discharges at a.c. or d.c. voltage. The choice of a suitable measure for the magnitude of discharges is considered. Deterioration is discussed, particular consideration being given to the effect of applied stress on the rate of deterioration.

Discharge detection is based on the phenomena which are caused by discharges such as light, heat, noise, chemical transformations, and electric impulses. Detection techniques and their relative merits as well as the sensitivity of different methods are considered in Chapter 2.

After discharges have been detected their magnitude must be estimated. In Chapter 3 methods for the measurement of discharges are described.

Different forms of discharge detection must be employed for the various types of high voltage equipment. The methods appropriate for testing cables, capacitors, transformers, bushings, coils of high voltage machines, etc., are discussed in Chapter 4. Consideration is given to the procedures to be followed during testing.

The location of a discharge may be of interest. Either the fault can be repaired or the cause can be established so that discharges may be prevented when manufacturing a new dielectric. Locating the site of discharges is discussed in Chapter 5 for different types of equipment. Such fault-locating techniques have been developed particularly for plastic cables.

In Chapter 6 consideration is given to the difficulties caused by disturbances. Furthermore, six different detectors as used in practice are considered in detail. The results of discharge detection in the form of oscillograms and recordograms are considered. The defects in insulation which may be found are described, as well as measures for preventing discharges. In the last section some estimations are made regarding the voltage life of dielectrics under the action of discharges.

As there has been considerable confusion regarding the terms used to describe discharges and discharge detecting techniques, the preferred terms have been grouped in a Table of Terminology. The various detection methods have been arranged according to their application in a Table of Survey of Discharge Detection.

CHAPTER 1

Behaviour of Discharges

1. PARTIAL DISCHARGES: CLASSIFICATION AND TERMINOLOGY

DEFINITION. Electric discharges which do not bridge electrodes are called partial discharges. Between the discharge and one or both electrodes a sound dielectric is present in the shape of a solid, liquid, or gaseous insulator. Examples of this type of discharge are discharges in a cavity in a solid dielectric (both electrodes are shielded from the discharges by the solid), discharges on a surface (at least one electrode is shielded by a solid dielectric), and discharges around a sharp point at high voltage (the discharge is shielded from one electrode by a column of non-ionized gas). Although the magnitude of such discharges is usually small they can cause progressive deterioration and ultimate failure, so that it is essential to detect their presence as a non-destructive control test.

Partial discharges belong to a far greater group of gas discharges. In all these discharges gas molecules are ionized by impact of electrons. The newly formed electrons gain speed in an electric field, ionizing more molecules by impact, so that an avalanche of electrons is formed. The electrons in the avalanche and the ions left behind move towards the electrodes, thereby forming a passage of current through the gas. For more details on gas discharges see Meek and Craggs [A4]†.

CLASSIFICATION. The term *ionization* is often used for partial or internal discharges. This is incorrect because the scope of this term is far broader according to its definition: a process by which an atom becomes electrically charged due to losing or gaining one or more of its extra nuclear electrons. Figure 1.1 shows the correlation between the various terms.

It is not always possible to classify a discharge as simply as in Figures 1.2–1.4. In Figure 1.5, for instance, an intermediate state between a

† See page 214 et seq. for Classified Bibliography.

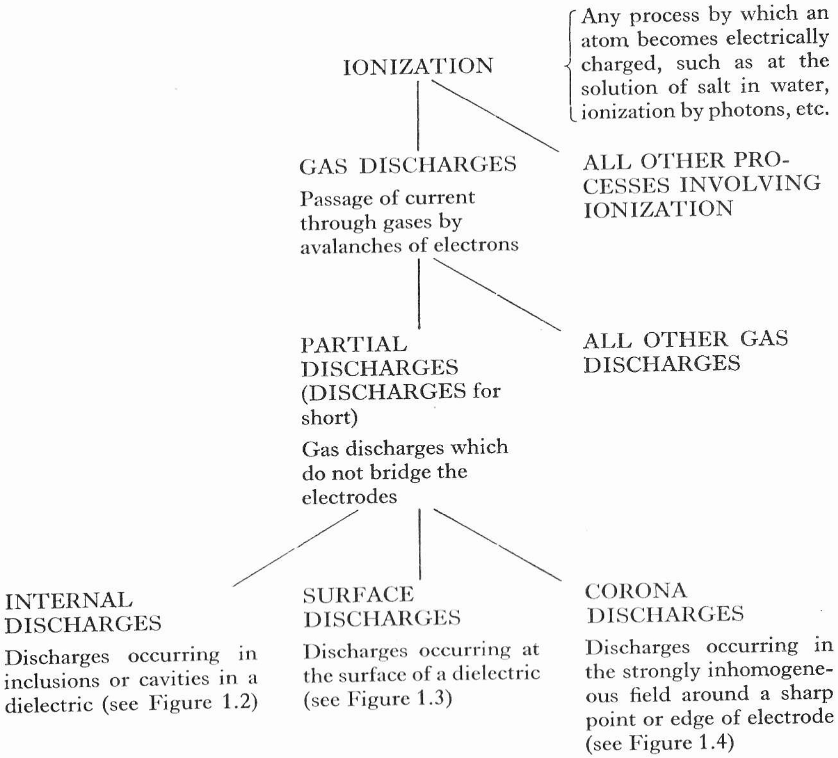


Figure 1.1

surface and internal discharge is shown. If the interspace becomes smaller and eventually is closed at the sides, the discharge becomes internal. In Figure 1.6 a combination of surface discharge and corona discharge is shown.

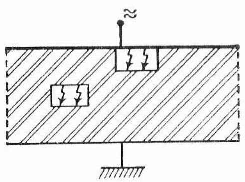


Figure 1.2

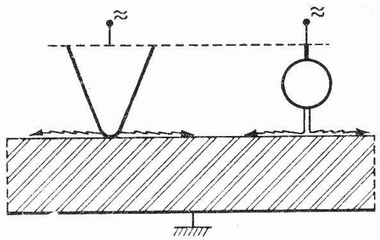


Figure 1.3

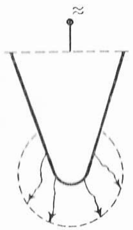


Figure 1.4

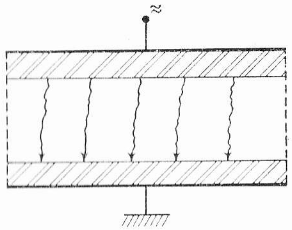


Figure 1.5

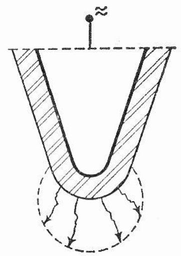


Figure 1.6

TERMINOLOGY. In English and American literature the term *ionization* is sometimes used for partial or internal discharges, as in French *ionisation gazeuse* and German *Ionisationsvorgänge*. This is incorrect as follows from Figure 1.1. Derived terms such as ionization point, ionization level, etc., are equally wrong. Another erroneously used term is *corona* when internal discharges are meant. In American literature the term *internal corona* and in German the word *Korona-entladung* are frequently used, even as derived terms such as *corona-detector*, *corona resistivity*, etc. In all these cases the words discharge, discharge-detector, discharge-resistivity, etc., are to be preferred. In the Table of Terminology at the end of this book these terms have been collected, together with various other terms which are connected with discharges and discharge detection.

2. INTERNAL DISCHARGES

2.1. Inception of internal discharges

Internal discharges in a dielectric occur in inclusions of low dielectric strength. The material in the inclusion breaks down at a stress which is low compared with the breakdown strength of the surrounding dielectric. Moreover, the dielectric constant of the material in the inclusion is often lower than that of the dielectric, so that the electric stress in the inclusion is higher than in the dielectric and the inclusion breaks down even earlier.

GAS-FILLED CAVITIES. A frequently occurring inclusion is the gas-filled cavity. It can occur in extruded plastics, cast resins, lapped resin-impregnated paper, etc. The stress in the dielectric at which the

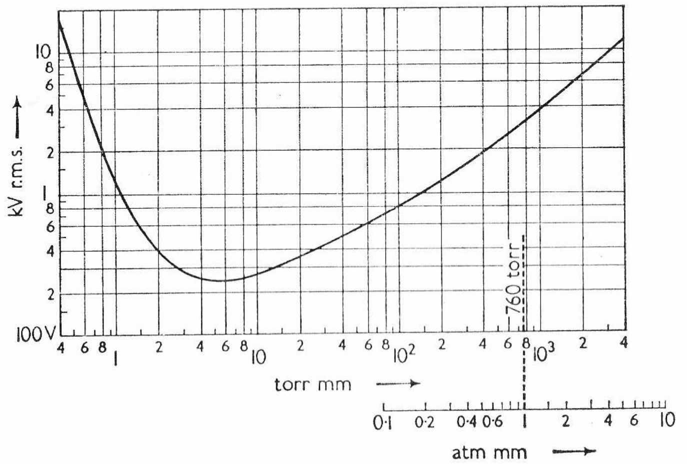


Figure 1.7. *Paschen's curve. Breakdown voltage of air as a function of pressure times electrode spacing*

discharges start depends on the stress in the cavity and the breakdown strength of the cavity. In some cases the stress in the cavity can be calculated. If a flat cavity is situated perpendicular to the electric field, the stress in the cavity is ϵ times the stress in the dielectric, where ϵ is the dielectric constant of the insulating material. If the cavity is spherical the stress in the cavity is $3\epsilon/(1+2\epsilon)$ times that in the dielectric, tending to 1·5 times if ϵ is large [C2]. If the cavity is long and parallel to the electric field the stress in the cavity tends to be equal to that in the dielectric.

The dielectric strength of the cavity depends on the kind of gas in the cavity, the gas pressure, and the dimensions of the cavity. According to

several investigators [B3, C1] the discharge in a cavity bounded by insulating material occurs at approximately the same voltage as between equally spaced metal electrodes. This voltage is given for a certain gas by the Paschen curve for this gas. The Paschen curve shows the breakdown voltage of a gap as a function of electrode spacing times gas density

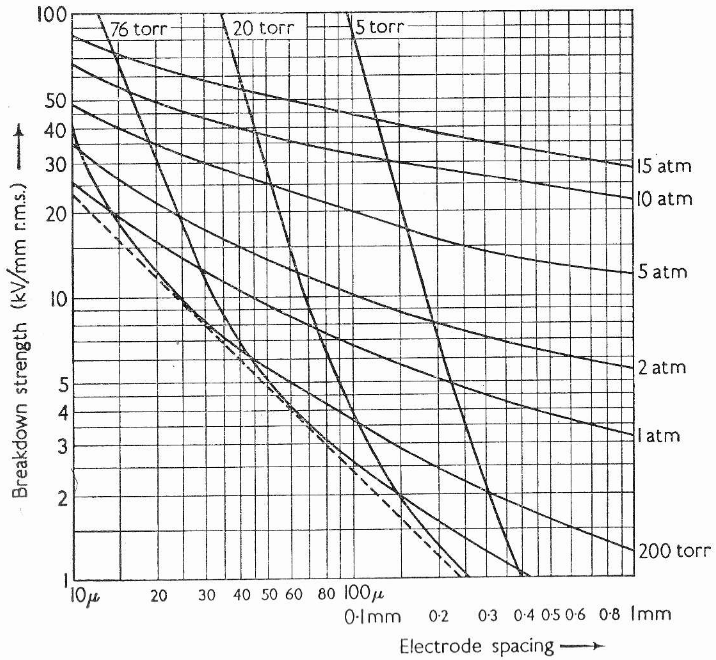


Figure 1.8. *The breakdown strength of air in kV/mm r.m.s. as a function of pressure and distance between opposite electrodes (derived from Paschen's curve)*

[A1, A13] (see Figure 1.7). The curve attains a minimum for a low value of the product distance times density. The Paschen curve may be modified so as to show the stress at which the gas breaks down. If the gas pressure is taken as a parameter and electrode spacing as a variable, a set of curves results [G2]. In Figure 1.8 such curves are shown for air. The minimum of the Paschen curve is indicated by a dotted line.

may be regarded as a step function. After the discharge has been extinguished the voltage over the cavity increases again. This voltage is determined by the superposition of the main electric field and the field of the surface charges at the cavity walls left behind after the last discharge. These fields counteract one another. When the voltage over the void reaches U^+ a new discharge occurs. This happens several times, after which the high voltage v_a over the sample decreases and the voltage v_c drops to U^- before a new discharge occurs. In this way groups of regularly recurrent discharges will be found.

The discharges in the cavity cause current impulses in the leads of the sample. These impulses are also shown in Figure 1.10. Note that these impulses are concentrated in the regions where the voltage applied to the sample increases or decreases most. Austen and Whitehead [B1] have shown that if the voltage drops in both half-cycles are equal (i.e. $\Delta V^+ = \Delta V^-$) the impulses will give a stationary picture on a 50 c/s time base on the oscilloscope screen of a discharge detector. If $\Delta V^+ \neq \Delta V^-$, the impulses precess around the time base. Austen and Whitehead actually built the analogue circuit of Figure 1.9 with capacitors and a thyratron. They obtained discharge patterns which were similar to that of Figure 1.10.

TERMINOLOGY. The a.c. voltage across the sample at which discharges start to occur when the voltage is increased is called the *inception voltage*, the corresponding stress in the surrounding dielectric the *inception stress*. If the voltage is decreased after discharges have been started the voltage at which the discharges extinguish is usually lower than the inception voltage. This voltage is called the *extinction voltage* and the corresponding stress *the extinction stress*. The breakdown strength of the cavity, U^+ or U^- in Figure 1.10, is sometimes called the *ignition voltage* of the cavity; this ignition voltage usually is given by the Paschen curve of the gas in the cavity. The residual voltage, V^+ or V^- in Figure 1.10, is sometimes called the *remanent voltage*.

DISCHARGES OCCURRING BELOW THE INCEPTION VOLTAGE. After a discharge has once started, discharges can persist at a voltage lower than the inception voltage, theoretically as low as half the inception voltage. This is shown in Figure 1.11, where it is assumed that the first discharge starts due to a short overvoltage at A. The voltage v_c over the cavity, originally smaller than the ignition voltage U^+ or U^-, reaches the ignition voltage each half-cycle owing to the surface charges which are

left after each previous discharge. The minimum voltage at which discharges can persist is, according to Figure 1.11,

$$2v_c' - V^+ = U^-$$

$$v_c' = \frac{U^-}{2} + \frac{V^+}{2}$$

and as V^+ is small compared with U^-,

$$v_c' \simeq \frac{U^-}{2} \qquad \ldots (1.1)$$

or the voltage across the sample can be almost one-half of the inception voltage. In practice the extinction voltage in solid insulation is from zero

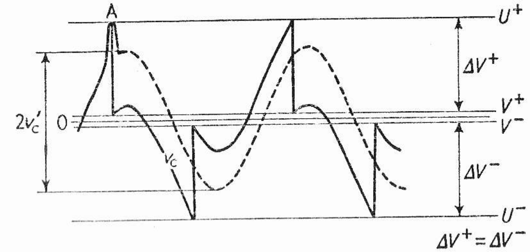


Figure 1.11. *Occurrence of discharges below the inception voltage*

to about 25 per cent lower than the inception voltage. In impregnated paper the extinction voltage is often much lower due to rapid formation of gas.

INTERMITTENT RECURRENCE. Intermittent discharges can arise in an asymmetrical cavity [A1] as is shown in Figure 1.12. The voltage over the cavity v_c reaches the breakdown voltage U^+ at point A, which results in a discharge. Due to the surface charge and the voltage v_c^- the void breaks down again at B. The next discharge occurs at C, earlier in the cycle than A. The voltage in the next half-cycle passes through its minimum without reaching the value U^-, so that no discharge can occur. The surface charge persists during many cycles and no more discharges occur until this charge has leaked away. Another sequence then starts and extinguishes again so that an intermittent discharge is observed. At a higher voltage, namely if v_c exceeds U^-, the discharges become constant.

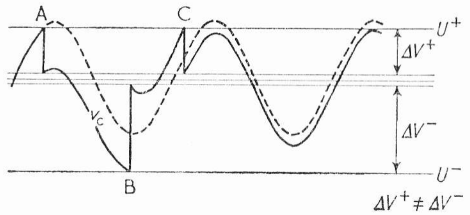


Figure 1.12. *Intermittent discharges in an asymmetrical cavity. The voltage drop ΔV^+ in the positive half-cycle is unequal to the voltage drop ΔV^- in the negative half-cycle*

Transverse leakage. In cavities exceeding a certain size discharges may occur at different sites in the cavity. This may cause tangential stresses along the surfaces of the cavity, and it is probable that a discharge site is partly recharged by neighbouring sites. According to Austen and Hackett [B2] the sequence of the discharges is affected by this transverse leakage of charge. The effect may be represented by the circuit of Figure 1.13. In Figure 1.14, which is taken from Drujon [D5], it is shown how discharges from different sites interact. The result is that small and large discharges succeed each other, in contrast to Figure 1.10, where all discharges have the same size.

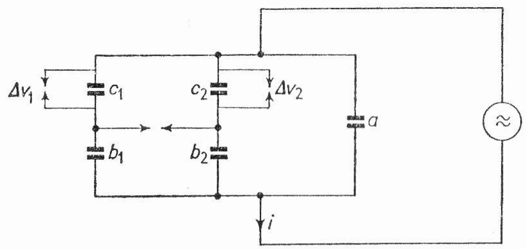


Figure 1.13. *Two adjacent discharge sites in one cavity*

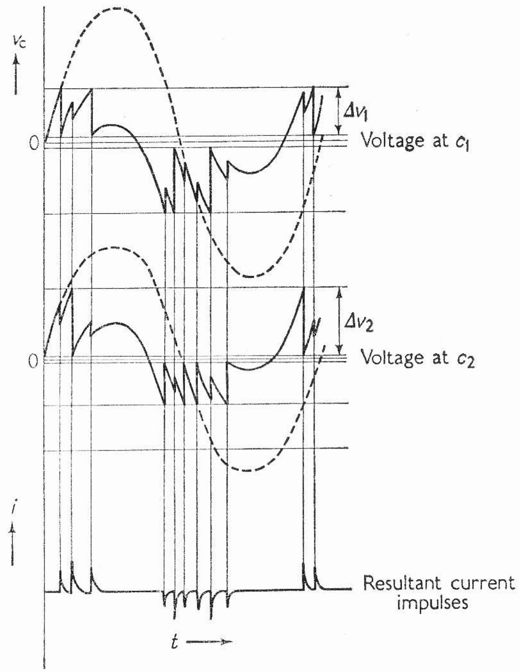


Figure 1.14. *Interaction of two discharges in a cavity by transverse leakage*

Irregular recurrence. The description of the phenomena by means of the analogue circuit of Figure 1.13 is still too simple. It is assumed that the cavity behaves like a capacitor with metallic electrodes, but in reality the situation is far more complicated. Friedlander and Reed [B6] and Mason [B4, B5] have shown that at the place where the discharge reaches the dielectric, Lichtenberg figures are formed (see Figure 1.15). When the discharge, which takes place in a relatively narrow channel, reaches the surface of the dielectric, a strong tangential field arises. This leads to discharges along the surface which leave surface charges behind. After the discharge has been extinguished a pattern of surface charges is left which neutralizes the main electric field completely at the discharge site and partially in the surroundings. These Lichtenberg figures have typical shapes, the positive being star-shaped with many branches, the negative being circular and diffuse. According to Thomas [B7], the residual surface charges can hardly move as they are trapped at the surface of the dielectric. Therefore, after several discharges of different polarity, positive surface charges can occur at places where no charges or negative surface charges are expected, and vice versa. This can lead to discharge patterns completely different from that in Figure 1.10 [B4, B5]. Different patterns may appear in the positive and negative half-

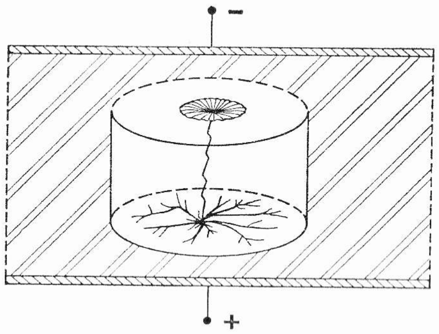


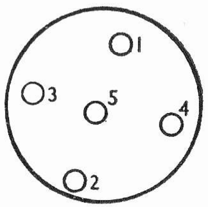
Figure 1.15. *Lichtenberg figures in a cavity*

cycles even if the void is symmetrical, the time between successive discharges can be different, and consecutive discharges may differ in size.

If several discharge sites are present in the cavity the first discharge takes place at an arbitrary site. The next discharge will occur at the other end of the cavity due to the screening effect of the surface charge, and further discharges fill up the as yet unaffected sites (see Figure 1.16). Mason [C1] has shown this for cavities in polythene.

When a cavity at one side is bounded by a conductor, a large discharge may occur during half-cycles when the conductor is negative, and several

Figure 1.16. *Distribution of discharge sites in a cavity*



small discharges may occur during the other half-cycles. This difference in size is explained by the cathode mechanism of the conductor. It has been noted, however, that the discharge pattern of such a cavity tends to become more symmetrical after a few cycles. This is due to the formation of moisture which tends to equalize surface conditions.

Usually a sample has several cavities, and these in turn may contain different discharge sites; again at one site several discharges may occur. Consequently, if discharges are made visible on an oscilloscope a complex picture will appear. Constant, intermittent, and wandering discharges may appear, separately or superimposed.

2.3. *Internal discharges at voltages other than a.c.*

D.C. VOLTAGE. When d.c. voltage is applied, discharges occur during the rise of the voltage, as in the case of a.c. voltage. After the voltage has become constant, discharges occur only infrequently. The dielectric can be represented by the circuit of Figure 1.17. The capacity of the void ***c***

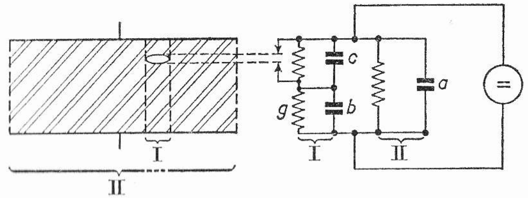


Figure 1.17. *Cavity in a dielectric stressed at d.c. voltage:* I *corresponds to the faulty part of the dielectric;* II *corresponds to the sound part of the dielectric*

is continually charged by the conductivity g of the dielectric in series with c; c discharges when the voltage has reached the ignition voltage of the cavity.

The number of discharges per unit of time increases with the voltage across the sample and decreases with the resistivity of the dielectric. Rogers and Skipper [B8] calculated the discharge repetition rate of a spheroidal cavity. In the special case where the cavity is laminar and the conductivity of the cavity walls is zero, the maximum repetition rate is

$$f \simeq 1\cdot13 \times 10^{11} \sigma \frac{E}{E_i} \text{ (Discharges per second per discharge site)} \quad \ldots (1.2)$$

If the cavity is spherical the repetition frequency is about half as great. The symbols used in this formula are

σ = Specific conductivity of the dielectric ($\Omega^{-1}m^{-1}$).
E = Stress in the dielectric (kV/mm).
E_i = Ignition stress of the cavity (kV/mm).

Rogers and Skipper verified their formula by experiment and found a repetition frequency which was about 2–3 times lower than the predicted maximum.

In the usual dielectrics the resistivity is so high that at stresses at which a sample shows discharges at a.c. voltage, discharges at d.c. voltage occur at intervals which range from a few hours to several weeks. According to Rogers and Skipper [B8] the d.c. repetition rate in polythene is about 10^4 to 10^5 times less than under a.c. conditions. According to Arman and Starr [G1] the repetition rate in impregnated paper cable at d.c. voltage reaches a value comparable with that at a.c. voltage if the d.c. voltage is 5–10 times higher than the a.c. voltage.

D.C. VOLTAGE WITH RIPPLE COMPONENT. The voltage in d.c. power systems may contain a ripple component. If this component exceeds the discharge inception voltage, recurrent discharges will occur in each half-cycle of the ripple component, as under a.c. conditions. However, even if the ripple voltage is insufficient to cause recurrent discharges, it will increase the d.c. discharge repetition frequency. If E_R is the peak ripple stress in the dielectric, the effect in a laminar cavity will be ϵE_R. Consequently, the stress in the cavity need not rise to the ignition stress E_i but to $E_i - \epsilon E_R$ only. The discharge repetition rate will therefore be increased by a factor $E_i/(E_i - \epsilon E_R)$. If the ripple voltage wave is non-symmetrical, E_R must be taken as the peak value of the ripple stress corresponding to voltage half-cycles of the same polarity as the d.c. stress [B8].

IMPULSE VOLTAGE. Tests with impulse voltage are performed at such high voltage levels that it must be expected that discharges will occur. Whitehead [A1] supposes that breakdown of solid dielectrics can be stimulated by field concentrations in the neighbourhood of a partial breakdown channel. However, little is known of the behaviour of discharges under impulse stress and of their damaging effect. Discharges caused by impulse voltage will not be considered in this book.

3. SURFACE DISCHARGES

3.1. Inception of surface discharges

Surface discharges may occur if there exists a stress component parallel to a dielectric surface. This applies to bushings, ends of cables, the overhang of generator windings, and if a discharge from outside hits the surface. The discharge affects the electric field, so that in general the discharges extend beyond the region where the original surface component of the electric field was high enough to cause discharges.

DISCHARGES IN AIR. In a few cases the inception voltage can be calculated. At the edge of a plane–plane configuration an air gap Δ in

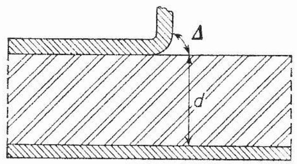


Figure 1.18

series with a solid dielectric d breaks down as shown in Figure 1.18. If the inhomogeneity of the electric field is neglected, the inception voltage is

$$V_i = \Delta E_i + d\frac{E_i}{\epsilon}$$

where E_i is the breakdown stress of the gap Δ; it varies with Δ and gas pressure as shown in Figure 1.18. If the breakdown voltage U_i of the air gap is introduced, it follows

$$V_i = U_i + \frac{d}{\epsilon\Delta}U_i$$

or

$$V_i = U_i\left(1+\frac{d}{\epsilon\Delta}\right) \qquad \ldots(1.3)$$

This formula has a minimum which follows from Figure 1.19, where V_i is shown as a function of Δ. At this minimum the gap breaks through.

Mason [D2] has verified this and found good agreement with experimental results. He also found an empiric formula for the minima of Figure 1.19, i.e. the inception voltage of an electrode edge in air:

$$(V_i)_{\text{edge}} = 4{\cdot}5\sqrt{\left(\frac{d}{\epsilon}\right)\cdot\frac{293}{T}} \quad \text{(kV r.m.s.)} \qquad \ldots (1.4)$$

where d = Insulation thickness (mm).

ϵ = Dielectric constant.

T = Temperature (°K).

The results are correct up to $d/\epsilon = 0{\cdot}5$ mm.

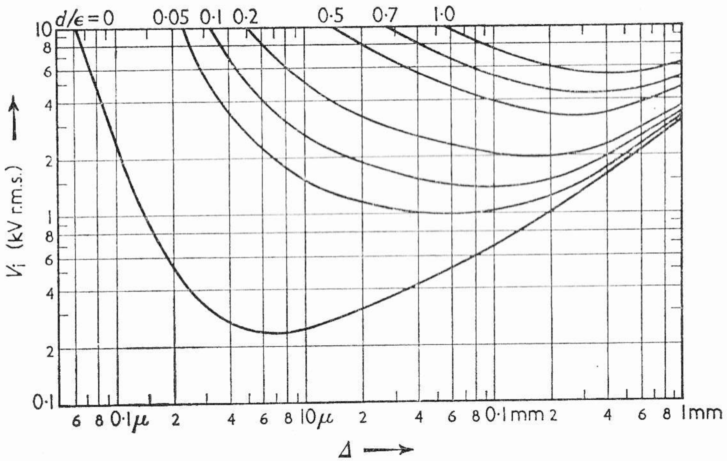


Figure 1.19. $V_i = f(\Delta)$ *according to equation* (1.3) *for different values of insulation thickness and dielectric constant. The minima in* V_i *correspond to the inception voltage of discharges at electrode edges, according to Mason* [D2] *and Halleck* [D6]

Halleck [D6] found good agreement too. If the radius of curvature of the edge is smaller than about 1 mm, the inception voltage is lowered by some 10–20 per cent due to concentration of field lines.

If the upper electrode is separated from the dielectric as in Figure 1.20, equation (1.3) applies; now V_i is not given by the minima of Figure 1.19

but by the actual distance Δ (unless the distance Δ is smaller than that corresponding to the minimum in Figure 1.19).

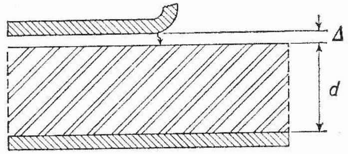


Figure 1.20

Discharges under oil. A similar formula as for air might apply to discharges under oil, but the breakdown voltage U_i of the oil gap is less precisely known than for air. Contamination of the oil and traces of moisture greatly affect the breakdown stress. The same applies to capacitors, where surface discharges may occur at the edges of the metal foils. Kappeler [D7] has investigated the inception voltage of an electrode arrangement such as is found in bushings and capacitors. He made his measurements both in air and under oil. In Figure 1.21 the electrode arrangement and the results are shown. The inception voltages in air are lower than those following from formula (1.3); the field concentrations at the edges of the thin capacitor layers are apparently the cause of this fact.

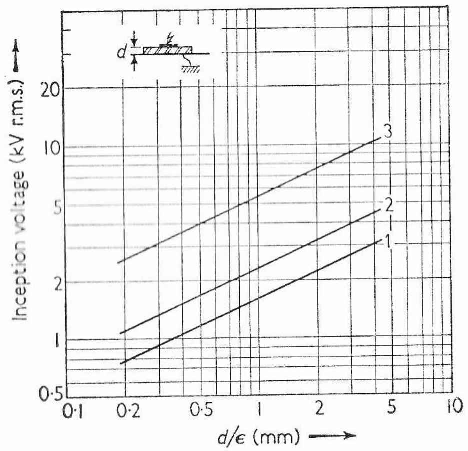


Figure 1.21. *Discharge inception voltage at the edge of capacitor foils according to Kappeler* [D7]*: (1) In air; (2) Semi-conducting foils in air; (3) In oil*

3.2 Behaviour of surface discharges

A.C. VOLTAGE. The behaviour of surface discharges can be deduced from the *abc* diagram shown in Figure 1.9. The capacity between the electrode and the region of the surface covered by the discharge corresponds to *c* (see Figure 1.22), *b* corresponds to the capacity of the dielectric in series with *c*, and *a* corresponds to the sample.

This circuit leads to similar discharge patterns as with internal discharges. However, as the electrode arrangement is asymmetric and the discharge is at one side bounded by metal, asymmetric patterns will occur as in the case of metal-bounded discharges in cavities. A frequently occurring discharge pattern is one in which many small discharges occur when the upper electrode is negative, and fewer larger discharges when this electrode is positive. The ratio between negative and positive

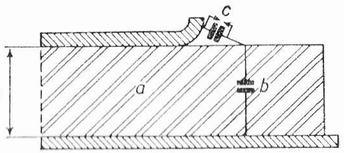


Figure 1.22. *abc Diagram for surface discharges*

discharges can be anything between 1:1 and 1:10. The difference is attributed to the difference in mobility of positive and negative surface charges.

D.C. AND IMPULSE VOLTAGE. Surface discharges may occur when d.c. voltage is switched on; after that discharges will occur very infrequently, like internal discharges. With impulse voltages surface discharges may also occur. Lichtenberg figures are formed on the surface, the size of these Lichtenberg figures being a measure of the height of the impulse. This fact has long been used for measuring impulse voltage in the *klydonograph*.

4. CORONA DISCHARGES

4.1 Inception of corona discharges

Corona discharges occur around sharp points or edges at high voltage. They appear sooner at negative than at positive voltage; with a.c. voltage they occur often during the negative half-cycle of the sine wave only.

NEGATIVE CORONA. Trichel [E1], who studied point-to-plane corona

with d.c. voltage, gives the following description of the phenomena. If a positive ion appears in the vicinity of the point it is attracted by the electric field and moves towards the point. The ion hits the electrode and releases one or more electrons which, by the Townsend mechanism, cause a cloud of positive ions near the point and negative electrons

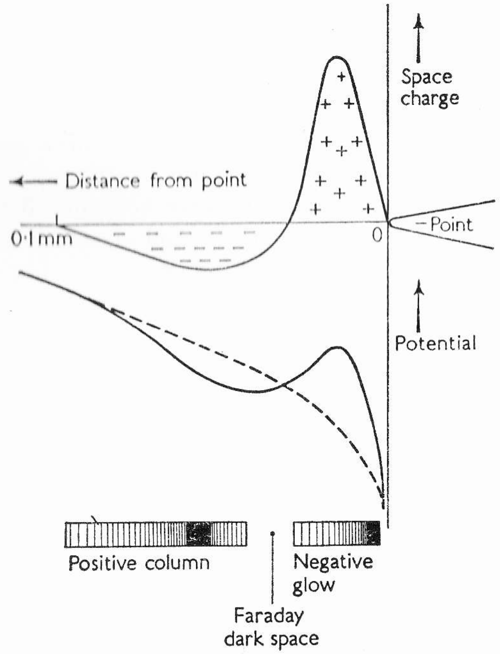


Figure 1.23. *Negative corona; space charge and potential distribution*

travelling away from the point. During this process radiation occurs which causes photoionization at the surface of the point; a lateral extension of the ionized region takes place until the so-called cathode spot is formed from which the corona discharge emanates.

At greater distance from the cathode the electrons slow down and attach themselves to the oxygen molecules in air. Two regions with space charge have been formed by now. A positive space charge has been built up in the nearest vicinity of the point by the slow positive ions which are left after the ionization of the air molecules. At greater distance the negative ions which are formed by adhesion of the electrons to the oxygen molecules cause a negative space charge. The whole process takes place within a distance of 0·1 mm from the point and in a time interval of the order of 10^{-8} sec. In Figure 1.23 a diagram of the space charge and the potential is given. The negative space charge shields the electric field at the point, the positive ions move into the point without producing further ionization as the field strength is too low, and the discharge extinguishes. After the extinction the negative space charge moves away to the anode, the electric stress rises, and the next discharge starts.

In the strong field just outside the point a luminous region appears, the so-called negative glow. In the region of the negative space charge a faint glow appears, which is called the positive column. Between the two luminous parts the Faraday dark space is found, which corresponds to a region of little stress where no ionization occurs (see Figure 1.23).

Positive corona. If the point is positive, discharges occur in a narrow channel. The mechanism is as follows. After the inception voltage has been reached an electron avalanche is formed which causes a distribution of particles as shown in Figure 1.24. The resulting charge distribution

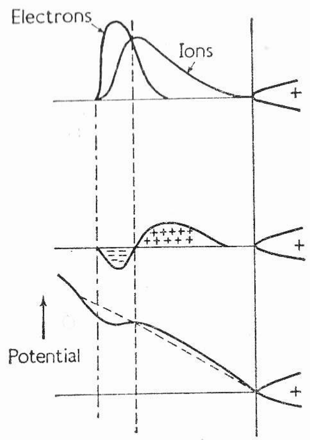


Figure 1.24. *Positive corona; space charge and potential distribution*

and potential are also shown. It follows from this Figure that the electric field at the head of the electron avalanche is increased. Photons arrive in this increased field and start new avalanches. Streamer discharges are formed as shown in Figure 1.25.

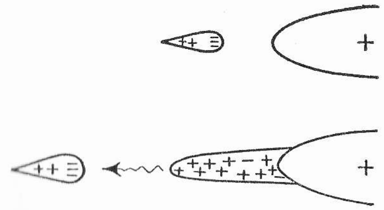


Figure 1.25. *Development of a channel discharge*

Inception voltage. The inception voltage of corona discharges is difficult to state. Much work has been done, for instance, on conductors of high voltage lines, but the results depend on surface smoothness and meteorological conditions. In Figure 1.26 the inception voltage of positive and negative corona in a point-to-plane arrangement is shown.

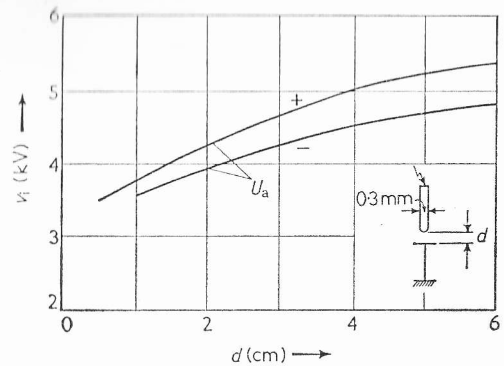


Figure 1.26. *Inception voltage of positive and negative corona*

1.2. *Recurrence of corona discharges*

At d.c. voltage. Negative corona discharges recur regularly according to the mechanism described in the preceding section. The impulses are equal in size. The repetition frequency is strongly dependent on the voltage as shown in Figure 1.27. Positive corona discharges recur irregularly, in outbursts of small and large discharges. The repetition rate increases with increasing voltage.

At a.c. voltage. Corona discharges occur at first in the negative cycle of the high voltage sine wave only. Typical oscillograms are shown in

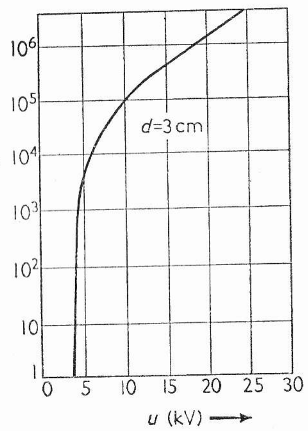


Figure 1.27. *Repetition frequency of negative corona discharges at d.c. voltage*

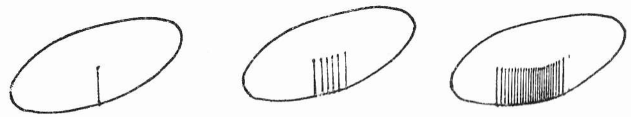


Figure 1.28. *Corona discharges at a.c. voltage, at the inception voltage, 6 per cent and 20 per cent above the inception voltage*

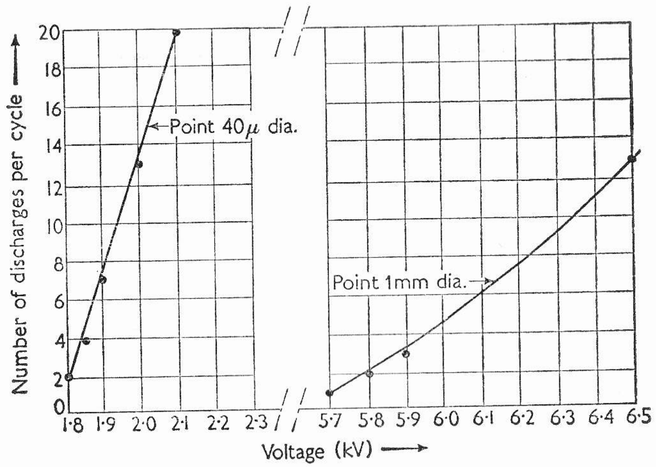


Figure 1.29. *Number of corona discharges per cycle at a.c. voltage*

Figure 1.28, where the discharge impulses are displayed on a 50 c/s time base [A3]. They are equal in size and their number increases to a first approximation linearly with the applied voltage, as shown in Figure 1.29 [A3]. At higher voltages discharges also occur in the positive half-cycles.

When placed in a detection circuit the corona discharge may also be represented by an *abc* diagram, as shown in Figure 1.30. The short-circuiting of the spark gap, however, is governed by other laws than in the case of internal or surface discharges. Furthermore, unidirectional charge transfer takes place between high voltage and earth.

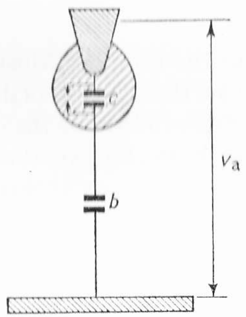


Figure 1.30. *abc Diagram for corona discharges*

5. MAGNITUDE OF DISCHARGES

5.1. *Quantities related to the magnitude of discharges*

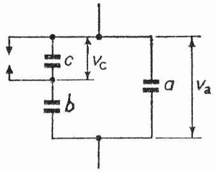
The magnitude of discharges can be described in several ways. In the following sub-sections some quantities will be studied which might be useful as a measure of discharges. A choice will be made.

CHARGE TRANSFER IN A CAVITY. In the first place the charge q_1 which is transferred in the cavity (or in the case of surface discharges, the charge transferred along the surface) could be taken as a measure. If the sample is large compared with the cavity, as will usually be the case, this charge transfer is equal to

$$q_1 \simeq (b+c)\Delta V \qquad \ldots (1.5)$$

where b, c, and ΔV have the same signification as before and are shown again in Figure 1.31. However, q_1 is not a practical choice as q_1 cannot be measured with any discharge detector.

Figure 1.31



APPARENT CHARGE TRANSFER IN THE SAMPLE. In the second place the displacement of charge q in the leads of the sample can be taken. This quantity is equal to

$$q = b\Delta V \qquad \ldots(1.6)$$

It causes a voltage drop $(b\Delta V)/(a+b)$ in the sample. Most discharge detectors respond to this voltage drop and are thus capable of determining q. However, the magnitude $q = b\Delta V$ is not determined by the dimensions of cavity or defect alone, as b is affected by the thickness of the insulation. Nevertheless, q can be considered a right measure of discharges, as follows from the consideration below.

DISCHARGE ENERGY. In the third place the energy dissipated by a discharge can be taken as a measure. This energy may be the cause of deterioration of the dielectric. It is denoted by w and can be related to the charge transfer q. When the voltage across the cavity drops from U^+ to V^+ (notations as in Figure 1.10) and if $a \gg b$, the energy amounts to

$$\begin{aligned} w &\simeq \tfrac{1}{2}(b+c)[(U^+)^2-(V^+)^2] \\ &= \tfrac{1}{2}(b+c)(U^+-V^+)(U^++V^+) \\ &= \tfrac{1}{2}(b+c)\Delta V(U^++V^+) \end{aligned}$$

If V^+ is neglected,

$$w \simeq \tfrac{1}{2}(b+c)\Delta V U^+$$

At the moment of the first breakdown of the cavity no residual charges are present and U^+ can be calculated as

$$U^+ = \frac{b}{b+c}V_i'$$

where V_i' is the inception voltage.

Thus,

$$\begin{aligned} w &\simeq \tfrac{1}{2}(b+c)\Delta V\frac{b}{b+c}V_i' \\ &\simeq \tfrac{1}{2}b\Delta VV_i' \end{aligned}$$

or

$$w \simeq \tfrac{1}{2}qV_i' \qquad \ldots(1.7)$$

Expressed in volts r.m.s.,

$$w \simeq 0{\cdot}7qV_i \qquad \ldots(1.8)$$

Thus the discharge energy w is in a simple way related to the apparent charge transfer. This is one of the reasons why the charge transfer q can be accepted as a relatively good measure of the magnitude of a discharge.

DIELECTRIC LOSSES DUE TO DISCHARGES. In the fourth place the total energy dissipated during a cycle by all discharges in a sample can be measured, $W \simeq \sum \tfrac{1}{2}(b+c)\Delta V^2$. This can be accomplished by means of a Schering bridge or with special discharge detectors. In samples where a great number of discharges occur simultaneously, this total energy is sometimes measured to evaluate the quality of insulation. However, in general this measurement is not recommended, as no distinction is made between a few large discharges which might be dangerous and several small ones which might be quite innocuous.

CHOICE OF DEFINITION OF DISCHARGE MAGNITUDE. Of the four possible choices considered above, the *charge transfer* q has widely been accepted as the magnitude of a discharge. This choice is justified by the following considerations.

(1) The largest discharge present can be stated. In Section 6 it will be shown that there exists a possibility that the largest discharge coincides with the largest cavity in the dielectric corresponding to the shortest voltage life,
(2) The charge transfer q is related in a simple way to the discharge energy w,
(3) It can readily be measured, and
(4) It is a good measure for the sensitivity of a detector, as will follow from Chapter 2. It is, in fact, the only quantity which can be used to compare the sensitivity of different detectors.

It must be emphasized that this discharge magnitude is *not* the charge transfer in a cavity. It can conveniently be regarded as a practical measure with the dimensions of charge.

5.2. *Some relationships*

The quantities discussed above are sufficient to describe fully the phenomena with regard to discharge detection. However, in order to give more insight into the phenomena some special relationships are studied below.

VOLTAGE–TIME RELATIONSHIPS. It was assumed in sub-section 2.2 that the voltage drop in a cavity occurs almost instantaneously. In reality it takes some time before the voltage has decreased. It has been shown

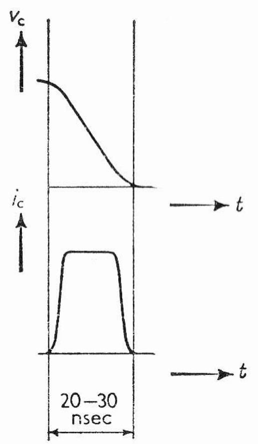


Figure 1.32. *Internal discharge, voltage and current in cavity c as a function of time*

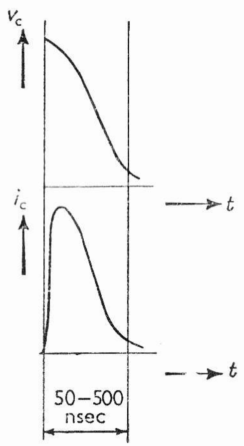


Figure 1.33. *Surface and corona discharge, voltage and current in c as a function of time*

[A3] that the voltage in the cavity drops almost linearly with time in about 20 nsec ($20 \cdot 10^{-9}$ sec). The corresponding current in the cavity has a shape as shown in Figure 1.32. The resulting frequency spectrum extends to the region of 100 Mc/s.

The voltage drop in a surface or corona discharge takes more time [A3, E3]. The voltage in a negative corona discharge decreases almost

exponentially, as shown in Figure 1.33. The time constant is about 50–500 nsec for negative corona. Positive corona impulses are much slower.

With the conventional discharge detectors these current or voltage wave shapes are not shown; the shape of the impulses is entirely determined by the detection circuit and the amplifiers. It will be shown later that travelling waves which are caused by discharges in long lines and cables have the same shape as the current waves shown here. If sufficiently fast detectors are used these shapes are shown.

ENERGY BALANCE. The number of discharges at one discharge site during one cycle of the fifty cycle sine wave is

$$n = 4\,\frac{\text{Max. voltage over } c}{\Delta V}$$

$$= \frac{4}{\Delta V}\frac{b}{b+c}V'$$

where V' is the crest voltage over the sample. The energy dissipated in these discharges is

$$W_1 = n\tfrac{1}{2}(b+c)\Delta V^2$$

$$= \frac{4}{\Delta V}\frac{b}{b+c}V'\tfrac{1}{2}(b+c)\Delta V^2$$

$$W_1 = 2b\Delta VV' = 2qV' \qquad \ldots(1.9)$$

On the other hand, the energy supplied by the high voltage source can be calculated. The energy supplied by the high voltage source during the first discharges is

$$w_1 = qV_i'$$

where V_i' is the inception voltage; the energy supplied at the mth discharge is

$$w_m = qmV_i'$$

Energy is returned at the kth discharge when the voltage still has the same polarity but the discharges are reserved (see Figure 1.34)

$$w_k = q(m-1)\,V_i'$$

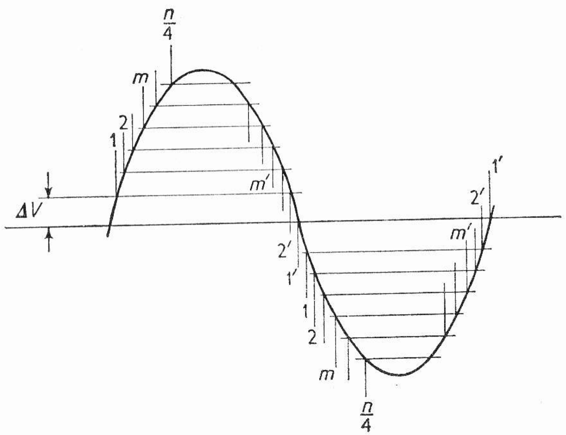


Figure 1.34

The difference between supplied and returned energy is

$$w_{\mathrm{m}} - w_{\mathrm{k}} = qmV_{\mathrm{i}}' - q(m-1)\,V_{\mathrm{i}}' = qV_{\mathrm{i}}'$$

This difference occurs $n/2$ times during one cycle; thus the total difference supplied by the high voltage source is

$$W_2 = \frac{n}{2}\cdot qV_{\mathrm{i}}'$$

$$= \frac{2}{\Delta V}\frac{b}{b+c}V'q\frac{b+c}{b}\Delta V$$

so that

$$W_2 = 2qV' \qquad \ldots(1.10)$$

where W_2 = The supplied energy during one cycle,

q = Discharge magnitude,

V' = Crest voltage over the sample.

Equation (1.9) is equal to equation (1.10), so that the dissipated and supplied energy are in balance.

Loss tangent. The loss tangent caused by the discharges at one discharge site can be calculated. The loss tangent is related to the losses according to

$$P = IV \tan\delta$$

$$= \omega a V^2 \tan\delta$$

According to equation (1.10) these losses are also equal to $fW_2 = 2fqV'$, if f is the frequency of the applied voltage, so that

$$2fqV' = 2\sqrt{(2)}fqV = 2\pi f a V^2 \tan\delta$$

$$\tan\delta = \frac{\sqrt{(2)}\,q}{\pi a V}$$

or

$$\tan\delta = 4{\cdot}5\ 10^{-4}\frac{q}{aV} \qquad \ldots(1.11)$$

where q = Magnitude of the discharges proceeding from one discharge site (picocoulombs (pC)),

a = Capacity of the sample (pF),

V = Voltage over the sample (kV r.m.s.).

In practice it is difficult to decide from an oscillogram whether a train of discharges originates from one or more discharge sites. If few discharges are present the smaller ones can be neglected, and the magnitude of the train of largest discharges is inserted in equation (1.11). In this way a fair estimation can be made of the contribution of the discharges to the loss tangent. In cases where the result of discharge detection and loss measurement must be correlated, this estimation might be useful.

Relation between q_1 and q. If the apparent charge transfer in the sample is

$$q = b\Delta V$$

and the charge transfer in the cavity (or along a surface) is

$$q_1 = (b+c)\Delta V$$

the relation between the two is

$$q_1 = \left(1+\frac{c}{b}\right)q \qquad \ldots(1.12)$$

or in a cavity the dimensions of which are known,

$$q_1 = \left(1+\frac{d}{\epsilon\Delta}\right)q \qquad \ldots(1.13)$$

where
q_1 = Charge transfer in the cavity,
q = Discharge magnitude,
d = Thickness of the dielectric,
ϵ = Dielectric constant of the dielectric,
Δ = Thickness of the cavity.

The actual charge transfer in the cavity is usually larger than the apparent charge transfer measured in the sample.

5.3. *Connections with dimensions and field strength*

DISCHARGE MAGNITUDE. A general formula can be derived for the discharge magnitude. According to equation (1.6) this magnitude is

$$q = b\Delta V$$

According to Figure 1.35, supposing that the thickness of the cavity is small compared with the thickness of the dielectric and supposing that

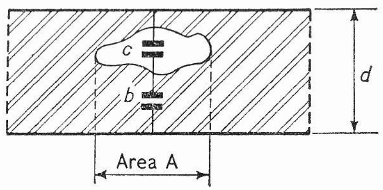


Figure 1.35. *Cavity in a dielectric*

only η per cent of the cavity surface takes part in the discharge, it is

$$q \simeq \epsilon_0 \frac{\epsilon}{d} \cdot \eta A \cdot \Delta V \qquad \ldots(1.14)$$

where
q = Discharge magnitude (coulombs),
ϵ_0 = Dielectric constant of air ($\simeq 9 \times 10^{-12}$ F/m in Giorgi units),
ϵ = Relative dielectric constant of the insulating material,
d = Thickness of the dielectric (metres),

η = Part of the surface of the cavity which discharges; η usually lies between 10 and 80 per cent, it attains the higher values after some time or at higher voltages,
A = Surface of the cavity (square metres),
ΔV = Ignition voltage of the cavity (volts).

It follows from equation (1.14) that

(1) The measured discharge magnitude decreases with increasing thickness of the dielectric. Alternatively, the sensitivity of detection decreases as the insulation becomes thicker.
(2) The discharge magnitude increases with increasing surface of the cavity.
(3) The discharge magnitude increases with increasing ΔV, i.e. if the pressure in the cavity increases or if the thickness of the cavity increases.

In general, the discharge magnitude increases with increasing cavity dimensions.

RELATIVE CHARGE TRANSFER $q_{1/A}$. It is interesting to determine the amount of charge per unit of surface which is disposed on the walls of a cavity. Although a discharge site is usually not fully charged or discharged, the centre of the site is completely charged or discharged. In this centre the charge density is given by q_1/A, where A is the surface of the centre. If the capacities b and c are related to this centre too,

$$q_1 = (b+c)\Delta V$$

Introducing the inception voltage

$$q_1 = (b+c)\frac{b}{b+c}V_i'$$

$$q_1 = bV_i'$$

and if d is the thickness of the dielectric

$$q_1 = \epsilon_0 \epsilon \frac{A}{d} V_i'$$

Then the relative charge transfer is (if F_i' is the inception stress in the sample)

$$q_1/A = \epsilon_0 \epsilon F_i'$$

This charge is moved n times during a cycle, where $n = 4F/F_i'$. Thus the total relative charge transfer is

$$\sum_{1 \text{ cycle}} q_1/A = 4\epsilon_0 \epsilon F' \qquad \ldots(1.15)$$

which is independent of discharge magnitude, inception voltage, or cavity dimensions, but depends on the field strength in the dielectric only. As the relative charge transfer is thought to be related to the deterioration of the dielectric, this formula is an indication that the stress in a sample is an important measure for the rate of deterioration, more than discharge magnitude. This view is supported by experimental results, which are given in the next section.

6. DETERIORATION OF DIELECTRICS

6.1. *Mechanism of deterioration*

Internal and surface discharges are known to be injurious to dielectrics. The damage may be caused by several phenomena such as the following:

(1) Ion and electron bombardment, causing heating of anode and cathode, erosion of these surfaces, and chemical processes at the surface (polymerization, cracking, gassing),
(2) Formation of chemical products in the ionized gas, such as nitric acid and ozone,
(3) Ultra-violet rays or soft X-rays.

The causes differ from case to case and are strongly dependent on the kind of dielectric. Mason [C1] has shown that for polythene thermal degradation is paramount. In the case of mica-insulated coils of alternators the deterioration is thought to be caused by ion bombardment [A6].

INTERNAL DISCHARGES IN PLASTICS. The deterioration by discharges in polythene, polystyrene, polytetrafluoroethylene, and glass has extensively been studied by Mason [C1, C2, C3]. He distinguishes three stages of deterioration. It begins as uniform surface erosion. This surface erosion may be caused by thermal degradation, soft X-rays, or ultra-violet radiation. Another explanation is given by Thomas [D1], who has shown that electrons are trapped slightly below the surface, so that ions laid down by consecutive discharges cannot neutralize them. The close proximity of such charges causes high field strengths in the dielectric which eventually may reach the intrinsic breakdown strength and result in surface erosion.

In the second stage the discharges become concentrated near the periphery of the cavity. It is not clear why this concentration occurs. It may be that field concentration in the dielectric near the periphery of the void is the cause. It is also known that the presence of a dielectric plane parallel to the field lowers the breakdown voltage, so that discharges occur sooner near the walls of the cavity than in the centre. Anyway, the discharges become concentrated and a number of deep pits is formed at the periphery of the cavity. As the length of the pits grows, the energy

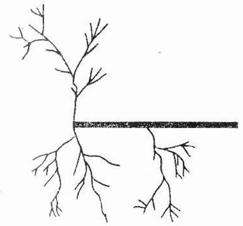


Figure 1.36. *Trees starting from fibre in contaminated polythene*

of the discharges increases, and sometimes carbonization of the pits occurs.

Now the third stage is reached. The stress at the top of the pit is believed to approach the intrinsic electric strength of the dielectric over a distance of some microns owing to the field concentration around this sharp tip. The dielectric breaks down over this distance, the field concentration moves on to the new tip, and narrow channels propagate quickly through the dielectric initiating complete breakdown. Such channels have also been found by Kitchin and Pratt [C6] in polythene and rubber. The channels tend to form trees, as shown for instance in Figure 1.36, where trees start from an inclusion in a dielectric.

The first two stages (surface erosion and forming of pits) take the major part of the time-to-breakdown. This time may be anything from a few hours at high stresses, e.g. 10–20 kV/mm, to many years at a lower stress, say 3–5 kV/mm, when stressed at 50 c/s.

The third stage, the propagation of channels leading to ultimate breakdown, may take place in a few voltage cycles only [C2]. This explains why treeing seldom is observed when the voltage is switched off before breakdown has occurred.

INTERNAL DISCHARGES IN IMPREGNATED PAPER. The deterioration by discharges in impregnated paper insulation has been studied by Robinson [A2]. Discharges in voids adjacent to the conductor attack the insulation and penetrate after some time the first paper layer. As in the case with cavities in plastic insulation, the penetration occurs at the edge of the void. After coring the first few paper layers, surface discharges occur along the layers and trees or carbonized tracks are formed. The tracks follow the weakest points in the insulation, i.e. the butt-gaps between the paper tapes as shown in Figure 1.37. At the foot of the tree local overheating takes place, which results in an ultimate thermal breakdown.

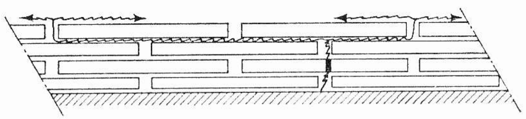


Figure 1.37. *Coring and treeing as a result of discharges in a void in impregnated paper insulation*

SURFACE DISCHARGES. Deterioration by surface discharges has often been studied because surface discharges are used for the assessment of the discharge resistance of materials. The phenomena are about the same as with internal discharges. Ogilvie [D3], for instance, found the same kind of treeing when testing polystyrene sheets under oil.

CORONA DISCHARGES. As corona discharges usually occur around bare conductors, they cannot attack insulation in the same way as internal and surface discharges. Only indirect action by ozone formed by corona may deteriorate neighbouring dielectrics. However, corona is of interest because it produces radio disturbances and causes electric losses at high voltage lines. The measuring and controlling of these phenomena, however, falls outside the scope of this book.

6.2. Rate of deterioration, voltage life

INTERNAL DISCHARGES. There are many variables affecting the rate of deterioration in dielectrics. The deterioration increases with the number

of discharges and is consequently proportional to the frequency of the applied voltage, and is dependent on the amplitude of this voltage. It also depends on the intensity of the discharge and the nature of the dielectric.

FREQUENCY. The number of discharges increases proportionally with frequency. The life of a dielectric under voltage is consequently inversely proportional to frequency, unless the frequency is so high that thermal breakdown is initiated and the voltage life is shorter than expected.

If d.c. voltage is applied the number of discharges is small; consequently the voltage life at d.c. voltage is many times that at a.c. voltage, even if the stress in the dielectric is higher than the stress which is usual for a.c. voltage.

STRESS. The number of discharges increases with increasing stress in the dielectric. Moreover, the mechanism of deterioration is affected by

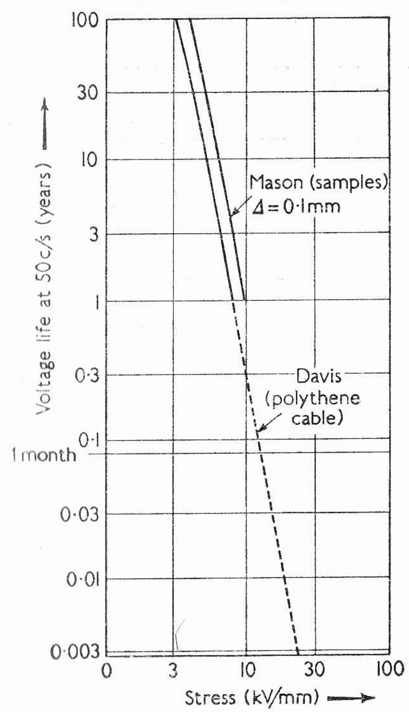


Figure 1.38. *Voltage life as a function of stress. Results of Mason [C1] obtained with artificial cavities in polythene at 150 kc/s. Results of Davis [C5] obtained with natural voids in polythene-insulated cables at unidirectional pulses at 500 c/s. The results of these accelerated tests are converted into years at 50 c/s*

stress, e.g. the formation of pits occurs sooner at higher stresses. It can also be expected that the conditions for the propagation of channels are reached sooner at a higher stress. Consequently, the effect of stress upon voltage life is very large; the voltage life decreases as the 7th to 9th power of the stress. Several authors have shown this (see, for instance, Figure 1.38, where data from Mason [C1] and Davis [C5] are collected, and Figure 1.40 with data obtained by the author.

DISCHARGE MAGNITUDE. The discharge magnitude increases with the depth of the cavity and its area. The voltage life is not affected by the

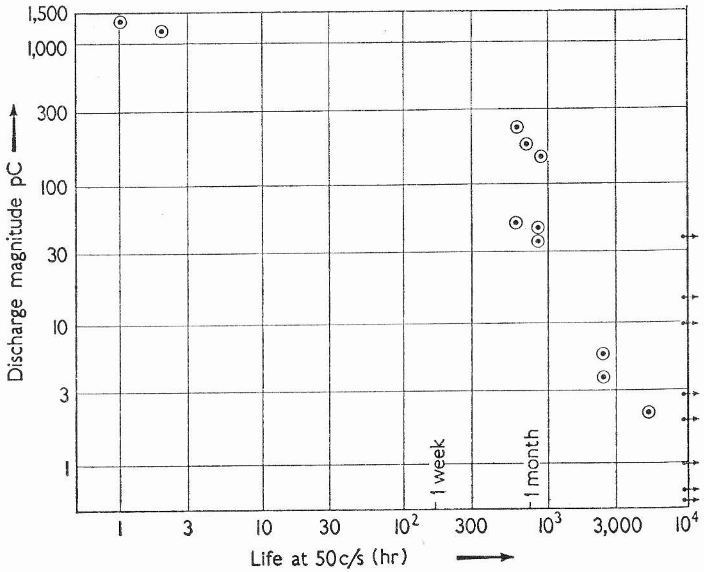


Figure 1.39. *Voltage life against discharge magnitude. Results obtained with discharges in PVC-insulated cable aged at 6 kV/mm*

surface of the cavity but it is affected by its depth. Consequently, the correlation between discharge magnitude and voltage life is uncertain. The author found this with discharges in a PVC-insulated cable; discharges of different magnitude were maintained at the same voltage. The result is shown in Figure 1.39, where little correlation between discharge magnitude and voltage life is found. Only with very large discharges the voltage life is definitely short. In that case the large

discharge magnitude is certainly indicating a large cavity depth. Moreover, thermal effects may co-operate.

CAVITY DEPTH. Voltage life is shorter if the cavity is deeper. The author has shown this for artificial cavities in PVC films. The films have been stressed at different voltages. The results are shown in Figure 1.40.

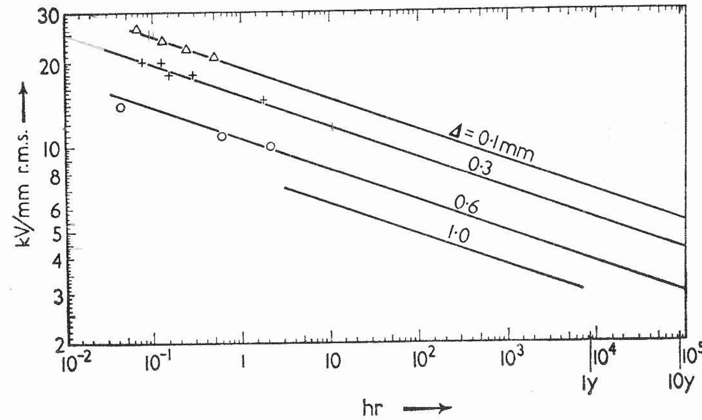


Figure 1.40. *Voltage life as a function of stress for different cavity depths. Results obtained by the author. The curves are extrapolated to illustrate the speculations made in sub-section* 6.4

THICKNESS OF DIELECTRIC. It is probable that the effect of insulation thickness is of minor importance. The time until treeing sets in is the same for all insulation thicknesses if stresses are identical. The penetration of trees leads to breakdown in a few voltage cycles and has in this way little effect on the total time-to-breakdown.

TYPE OF INSULATION. Different types of insulation have different resistance to discharges. Mica and glass are known to have good resistance to discharges. Polythene, PVC, and polystyrene are less resistant, whereas rubber and tetrafluoroethylene are easily attacked by discharges. In order to determine the resistance to discharges many methods have been devised, but up till now none of them has been entirely satisfactory. Some of these methods are considered in sub-section 6.3.

SELF-EXTINCTION OF DISCHARGES. A complication for the study of voltage life is the fact that discharges in cavities and surfaces sometimes extinguish because of semiconducting layers formed by the discharges themselves. Rogers [C4] investigated these phenomena in cavities in polythene, PVC, and rubber. In nearly all cavities embedded in a dielectric, discharges are extinguished or become intermittent. If the ratio diameter: cavity depth is small the extinction tends to be more complete. Extinction occurs at any test voltage. Rogers showed that both at two and four times the inception voltage the discharges extinguish after some hours.

Cavities adjacent to a conductor show a pattern of behaviour which also depends on the cavity diameter. If D is the cavity diameter and Δ the depth, the discharges tend to extinguish if $D/\Delta < 5$ and to remain if $D/\Delta > 5$. During periods of rest the original conditions are regained; after four days resting the inception voltage recovers almost to the original value. The self-extinction of discharges is a temporary and repeatable effect. At higher frequencies (e.g. 1,000 c/s) the discharges

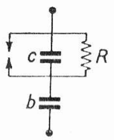


Figure 1.41. *Self-extinction of discharges; R short-circuits c*

are not extinguished. Rogers explains this as follows. At higher frequencies more current is passing through the capacities b and c (see Figure 1.41) and the leakage path R becomes relatively less important.

SURFACE DISCHARGES. The rate of deterioration caused by surface discharges is governed by the same variables. Deterioration is more severe at higher frequencies and higher stresses and it also depends on the kind of dielectric. However, the distance Δ between electrode and surface, which is comparable with the cavity depth, is of lesser importance. Damstra [D8] has shown that between $\Delta = 0{\cdot}1$ mm and $\Delta = 2$ mm there is no appreciable difference in voltage life.

6.3. *Discharge resistance*

In order to compare the resistance to discharges of different materials many methods are in use. In most methods surface discharges are used and dry air is circulated over the specimen to avoid the formation of semiconducting films. In this way self-extinction of discharges is prevented. Usually the time-to-breakdown is taken as a measure, in some cases

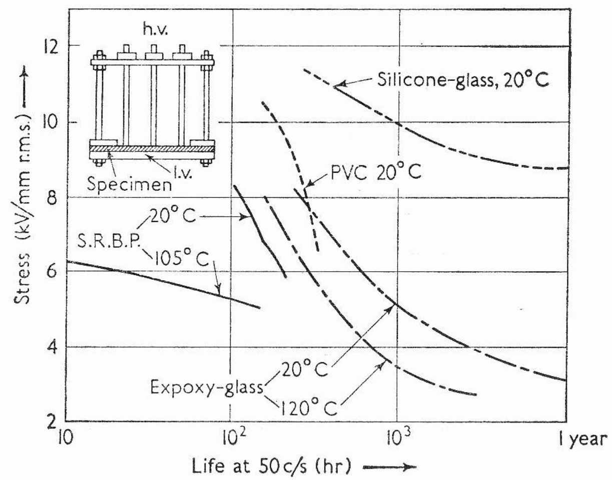
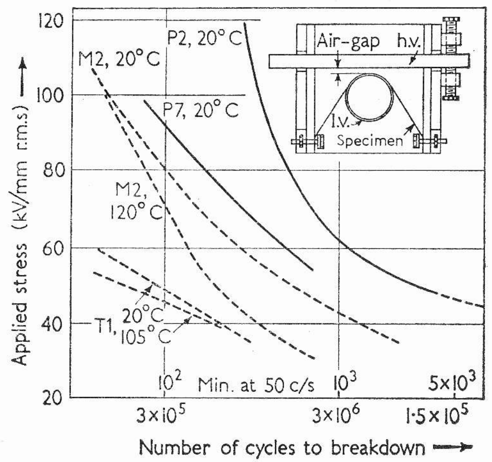


Figure 1.42. *The resistance of sheet insulation to surface discharges according to Mason* [*D*2]



M2: Melinex
P2: Polythene Grade 2
P7: Polythene Grade 7
T1: PTFE from dispersion

Figure 1.43. *The resistance of sheet insulation to surface discharges according to Mason* [*D*2]

changes in properties such as loss in weight or increase in loss angle are chosen as a criterion.

TIME-TO-BREAKDOWN TESTS. A well known method is that of Mason [D2]. Mason uses a simple rod and plane electrode system. In Figure 1.42 some results are shown, from which it follows that the discharge resistance

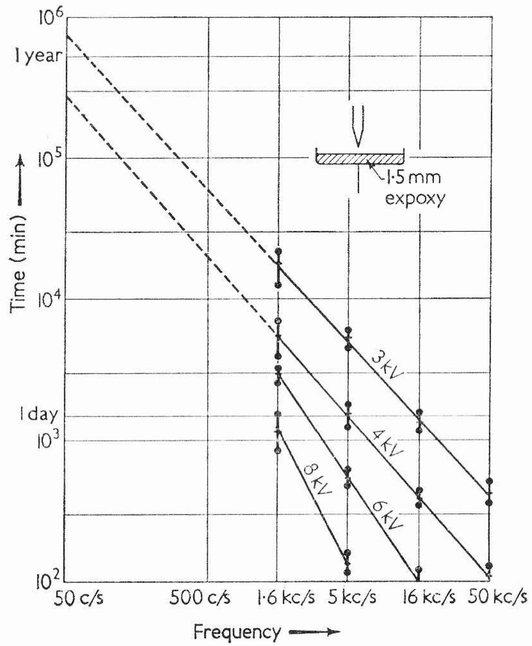


Figure 1.44. *Accelerated breakdown tests at higher frequencies according to Damstra [D8]. Dry air is circulated over the specimen*

is reduced by increasing the ambient temperature. For thin films Mason advocates the use of crossed cylinders as shown in Figure 1.43.

In these cases the tests are accelerated by applying high stresses to the dielectric. Rollinson [D9] and Damstra [D8] accelerate their tests by using high frequencies. They use sharp points (e.g. gramophone needles) facing the specimen on a plane electrode. In Figure 1.44 results of Damstra are shown, which prove that the test is linearly accelerated by

increasing the frequency unless the voltage is so high that thermal effects are involved.

CHANGE IN PROPERTIES. In France much work has been done on a test cell with parallel plane electrodes as shown in Figure 1.45 [D10]. A sample is inserted in the test cell for a certain time. Afterwards the change in some properties is determined, such as the loss of weight, the change in dielectric strength, or increase in loss angle.

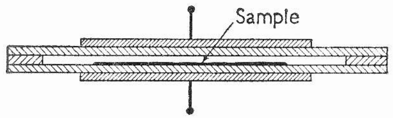


Figure 1.45. *French test cell for assessing discharge resistance* [*D*10]

ASSESSMENT OF $(\Sigma q_1)/d_1$. Lang [D11] uses a semisphere facing a plane electrode as shown in Figure 1.46. He integrates the amount of charge Σq_1 which is necessary to erode a certain depth d_1 in the insulating material. Lang states that the ratio $(\Sigma q_1)/d_1$ is a constant for a given material, unaffected by frequency, stress, or electrode spacing. By determining $\Sigma q_1/d_1$ for different materials the discharge resistance of each material can be established. However, little experience is available and some results raise doubts as to the constancy of the ratio $\Sigma q_1/d_1$.

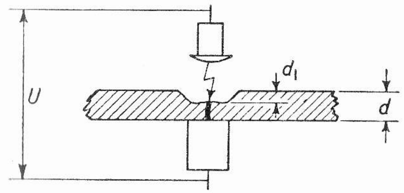


Figure 1.46. *Electrode system used by Lang* [*D*11]

LIFE TESTS. The results obtained with the methods mentioned above are not mutually agreeing. Moreover, these methods show the disadvantage that only a comparative measure is obtained. No statements can be made of the voltage life of a certain insulation under normal stress conditions. In order to obtain this information a life test must be done on the insulation in question. In that case, however, the test will take some ten years or more. Alternatively, if the test is accelerated by using higher frequencies or higher stresses, the extrapolation to normal conditions is uncertain, e.g. because of the self-extinction of the discharges which takes place in an unpredictable and irregular way. However, results of such tests combined with the experience gained with equipment in service can yield definite knowledge of this subject.

6.4. *Permissible discharge magnitude*

It is believed that discharges below a certain magnitude deteriorate the insulation material so slightly that a practically infinite life of the dielectric may be expected. This magnitude is called the *permissible discharge magnitude.* It is an important value for discharge detection. The detection circuit used must be able to detect discharges of at least that magnitude and preferably smaller. The samples under test must be free from discharges larger than this permissible discharge magnitude.

The permissible discharge magnitude depends greatly on the stress in the dielectric, as voltage life tends to decrease as the 7th to 9th power of stress. The permissible discharge magnitude depends also on the frequency of the applied voltage. A discharge magnitude which is tolerable at 50 c/s is likely not to be acceptable at 100 kc/s.

SOME ESTIMATES. The permissible discharge magnitude is not a sharply defined value because there are considerable variations in the results of long-time breakdown tests. Only a few estimates have become known. Davis [C5] has inferred that discharges in polythene-insulated cables of a magnitude smaller than 2 pC are harmless; this applies to a stress in the dielectric of about 3 kV/mm at 50 c/s. Mildner and Humphries [I2] consider it sufficient to test PVC-insulated cable with a sensitivity which permits detection of discharges of 3 pC and larger. The maximum stress in these cables is 3 kV/mm.

RELATION WITH VOLTAGE LIFE TESTS. The permissible discharge magnitude for a certain stress may also be inferred from the voltage life versus stress curves (see Figure 1.40). It follows from this Figure that the voltage life of a dielectric comprising cavities is dependent on the cavity depth.

At first an estimation is made of the permissible discharge magnitude at a working stress of 2 kV/mm. It follows from Figure 1.40 that a fairly large cavity depth is permissible to obtain a life of about 100 years; it is estimated to be 0·7–1 mm. From this cavity depth an estimation of the expected discharge magnitude can be made. Therefore the discharge magnitude of a flat cavity, Figure 1.47(a), a spherical cavity, Figure

1.47(b), and a bar-shaped cavity, Figure 1.47(d), is calculated. It appears that the discharge magnitude decreases in this order of succession. At

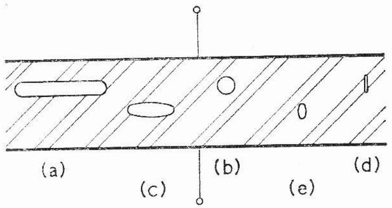


Figure 1.47. *Different cavity shapes in insulation*

the same time the corresponding inception stresses are calculated; the inception stresses increase. The different cases are as follows:

(a) Flat cavity. This cavity must be at least three times broader than its depth in order to be regarded as flat. The discharge magnitude can be calculated to be 100 pC or more (supposed that 100 per cent of the surface discharges and that the insulation thickness is about 4 mm). The inception stress ($\epsilon = 2{\cdot}2$) is about 1·7 kV/mm.

(b) Spherical cavities. In a spherical cavity the discharge magnitude can be calculated to be about 10 pC. The inception stress is about 2·5 kV/mm, which is higher than the working stress so that these cavities involve no danger.

(c) Cavities in between (a) and (b). These cavities are oval and have a diameter greater than 1 mm but smaller than 3 mm, which yields a discharge magnitude larger than 10 pC and an inception stress between 1·7 and 2·5 kV/mm.

(d) Bar-shaped cavities. These cavities may give discharge magnitudes smaller than 10 pC and are thus difficult to detect, but the inception stress is higher than 3 kV/mm so that they are not dangerous at the working stress.

(e) Cavities in between (b) and (d). These cavities show an inception voltage higher than 2·5 kV/mm and are also not dangerous at the working stress of 2 kV/mm.

From these conditions a specification for a discharge detection test can be derived as follows: The dielectric should be discharge-free up to a stress of 2 kV/mm and measured with a sensitivity of 10–30 pC.

If the working stress is 3 kV/mm the permissible cavity depth becomes about 0·4 mm. The expected discharge magnitudes are

(a) In flat cavities 10 pC or more with an inception stress of 2 kV/mm.
(b) In spherical cavities about 1 pC with an inception stress of 3·2 kV/mm.
(c) Cavities between (a) and (b) may be dangerous and no discharges larger than 1 pC are permissible.
(d) Bar-shaped cavities discharge at stresses higher than 3 kV/mm and are not dangerous at a working stress of 3 kV/mm.
(e) The same applies to cavities between (b) and (d).

Thus the test specification becomes: The dielectric should be discharge-free up to at least 3 kV/mm and measured with a sensitivity of about 1 pC.

This requirement corresponds with the findings of Davis [C5] that discharges smaller than 2 pC are harmless at 3 kV/mm, and those of Mildner and Humphries [I2] that a plastic cable with a working stress of 3 kV/mm must be tested with a sensitivity of 1 to 3 pC.

Similar speculations can be held for stresses higher than 3 kV/mm; the bar-shaped cavities which may give very small discharges and thus are indetectable may discharge and become dangerous. In Table 1.1 these considerations are summarized.

TABLE 1.1

Working stress	*Permissible cavity depth*	*Permissible discharge magnitude = required sensitivity*	*Risk of undetected bar-shaped cavities*
< 2 kV/mm	(Usually no discharge detection is applied)		
2 kV/mm	0·7 to 1 mm	30 pC	None
3 kV/mm	0·4 mm	1 pC	None
4 kV/mm	0·1 mm	0·05 pC	Small
> 4 kV/mm	< 0·1 mm	< 0·05 pC	Large

It must strongly be emphasized that the values stated in this Table are speculative. The actual values, which will be found after considerable experiment, may differ from these statements. The general tendency, however, will remain unaltered.†

† This statement is confirmed by results of life-tests which became available after completion of this book. The permissible discharge magnitudes are highly stress-dependent. The absolute values tend to be somewhat larger than stated above.

It follows from Table 1.1 that the requirements become rather stringent if the working stress is raised. The requirements for 4 kV/mm are almost unrealizable, both because the required sensitivity is difficult to obtain and because such small discharges are difficult to prevent. At stresses higher than 5 kV/mm plastic dielectrics cannot be used, unless more discharge-resistant plastics are found. At a stress of, for instance, 6 kV/mm breakdown may occur already after 1–2 months (discharges between 2 and 300 pC), as may be seen from Figure 1.39.

The above calculations are made assuming that the air pressure in the cavities is 1 atm. If the air pressure is less, discharges will start earlier; if the air pressure is larger, the cavities will start later and are perhaps not detected. However, if the dielectric is kept at 1 atm for some time the air will diffuse through the dielectric and the cavities will reach a pressure of about 1 atm.

If inclusions are taken into account, their inception voltage may be higher at the first rise of the voltage. It is therefore useful to give the dielectric an overvoltage of, say, 1·5 times the working voltage before testing.

7. CONCLUSIONS

(1) Internal discharges occur in cavities or inclusions in dielectrics. They may be injurious to the dielectric. They are more numerous and therefore more injurious at a.c. than at d.c. voltage.

(2) Surface discharges may occur everywhere a field component exists parallel to a dielectric surface, such as at the edges of electrodes. They also deteriorate the dielectric and are more injurious at a.c. voltage.

(3) Corona discharges may occur in air or other gases around strongly curved electrodes at high voltage. They attack dielectrics only indirectly by the formation of ozone and other aggressive products. They are as numerous with d.c. voltage as with a.c. voltage.

(4) The inception voltage of discharges in cavities and of surface discharges is quite well calculable, starting from the Paschen curve of the gas in question. According to several authors [B3, C1] there exists good agreement between calculated and measured values, provided that the walls in the cavity are not short-circuited by semiconducting films, which either may be produced during the manufacturing of the dielectric or by the discharges themselves.

(5) The inception voltage of corona discharges is not readily calculable.

It depends on small effects such as sharpness of the electrode, moisture, surface conditions, etc.

(6) Discharges recur quite regularly during each half-cycle of an a.c. voltage. If the discharge impulses are displayed on an oscilloscope with appropriate time-base they are seen as fairly stationary groups of discharges. In some cases the discharge pattern is characteristic for the kind of discharge, such as discharges adjacent to an electrode, surface or corona discharges.

(7) The magnitude of a discharge is defined by the amount of charge transferred in the leads of the sample. The discharge magnitude q is related in a simple way to discharge energy w and inception voltage V_i: $w \simeq 0{\cdot}7qV_i$. The magnitude of internal discharges increases with increasing cavity dimensions.

(8) According to Mason the deterioration of dielectrics generally takes place in three stages. At first the attacked surface is uniformly eroded; then pits are formed (in case of internal discharges at the periphery of the cavity); after that sharp channels are formed which lead to breakdown (treeing). The rate of deterioration is proportional to frequency, increases strongly with stress, and depends on the kind of dielectric.

(9) In order to determine the discharge resistance of insulating materials several test methods have been devised. With most methods surface discharges are used. The tests are accelerated with higher stresses or higher frequencies. Tables have been drawn up in which the insulating materials are placed in order of succession of their discharge resistance. However, these Tables do not prove to be valid under all circumstances, and differences exist between the results of different methods.

(10) It is believed that discharges below a certain magnitude are harmless to the dielectric. This limit is called the permissible discharge magnitude; it is strongly dependent on the stress at which the dielectric is operated. Some estimations of this permissible discharge magnitude are found in literature; they amount to about 2 pC at 3 kV/mm and correspond to speculations made by the author in Section 6. In these speculations it is assumed that there is a maximum cavity depth which is permissible. The smallest discharge which may occur in a cavity of that depth is calculated and taken as the permissible discharge magnitude. From this point of view not every discharge larger than 2 pC is dangerous but only those occurring in cavities of the critical depth.