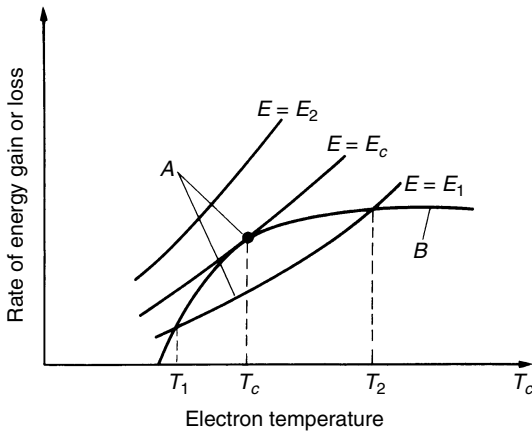
Figure 6.5 *Rate of energy gain and loss for h.t. intrinsic breakdown model*

the single curve represents the r.h.s. The intersections give possible solutions for the various electron temperatures.

For the analytical expressions for the critical field strength (E_c) for both of the above two models the reader should refer to reference 6.

To date there has been no direct experimental proof to show whether an observed breakdown is intrinsic or not, except for plastic materials such as polyethylene and so conceptually it remains an ideal mechanism identified as the highest value obtainable after all secondary effects have been eliminated.

6.1.2 Streamer breakdown

Under certain controlled conditions in strictly uniform fields with the electrodes embedded in the specimen, breakdown may be accomplished after the passage of a single avalanche. An electron entering the conduction band of the dielectric at the cathode will drift towards the anode under the influence of the field gaining energy between collisions and losing it on collisions. On occasions the free path may be long enough for the energy gain to exceed the lattice ionization energy and an additional electron is produced on collision. The process is repeated and may lead to the formation of an electron avalanche similar to gases. Seitz[7] suggested that breakdown will ensue if the avalanche exceeds a certain critical size and derived an expression for a single avalanche breakdown strength. The concept is similar to the streamer theory developed by Raether, and Meek and Loeb for gases discussed earlier.

6.1.3 Electromechanical breakdown

Substances which can deform appreciably without fracture may collapse when the electrostatic compression forces on the test specimen exceed its mechanical compressive strength. The compression forces arise from the electrostatic attraction between surface charges which appear when the voltage is applied. The pressure exerted when the field reaches about 10^6 V/cm may be several kN/m^2. Following Stark and Garton,[8] if d_0 is the initial thickness of a specimen of material of Young's modulus Y, which decreases to a thickness of d (m) under an applied voltage V, then the electrically developed compressive stress is in equilibrium with the mechanical compressive strength if

$$\varepsilon_0 \varepsilon_r \frac{V^2}{2d^2} = Y \ln\left(\frac{d_0}{d}\right) \tag{6.4}$$

or

$$V^2 = d^2 \frac{2Y}{\varepsilon_0 \varepsilon_r} \ln\left(\frac{d_0}{d}\right)$$

where ε_0 and ε_r are the permittivity of free space and the relative permittivity of the dielectric.

Differentiating with respect to d we find that expression (6.4) has a maximum when $d/d_0 = \exp[-1/2] = 0.6$. Therefore, no real value of V can produce a stable value of d/d_0 less than 0.6. If the intrinsic strength is not reached at this value, a further increase in V makes the thickness unstable and the specimen collapses. The highest apparent strength is then given by

$$E_a = \frac{V}{d_0} = 0.6 \left[\frac{Y}{\varepsilon_0 \varepsilon_r} \right]^{1/2} \tag{6.5}$$

This treatment ignores the possibility of instability occurring in the lower average field because of stress concentration at irregularities, the dependence of Y on time and stress, and also on plastic flow.

6.1.4 Edge breakdown and treeing

In practical insulation systems, the solid material is stressed in conjunction with one or more other materials. If one of the materials is, for example, a gas or a liquid, then the measured breakdown voltage will be influenced more by the weak medium than by the solid.

A cross-section of a simplified example is shown in Fig. 6.6 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
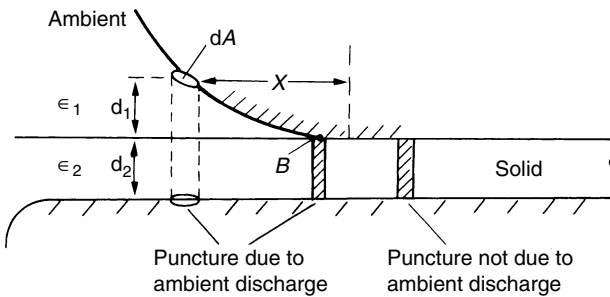
Figure 6.6 *Breakdown of solid specimen due to ambient discharge-edge effect*

elementary cylindrical volume of end area dA spanning the electrodes at distance x as shown in Fig. 6.5, then on applying the voltage V between the electrodes, according to Section 4.3.1 a fraction V_1 of the voltage appears

across the ambient given by

$$V_1 = \frac{Vd_1}{d_1 + \left(\dfrac{\varepsilon_1}{\varepsilon_2}\right)d_2} \tag{6.6}$$

here d_1 and d_2 represent the thickness of the media 1 and 2 in Fig. 6.6 and ε_1 and ε_2 are their respective permittivities. For the simple case when a gaseous dielectric is in series with a solid dielectric stressed between two parallel plate electrodes, the stress in the gaseous part will exceed that of the solid by the ratio of permittivities or $E_1 = \varepsilon_r E_2$. For the case shown in Fig. 6.6, the stress in the gaseous part increases further as x is decreased, and reaches very high values as d_1 becomes very small (point B). Consequently the ambient breaks down at a relatively low applied voltage. The charge at the tip of the discharge will further disturb the applied local field and transform the arrangement to a highly non-uniform system. The charge concentration at the tip of a discharge channel has been estimated to be sufficient to give a local field of the order of 10 MV/cm, which is higher than the intrinsic breakdown field. A local breakdown at the tips of the discharge is likely, therefore, and complete breakdown is the result of many such breakdown channels formed in the solid and extending step by step through the whole thickness.

The breakdown event in solids in general is not accomplished through the formation of a single discharge channel, but assumes a tree-like structure as shown in Fig. 6.7 which can be readily demonstrated in a laboratory by applying an impulse voltage between point-plane electrodes with the point embedded in a transparent solid, e.g. plexiglass. The tree pattern shown in Fig. 6.7 was recorded by Cooper[9] with a $1/30 -$ μsec impulse voltage of the same amplitude. After application of each impulse the channels were observed with a microscope and new channels were recorded. Not every impulse will produce a channel. The time required for this type of breakdown under alternating voltage will vary from a few seconds to a few minutes.

The tree-like pattern discharge is not limited specifically to the edge effect but may be observed in other dielectric failure mechanisms in which non-uniform field stresses predominate.

6.1.5 Thermal breakdown

When an insulation is stressed, because of conduction currents and dielectric losses due to polarization, heat is continuously generated within the dielectric. In general, the conductivity (σ) increases with temperature, conditions of instability are reached when the rate of heating exceeds the rate of cooling and the specimen may undergo thermal breakdown. The situation is illustrated graphically in Fig. 6.8 in which the cooling of a specimen is represented by the straight line and the heating at various field strengths by curves of increasing
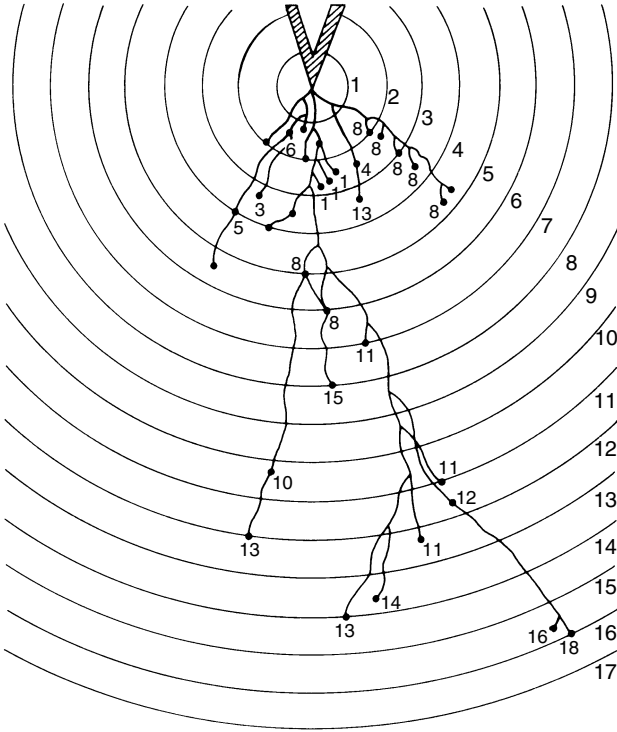
Figure 6.7 *Breakdown channels in plexiglass between point-plane electrodes. Radius of point = 0.01 in; thickness 0.19 in. Total number of impulses = 190. Number of channels produced = 16; (n) point indicates end of nth channel. Radii of circles increase in units of 10^{-2} in*
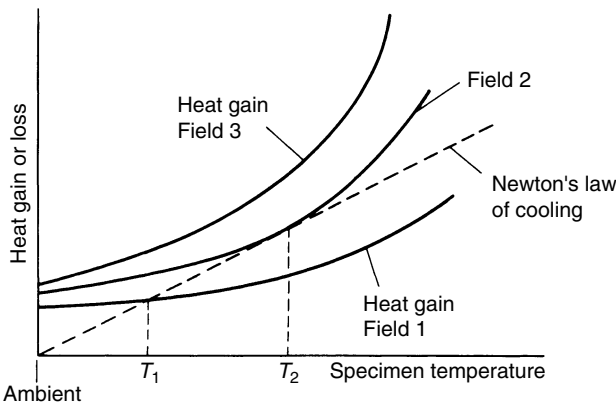

Figure 6.8 *Thermal stability or instability under different applied fields*

slope. Field (1) is in equilibrium at temperature T_1, field (2) is in a state of unstable equilibrium at T_2 and field (3) does not reach a state of equilibrium at all. To obtain the basic equation for thermal breakdown let us consider a cube of face area A (m^2) within dielectric. Assume that the heat flow in the x-direction is as shown in Fig. 6.9, then the

heat flow across face (1) $= KA\dfrac{\mathrm{d}T}{\mathrm{d}x}$ (K-thermal conductivity).

heat flow across face (2) $= KA\dfrac{\mathrm{d}T}{\mathrm{d}x} + KA\dfrac{\mathrm{d}}{\mathrm{d}x}\left(\dfrac{\mathrm{d}T}{\mathrm{d}x}\right)\Delta x.$
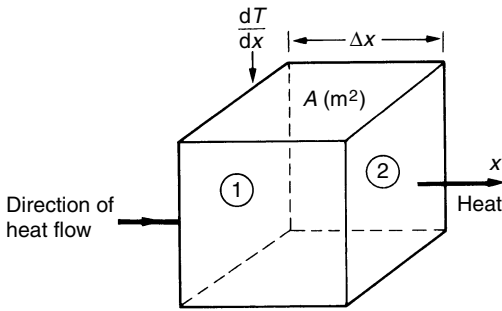
Figure 6.9 *Heat input and output, cubical specimen*

The second term represents the heat input into the block.
Hence

heat flow/volume $K\dfrac{\mathrm{d}}{\mathrm{d}x}\left(\dfrac{\mathrm{d}T}{\mathrm{d}x}\right) = \mathrm{div}\ (K\ \mathrm{grad}\ T).$

The conservation of energy requires that heat input into the element must be equal to the heat conducted away, plus the heat used to raise the temperature T of the solid or

heat generated $=$ heat absorbed $+$ heat lost to surroundings,

i.e.

$$C_v\frac{\mathrm{d}T}{\mathrm{d}t} + \mathrm{div}\ (K\ \mathrm{grad}\ T) = \sigma E^2 \tag{6.7}$$

where C_v is the thermal capacity of the dielectric, σ is the electrical conductivity and in the case of alternating voltage the heat is generated primarily as a result of dipole relaxation and the conductivity is replaced by $\omega\varepsilon_0\varepsilon_r''$ where ε_0 represents permittivity of free space and ε_r'' the imaginary component of the complex relative permittivity of the material.

Calculation of the critical thermal situation involves the solution of eqn (6.7). In solving it, one assumes that a critical condition arises and the insulation properties are lost, when at some point in the dielectric the temperature exceeds a critical temperature T_c. The solution gives the time required to reach T_c for a given field and boundary condition. The equation cannot be solved analytically for the general case since C_v, K and σ may be all functions of temperature (T) and σ may also depend upon the applied field. We consider two extreme cases for the solution of eqn (6.7).

Case 1. This assumes a rapid build-up of heat so that heat lost to surroundings can be neglected and all heat generated is used in raising the temperature of the solid. We obtain an expression for 'impulse thermal breakdown' and eqn (6.7) reduces to

$$C_v \frac{\mathrm{d}T}{\mathrm{d}t} = \sigma E^2.$$

To obtain the critical field E_c, assume that we apply a ramp function field. Then

$$E = \left(\frac{E_c}{t_c} \right) t$$

and

$$\sigma E^2 = C_v \frac{\mathrm{d}T}{\mathrm{d}E} \frac{\mathrm{d}E}{\mathrm{d}t}.$$

For the conductivity, we can assume

$$\sigma = \sigma_0 \exp \left[-\frac{u}{kT} \right].$$

σ_0 is here the conductivity at ambient temperature T_0. Substituting for σ and rearranging, we get

$$\int_0^{E_c} \frac{t_c}{E_c} \frac{\sigma_0}{C_v} E^2 \mathrm{d}E = \int_{T_0}^{T_c} \exp \left(\frac{u}{kT} \right) \mathrm{d}T.$$

For the case when

$$u \gg kT$$

and

$$T_c > T_0 \quad (T_c - \text{ critical temperature})$$

the solution of the r.h.s. is

$$\int_{T_0}^{T_c} \exp \left(\frac{u}{kT} \right) \mathrm{d}T \rightarrow T_0^2 \frac{k}{u} \exp \left(\frac{u}{kT_0} \right)$$

and that of the l.h.s. is

$$\int_0^{E_c} \frac{t_c}{E_c} \frac{\sigma_0}{C_v} E^2 dE \rightarrow \frac{1}{3} t_c \frac{\sigma_0}{C_v} E_c^2.$$

Therefore

$$E_c = \left[\frac{3C_v k T_0^2}{\sigma_0 u t_c}\right]^{0.5} \exp\left(\frac{u}{2kT_0}\right). \tag{6.8}$$

It is seen that reaching the critical condition requires a combination of critical time and critical field and that the critical field is independent of the critical temperature T_c due to the fast rise in temperature.

Case 2 concerns minimum thermal voltage, i.e. the lowest voltage for thermal breakdown. For this case we assume a thick dielectric slab that is constrained to ambient temperature at its surfaces by using sufficiently large electrodes as shown in Fig. 6.10.
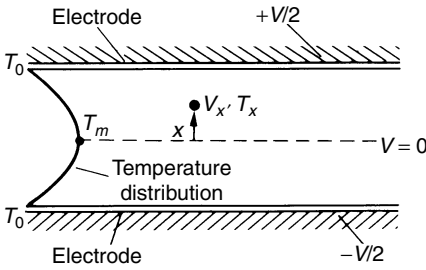

Figure 6.10 *Arrangement for testing a dielectric for minimum thermal breakdown voltage*

On application of voltage, after some time, a temperature distribution within the dielectric will be established with the highest temperature at the centre (T_1), that at the surface remaining at ambient temperature. On increasing the voltage to a new higher value, an equilibrium will be established at a higher central temperature (T_2). If the process is continued, a thermal runaway will eventually result as shown in Fig. 6.11.

To calculate the minimum thermal voltage, let us consider a point inside the dielectric distance x from the centre, and let the voltage and temperature at that point be V_x and T_x respectively. For this case we assume that all the heat generated in the dielectric will be carried away to its surroundings through the electrodes. Neglecting the term $C_v(dT/dt)$, eqn (6.6) becomes

$$\sigma E^2 = \frac{d}{dx}\left(K\frac{dT}{dx}\right).$$
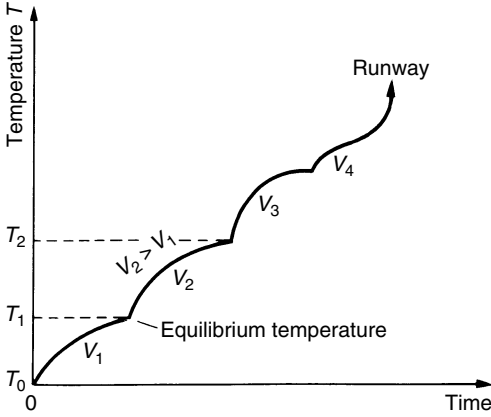
Figure 6.11 *Temperature–time relationship for slow thermal stressing under various applied voltages*

Using the relations of $\sigma E = j$ and $E = \partial V/\partial x$ (j-current density), and inserting in the above equation, we obtain

$$-j\frac{\partial V}{\partial x} = \frac{\mathrm{d}}{\mathrm{d}x}\left(K\frac{\mathrm{d}T}{\mathrm{d}x}\right).$$

Integrating to an arbitrary point x in the dielectric

$$-j\int_0^{V_x}\mathrm{d}V = \int_0^x \frac{\mathrm{d}}{\mathrm{d}x}\left(K\frac{\mathrm{d}T}{\mathrm{d}x}\right)\mathrm{d}x$$

$$-jV_x = K\frac{\mathrm{d}T}{\mathrm{d}x}$$

or

$$V_x\sigma\frac{\mathrm{d}V}{\mathrm{d}x} = K\frac{\mathrm{d}T}{\mathrm{d}x}.$$

Substituting for $\sigma = \sigma_0\exp[-u/kT]$, and integrating from the centre of the dielectric to the electrode,

$$\int_0^{V_c/2} V_x\mathrm{d}V = \frac{K}{\sigma_0}\int_{T_0}^{T_c}\exp\left[\frac{u}{kT}\right]\mathrm{d}T$$

$$V_c^2 = 8\frac{K}{\sigma_0}\int_{T_0}^{T_c}\exp\left[\frac{u}{kT}\right]\mathrm{d}T \tag{6.9}$$

Equation (6.9) gives the critical thermal breakdown voltage, where T_c is the critical temperature at which the material decomposes and the calculation

assumes that T_c corresponds to the centre of the slab. The voltage is independent of the thickness of the specimen, but for thin specimens the thermal breakdown voltage becomes thickness dependent and is proportional to the square root of the thickness tending asymptotically to a constant value for thick specimens. Under alternating fields the losses are much greater than under direct fields. Consequently the thermal breakdown strength is generally lower for alternating fields, and it decreases with increasing the frequency of the supply voltage. Table 6.1 shows thermal breakdown values for some typical dielectrics under alternating and direct voltages at 20°C. These results correspond to a thick slab of material.

The thermal breakdown is a well-established mechanism, therefore the magnitude of the product $\varepsilon \tan \delta$ which represents the loss is a very essential parameter for the application of insulation material.

Table 6.1 *Thermal breakdown voltages for some typical dielectrics* (20°C)

| *Material*		*Thermal voltage in MV/cm*	
		d.c.	*a.c.*
Crystals:	Mica muscovite	24	7–18
Rock salts		38	1.4
Quartz:	Perpendicular to axis	12 000	–
	Parallel to axis	66	–
	Impure	–	2.2
Ceramics:	H.V. steatite	–	9.8
	L.F. steatite	–	1.5
	High-grade porcelain	–	2.8
Organic materials:	Capacitor paper	–	3.4–4
	Ebonite	–	1.45–2.75
	Polythene	–	3.5
	Polystyrene	–	5
	Polystyrene at 1 MHz	–	0.05
	Acrylic resins		0.3–1.0

6.1.6 Erosion breakdown

Practical insulation systems often contain cavities or voids within the dielectric material or on boundaries between the solid and the electrodes. These cavities

are usually filled with a medium (gas or liquid) of lower breakdown strength than the solid. Moreover, the permittivity of the filling medium is frequently lower than that of the solid insulation, which causes the field intensity in the cavity to be higher than in the dielectric. Accordingly, under normal working stress of the insulation system the voltage across the cavity may exceed the breakdown value and may initiate breakdown in the void.

Figure 6.12 shows a cross-section of a dielectric of thickness d containing a cavity in the form of a disc of thickness t, together with an analogue circuit. In the analogue circuit the capacitance C_c corresponds to the cavity, C_b corresponds to the capacitance of the dielectric which is in series with C_c, and C_a is the capacitance of the rest of the dielectric. For $t \ll d$, which is usually the case, and assuming that the cavity is filled with gas, the field strength across C_c is given by the expression

$$E_c = \varepsilon_r E_a$$

where ε_r is the relative permittivity of the dielectric.
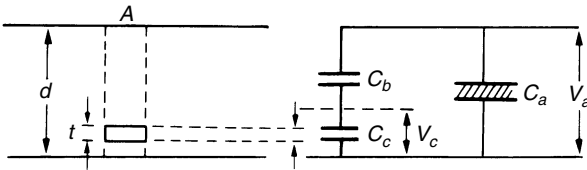
Figure 6.12   *Electrical discharge in cavity and its equivalent circuit*

For the simple case of a disc-shaped dielectric in solid shown in Fig. 6.12, the discharge inception voltage applied across the dielectric can be expressed in terms of the cavity breakdown stress. Assuming that the gas-filled cavity breakdown stress is E_{cb}, then treating the cavity as series capacitance with the healthy part of the dielectric we may write

$$C_b = \frac{\varepsilon_0 \varepsilon_r A}{d - t}$$

$$C_c = \frac{\varepsilon_0 A}{t}.$$

The voltage across the cavity is

$$V_c = \frac{C_b}{C_c + C_b} V_a = \frac{V_a}{1 + \dfrac{1}{\varepsilon_r}\left(\dfrac{d}{t} - 1\right)}.$$

Therefore the voltage across the dielectric which will initiate discharge in the cavity will be given by

$$V_{ai} = E_{cb}t \left\{ 1 + \frac{1}{\varepsilon_r} \left(\frac{d}{t} - 1 \right) \right\}. \tag{6.10}$$

In practice a cavity in a material is often nearly spherical, and for such a case the internal field strength is

$$E_c = \frac{3\varepsilon_r E}{\varepsilon_{rc} + 2\varepsilon_r} = \frac{3E}{2} \tag{6.11}$$

for $\varepsilon_r \gg \varepsilon_{rc}$, where E is in the average stress in the dielectric, under an applied voltage V_a when V_c reaches breakdown value V^+ of the gap t, the cavity may break down. The sequence of breakdowns under sinusoidal alternating voltage is illustrated in Fig. 6.13. The dotted curve shows qualitatively the voltage that would appear across the cavity if it did not break down. As V_c reaches the value V^+, a discharge takes place, the voltage V_c collapses and the gap extinguishes. The voltage across the cavity then starts increasing again until it reaches V^+, when a new discharge occurs. Thus several discharges may take place during the rising part of the applied voltage. Similarly, on decreasing the applied voltage the cavity discharges as the voltage across it reaches V^-. In this way groups of discharges originate from a single cavity and give rise to positive and negative current pulses on raising and decreasing the voltage respectively. For measurements of discharges refer to Chapter 7.
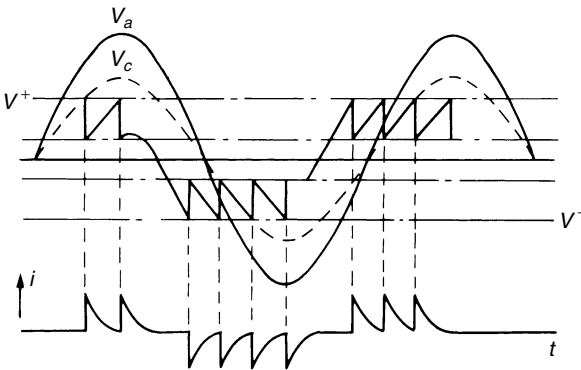
Figure 6.13 *Sequence of cavity breakdown under alternating voltages*

When the gas in the cavity breaks down, the surfaces of the insulation provide instantaneous cathode and anode. Some of the electrons impinging upon the anode are sufficiently energetic to break the chemical bonds of the insulation surface. Similarly, bombardment of the cathode by positive ions

may cause damage by increasing the surface temperature and produce local thermal instability. Also channels and pits are formed which elongate through the insulation by the 'edge mechanism'. Additional chemical degradation may result from active discharge products, e.g. O_3 or NO_2, formed in air which may cause deterioration. Whatever is the deterioration mechanism operating, the net effect is a slow erosion of the material and a consequent reduction of the breakdown strength of the solid insulation.

When the discharges occur on the insulation surface, the erosion takes place initially over a comparatively large area. The erosion roughens the surface and slowly penetrates the insulation and at some stage will again give rise to channel propagation and 'tree-like' growth through the insulation.

For practical application it is important that the dielectric strength of a system does not deteriorate significantly over a long period of time (years). In practice, however, because of imperfect manufacture and sometimes poor design, the dielectric strength (e.g. in cables) decreases with the time of voltage application (or the life) and in many cases the decrease in dielectric strength (E_b) with time (t) follows the empirical relationship

$$tE_b^n = \text{const} \tag{6.12}$$

where the exponent 'n' depends upon the dielectric material, the ambient conditions, and the quality of manufacture. Figure 6.14 illustrates the case for
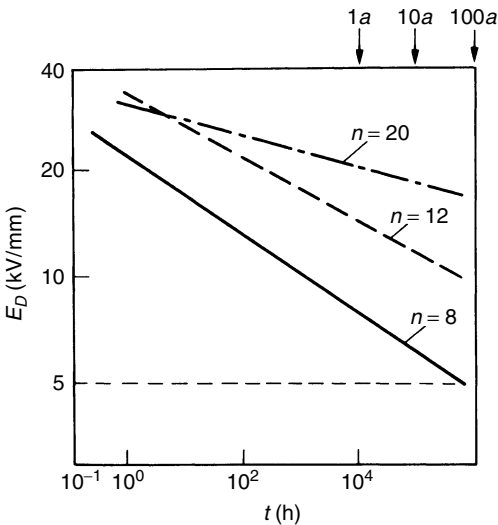
Figure 6.14 *Lifetime (t) stress relationship of polyethylene m.v. cables determined by different manufacturers*[10]

several m.v. polyethylene cables produced by different manufacturers. The breakdown strength has been plotted against time on a log–log scale.

In earlier years when electric power distribution systems used mainly paper-insulated lead-covered cables (PILC) on-site testing specifications called for tests under d.c. voltages. Typically the tests were carried out at 4 to 4.5 V_0. The tests helped to isolate defective cables without further damaging good cable insulation. With the widespread use of extruded insulation cables of higher dielectric strength, the test voltage levels were increased to $5-8\,V_0$. In the 1970s premature failures of extruded dielectric cables that were factory tested under d.c. voltage at specified levels were noted.[26] Hence on-site testing of cables under very low frequency (VLF), $\sim$0.1 Hz, has been adopted. The subject has recently been reviewed by Gnerlich[10] and will be further discussed in Chapter 8.

6.1.7 Tracking

Tracking is the formation of a permanent conducting path, usually carbon, across a surface of insulation and in most cases the conduction path results from degradation of the insulation. For tracking to occur the insulation must contain some organic substance.

In an outdoor environment insulation will in time become covered with contaminant which may be of industrial or coastal origin. In the presence of moisture the contamination layer gives rise to leakage current which heats the surface and causes interruption in the moisture film; small sparks are drawn between the separating moisture films. This process acts effectively as an extension to the electrodes. The heat resulting from the small sparks causes carbonization and volatilization of the insulation and leads to formation of permanent 'carbon track' on the surface. The phenomenon of tracking severely limits the use of organic insulation in the outdoor environment. The rate of tracking depends upon the structure of the polymers and it can be drastically slowed down by adding appropriate fillers to the polymer which inhibit carbonization.

Moisture is not essential to tracking. The conducting path may arise from metallic dust; for example, in oil-immersed equipment with moving parts which gradually wear and deposit on the surface.

6.2 Breakdown in liquids

The general state of knowledge on the electrical breakdown in liquids is less advanced than is in case of gases or even solids. Many aspects of liquid breakdown have been investigated over the last decades, but the findings and conclusions of the many workers cannot be reconciled and so produce

a general theory applicable to liquids, as the independent data are at variance and sometimes contradictory. The principal reason for this situation is the lack of comprehensive theory concerning the physical basis of the liquid state which would form the skeleton structure in which observations could be compared and related.

Comprehensive reviews of the published data on the subject have been made periodically and the more recent ones include the reviews of Lewis,[11] Sharbaugh and Watson,[12] Swann,[13] Kok,[14] Krasucki,[15] Zaky and Hawley,[16] and Gallagher.[17] The work falls broadly into two schools of thought. On the one hand there are those who attempt to explain the breakdown of liquids on a model which is an extension of gaseous breakdown, based on the avalanche ionization of the atoms caused by electron collision in the applied field. The electrons are assumed to be ejected from the cathode into the liquid by either a field emission, in which case they are assumed to tunnel out through the surface aided by the field, or by the field enhanced thermionic (Schottky's) effect. This type of breakdown mechanism has been considered to apply to homogeneous liquids of extreme purity, and does not apply to commercially exploited liquid insulation. Conduction studies in highly pure liquids showed that at low fields the conduction is largely ionic due to dissociation of impurities and increases linearly with the field strength. This conduction saturates at intermediate fields. At high field, as we approach breakdown, the conduction increases more rapidly and tends to be unstable. It is believed that this increased current results from electron emission at the cathode by one or both of the above mechanisms, and possibly by field aided dissociation of molecules in the liquid.

It has long been recognized that the presence of foreign particles in liquid insulation has a profound effect on the breakdown strength of liquids. In one approach it has been postulated[14] that the suspended particles are polarizable and are of higher permittivity than the liquid. As a result they experience an electrical force directed towards the place of maximum stress. With uniform field electrodes the movement of particles is presumed to be initiated by surface irregularities on the electrodes, which give rise to local field gradients. The accumulation of particles continues and tends to form a bridge across the gap which leads to initiation of breakdown.

The impurities can also be gaseous bubbles of lower breakdown strength than the liquid, in which case on breakdown of the bubble the total breakdown of the liquid may be triggered. A mathematical model for bubble breakdown has been proposed by Kao.[18]

6.2.1 Electronic breakdown

Both the field emission and the field-enhanced thermionic emission mechanisms discussed earlier have been considered responsible for the current

at the cathode. Conduction studies in insulating liquids at high fields show
that most experimental data for current fit well the Schottky-type equation
(eqn (5.81)$^{(19-\text{Chapter 5})}$) in which the current is temperature dependent. Break-
down measurements carried out over a wide range of temperatures, however,
show little temperature dependence. This suggests that the cathode process is
field emission rather than thermionic emission. It is possible that the return of
positive ions and particularly positively charged foreign particles to the cathode
will cause local field enhancement and give rise to local electron emission.

Once the electron is injected into the liquid it gains energy from the applied
field. In the electronic theory of breakdown it is assumed that some electrons
gain more energy from the field than they lose in collisions with molecules.
These electrons are accelerated until they gain sufficient energy to ionize
molecules on collisions and initiate avalanche.

The condition for the onset of electron avalanche is obtained by equating
the gain in energy of an electron over its mean free path to that required for
ionization of the molecule.

$$eE\lambda = ch\nu \tag{6.13}$$

where E is the applied field, λ the electron mean free path, $h\nu$ the quantum
of energy lost in ionizing the molecule and c an arbitrary constant.

Typical strengths for several highly pure liquids are included in Table 6.2.

Table 6.2 *Electric strength of highly purified liquids*

Liquid	Strength (MV/cm)
Hexane	1.1–1.3
Benzene	1.1
Good oil	~1.0–4.0
Silicone	1.0–1.2
Oxygen	2.4
Nitrogen	1.6–1.88

The electronic theory satisfactorily predicts the relative magnitude of break-
down strength of liquids, but the observed formative time lags are much longer
than predicted by electronic theory.[18]

6.2.2 Suspended solid particle mechanism

Solid impurities may be present in the liquid either as fibres or as dispersed
solid particles. Let us consider a spherical particle of radius r and permittivity

ε to be suspended in dielectric liquid of permittivity $\varepsilon_{\text{liq.}}$. Then in a field the particle will become polarized and it will experience a force given by

$$F_e = \varepsilon_{\text{liq.}} r^3 \frac{\varepsilon - \varepsilon_{\text{liq.}}}{\varepsilon + 2\varepsilon_{\text{liq.}}} E \text{ grad } E. \tag{6.14}$$

This force is directed towards a place of maximum stress if $\varepsilon > \varepsilon_{\text{liq.}}$ but for bubbles $\varepsilon < \varepsilon_{\text{liq.}}$, it has the opposite direction. The force given by eqn (6.14) increases as the permittivity of the suspended particle (ε) increases, and for a conducting particle for which $\varepsilon \to \infty$ the force becomes

$$F_e = F_\infty = r^3 E \text{ grad } E. \tag{6.15}$$

Thus the force will urge the particle to move to the strongest region of the field.

In a uniform field gap or sphere gap of small spacing the strongest field is in the uniform region.

In this region grad E is equal to zero so that the particle will remain in equilibrium there. Accordingly, particles will be dragged into the uniform field region. If the permittivity of the particle is higher than that of the medium, then its presence in the uniform field region will cause flux concentration at its surface. Other particles will be attracted into the region of higher flux concentration and in time will become aligned head to tail to form a bridge across the gap. The field in the liquid between the particles will be enhanced, and if it reaches critical value breakdown will follow.

The movement of particles by electrical force is opposed by viscous drag, and since the particles are moving into the region of high stress, diffusion must also be taken into account. For a particle of radius r slowly moving with a velocity v in a medium of viscosity η, the drag force is given by Stokes relation

$$F_{\text{drag}} = 6\pi r \eta v(x) \tag{6.16}$$

Equating the electrical force with the drag force ($F_e = F_{\text{drag}}$) we obtain

$$v_E = \frac{r^2 E}{6\pi\eta} \frac{\mathrm{d}E}{\mathrm{d}x} \tag{6.17}$$

where v_E is the velocity of the particle towards the region of maximum stress. If the diffusion process is included, the drift velocity due to diffusion will be given by the equation

$$v_{\text{d}} = -\frac{D}{N} \frac{\mathrm{d}N}{\mathrm{d}x} = -\left(\frac{kT}{6\pi r\eta}\right) \frac{\mathrm{d}N}{N\mathrm{d}x}. \tag{6.18}$$

The relation on the r.h.s. of the equation follows from the Stokes–Einstein relation $D = kT/67\pi r\eta$, where k is Boltzmann's constant and T is the absolute

temperature. Equating v_E with v_d gives

$$\frac{r^2}{6\pi r \eta} E \frac{dE}{dx} = -\left(\frac{kT}{6\pi r \eta r N}\right) \frac{dN}{dx}. \tag{6.19}$$

This introduces breakdown strength dependence in time on concentration of particles N, their radii and the liquid viscosity. The critical value of transverse field $E(x)$, the equilibrium value above which breakdown will occur sooner or later, can be obtained from integration of eqn (6.19).

$$\left[\frac{r^2 E^2}{2}\right]_{E=E_{(\infty)}}^{E=E_{(x)}} = \left[-\frac{kT}{r} \ln N\right]_{N=N_{(\infty)}}^{N=N_{(x)}}$$

$$\frac{N_{(x)}}{N_{(\infty)}} = \exp\left[r^3 \frac{\{E_{(x)}^2 - E_{(\infty)}^2\}}{2kT}\right]. \tag{6.20}$$

If the increase in the electrostatic energy when the particles drift towards a place of maximum stress is much smaller than their kinetic energy, i.e. $r^3 \{E_{(x)}^2 - E_{(\infty)}^2\} \ll 2kT$, the life of the insulation is infinite. The criterion for breakdown resulting from movement of particles towards the high stress region corresponds to the condition

$$r^3 \left[E_{(x)}^2 - E_{(\infty)}^2\right] = 2kT. \tag{6.21}$$

If we consider the case where the initial non-uniformity of field is caused by a hemispherical hump on the electrode, discussed earlier in Chapter 4, and assume that an applied field E_0 will lead to breakdown after a long time of application, then the maximum stress at the tip of the sphere is $3E_0$, or in general the maximum stress is gE_0, where g is a geometrical factor. Then eqn (6.21) can be written as

$$r^3[g^2 - 1]E_0^2 = \tfrac{1}{4}kT. \tag{6.22}$$

For $g = 3$ we obtain

$$r^3 E_0^2 = \tfrac{1}{4}kT. \tag{6.23}$$

A more complete theory gives a relation which takes into account the permittivities and is of the form

$$\frac{\varepsilon - \varepsilon_{\text{liq.}}}{\varepsilon + 2\varepsilon_{\text{liq.}}} r^2 E_0^2 = \frac{1}{4}kT.$$

Equation (6.23) gives a breakdown strength E_0 after a long time as a function of the size of the suspended impurities. This relationship has been checked experimentally and reasonable agreement has been obtained with calculations.
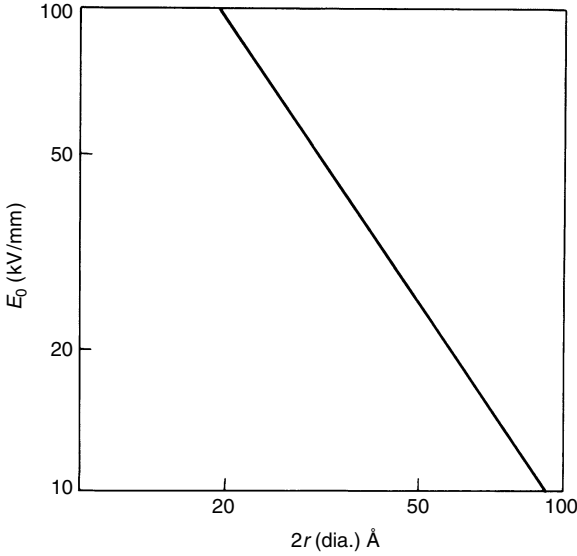
Figure 6.15 *Breakdown strength E_0 after a long duration of time as a function of the diameter $2r$ of foreign particles of high permittivity, with $T = 300\,K$*[18]

Figure 6.15 shows a plot of eqn (6.23) for a range of sizes up to 50 A in radius at temperature $T = 300\,K$, for the case where $\varepsilon_{liq.} \ll \varepsilon$.

6.2.3 Cavity breakdown

Insulating liquids may contain gaseous inclusions in the form of bubbles. The processes by which bubbles are formed include:

 (i) gas pockets on the electrode surface,
 (ii) changes in temperature and pressure,
(iii) dissociation of products by electron collisions giving rise to gaseous products,
(iv) liquid vaporization by corona-type discharges from points and irregularities on the electrodes.

The electric field in a spherical gas bubble[18] which is immersed in a liquid of permittivity $\varepsilon_{liq.}$ is given by:

$$E_b = \frac{3E_0}{\varepsilon_{liq.} + 2} \tag{6.24}$$

where E_0 is the field in the liquid in the absence of the bubble. When the field E_b becomes equal to the gaseous ionization field, discharge takes place which

will lead to decomposition of the liquid and breakdown may follow. Kao[18] has developed a more accurate expression for the 'bubble' breakdown field strength which is of the form

$$E_0 = \frac{1}{(\varepsilon_1 - \varepsilon_2)} \left\{ \frac{2\pi\sigma(2\varepsilon_1 + \varepsilon_2)}{r} \left[\frac{\pi}{4} \sqrt{\left(\frac{V_b}{2rE_0}\right) - 1} \right] \right\}^{1/2} \tag{6.25}$$

where σ is the surface tension of the liquid, ε_1 and ε_2 are the permittivities of the liquid and the bubble respectively, r is the initial radius of the bubble (initially spherical, which is assumed to elongate under the influence of the field), and V_b is the voltage drop in the bubble. This expression indicates that the critical electric field strength required for breakdown of liquid depends upon the initial size of the bubble which is affected by the external pressure and temperature. A strong dependence of liquid breakdown strength upon the applied hydrostatic pressure has been observed experimentally.[22]

Commercial insulating liquids cannot readily be subjected to highly elaborated purification treatment, and the breakdown strength will usually depend upon the nature of impurities present.

6.2.4 Electroconvection and electrohydrodynamic model of dielectric breakdown

The importance of electroconvection in insulating liquids subjected to high voltages was not appreciated until recently. Most of the work comes from Felici and his coworkers.[19,20,21,22] In highly purified dielectric liquids subjected to high voltage, electrical conduction results mainly from charge carriers injected into the liquid from the electrode surface. The resulting space charge gives rise to Coulomb's force, which under certain conditions causes hydrodynamic instability yielding convecting current. It follows that whenever conduction in a fluid is accompanied by a significant space charge formation, convection motion is very likely to occur. Lacroix *et al.*[19] have studied the conditions under which turbulent motion sets in. Using parallel plate electrodes and controlled injection current, they showed that the onset of instability is associated with a critical voltage. They observed that as the applied voltage is increased near the critical voltage the motion at first exhibits a structure of hexagonal cells. With a further increase in voltage the motion becomes turbulent. Thus the interaction between electric field and space charge gives rise to forces creating an eddy motion of the liquid. It has been shown that at voltages close to breakdown the speed of this motion approaches a value given by $\sqrt{\varepsilon/\rho}/E$ where ε is the permittivity of the liquid, ρ the specific mass and E the electric field strength. In liquids the ratio of this speed to ionic drift velocity (KE), K being the mobility, $M = \sqrt{\varepsilon/\rho}/K$, is always larger than unity and the ratio sometimes is very much larger than unity (see Table 6.3). M is considered to play a dominant role in the theory of electroconvection.

Thus, the charge transport will be largely by liquid motion and not by ionic drift. The key condition for the instability onset is that local flow velocity $u(=\sqrt{\varepsilon/\rho}/E)$ exceeds the ionic drift velocity ($u > KE$).

Table 6.3 $M = \sqrt{\varepsilon/\rho}/K$

Medium	Ion	Relative permittivity	M number
Methanol	H^+	33.5	4.1
Ethanol	Cl^-	25	26.5
Nitrobenzene	Cl^-	35.5	22
Propylene carbonate	Cl^-	69	51
Transformer oil	H^+	2.3	~ 200
Air N.T.P.	O_2^-	1.0	2.3×10^{-2}

The experimental values for M for various fluid media and common ions obtained by Lacroix et al.[19] are included in Table 6.3. The table also contains the value for air at NTP. It is seen that in this case $M \ll 1$ and the rate of electroconvection is negligible. Experiments show that electroconvection is prevalent in all experimental settings in dielectric liquids subjected to electric fields irrespective of the gap geometries, provided the applied voltage is high enough. This is true even in thoroughly deionized liquids because of the adequate supply of ions by the high field processes at the electrodes.

Cross et al.,[23] have studied electric stress-induced motion in transformer oil under d.c. and 60 Hz stresses. Using high-speed schlieren photography, they found that the turbulent motion was due to injection of positive charges from one electrode. This was confirmed for both d.c. and 60 Hz stresses. They also observed that the delay time in the onset of instability is related to the condition for the injection or creation of charges at the electrode surface. The time delay was found to decrease rapidly with increasing the field strength ranging from a few seconds at 10^6 V/m to a few milliseconds at 6×10^6 V/m. Also as the temperature of the liquid increased, the time delay for the given field decreased. Under 60 Hz voltage the time delay was found to reach a minimum value approximately 4 msec, which is to be expected. A 60 Hz wave requires 4.17 msec to reach the peak. From these observations and calculations Cross et al. concluded that under these conditions instability occurs when the injection strength, which is the ratio of the space charge field to the applied field, reaches a large enough value for a critical voltage to develop across the space charge layer within one half-cycle period. The lowest value of the critical voltage occurs where space charge limited conditions prevail at the injecting electrode.

6.3 Static electrification in power transformers

Static electrification (SE) in transformers is an interfacial phenomenon, which involves oil, paper and transformer board. Its physical mechanism involves a source of charge and region of excessive charge accumulation. Extensive investigations about this phenomena have been made during recent years.[25] When oil is forced through the tank and coolers, it acquires an electrostatic charge, i.e. it contains an equal number of positive and negative ions. When the oil passes the paper and solid insulation in the windings, the insulation becomes negatively charged and the oil positively charged with the charge separation occurring at the oil-insulated interface (Fig. 6.16). The earliest reports on this phenomenon were in the 1970s from Japan, where number
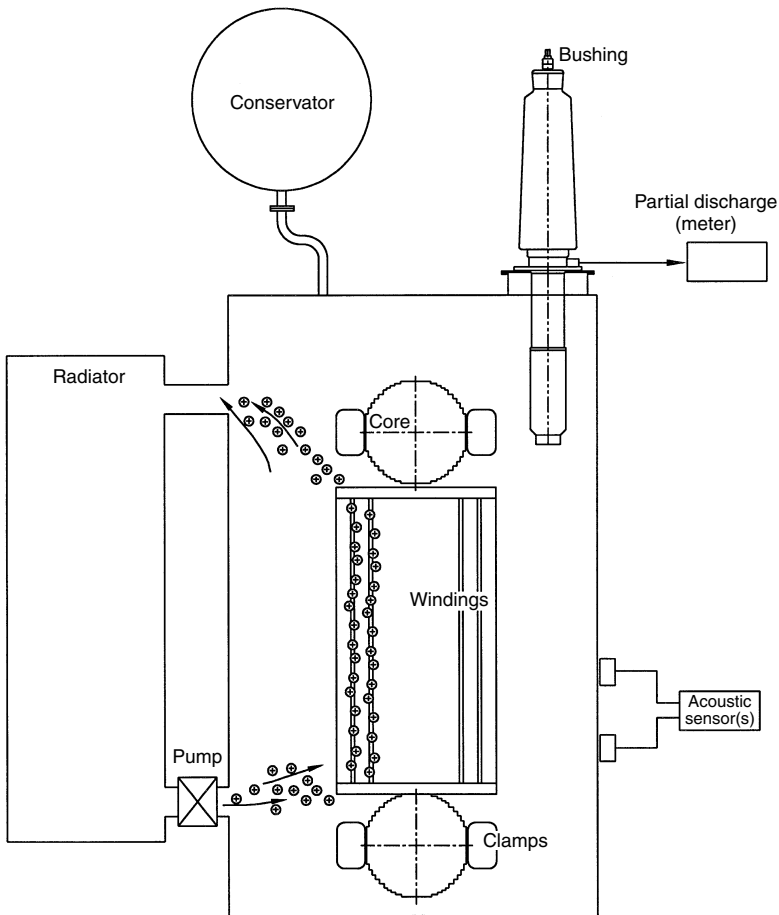
Figure 6.16 *Schematic of flow electrification density in transformers*

of h.v. large transformer failures occurred. And later quite a few SE-related incidents were also reported in the USA and other countries. It is believed that transformers of large rating (e.g. $>100\,\mathrm{MVA}$) are most likely affected by SE because they possess greater amounts of insulation and require larger oil flow volumes than transformers of smaller ratings. As different oils have different electrostatic charging tendencies (ECT), oil additives might be a way to reduce oil ECT. As an alternative to the additive, used oil can be regenerated because new oil exhibits a lower ECT than aged oil. On the other hand, operation practices are also of great importance. SE incidents can be caused by poor operating practices such as increasing forced oil cooling capacity beyond manufacturer's recommendations, or having more forced oil cooling in operation than the load on the transformer justifies.