(iii) *Photo-ionization.* A molecule in the ground state can be ionized by a photon of frequency ν provided

$$h\nu > E_i.$$

Experimental determination of the probability of the photo-ionization process in the common gases is difficult partly because of the higher absorption of radiation of short wavelength (i.e. $\leqslant 900$ Å). Photons will be absorbed in passing through a gas according to the equation $I = I_0 \epsilon^{-\mu x}$, where I_0 is the initial number of photons entering the gas and x is the distance travelled by the beam. μ is the absorption coefficient (dependent on gas and wavelength).

The above processes are the most important in relation to the gas discharge phenomena under discussion here. Other possible gas processes include ion–atom collisions, excited atom–molecule collisions, auto-ionization, atom–atom collisions. It should be noted, under the present conditions, that collisions between ions and atoms do not normally result in ionization, due to the relatively slow interaction time which allows the internal motion of the atomic system to adjust itself gradually to the changing condition without any energy transition occurring; i.e. such collisions are elastic. In order to cause ionization of a neutral unexcited atom of its own kind, a positive ion must possess energy of at least $2eV_i$: normally ions and atoms having such energies are encountered only in high current arc and thermonuclear discharges.

A more detailed account of these gas processes is available, for example, in Ref. 3.

Electrode processes are discussed in Chapter 5.

3 *Breakdown Characteristics in Gases*

By L. L. ALSTON

3.1. Phenomena in uniform fields

3.1.1. *Paschen's law*

IT HAS been shown in Section 2.2.1.2 that in a uniform field the Townsend criterion for the breakdown of gases which are not electronegative is

$$\gamma(\epsilon^{\alpha d} - 1) = 1 \tag{1}$$

and the coefficients, γ and α, are functions of E/p, viz.[1]

$$\alpha = pf_1\left(\frac{E}{p}\right)$$

and

$$\gamma = f_2\left(\frac{E}{p}\right),$$

also

$$E = V/d,$$

since the field is uniform.

Substituting for E in the expressions for α and γ, and then substituting for α and γ in eqn (1) gives:

$$f_2\left(\frac{V}{pd}\right)\{\epsilon^{pdf_1(V/pd)} - 1\} = 1. \tag{2}$$

Equation (2) gives the breakdown voltage, V, implicitly in terms of the product of gas pressure, p, and electrode separation, d; in other words, variations in pressure and spacing affect the breakdown voltage only because they affect the product pd. It can be shown that this conclusion applies also to attaching gases, so that in general

$$V = f(pd). \tag{3}$$

This is Paschen's law, so named after the scientist who established it towards the end of the last century, from measurements of breakdown voltage in air, CO_2, and hydrogen. It is one of the most important laws in high-voltage technology.

The relation between V and pd has been sketched in Fig. 3.1. Typically the voltage minimum is 300 V and occurs at $pd = 5$ mmHg cm. To explain the shape of the curve, consider a gap of fixed spacing, and let the pressure decrease from a point to the right of the minimum. The density therefore decreases, and consequently an electron makes fewer collisions with gas molecules as it travels towards the anode. Since each collision results in a loss of energy, it follows that a lower electric stress suffices to impart to electrons the kinetic energy required to ionize by collision.

When the minimum is reached, the density is low and there are relatively few collisions. It is necessary now to take into account the fact that an electron does not necessarily ionize a molecule on colliding with it, even if the energy of the electron exceeds the ionization energy; the electron has

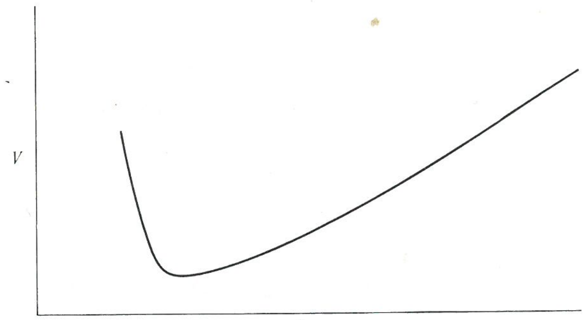

FIG. 3.1. Breakdown characteristic.

a finite chance of ionizing, which depends upon its energy. If the density and hence the number of collisions is decreased (the density being quite small) breakdown can occur only if the chance of ionizing is increased, and this accounts for the increase in voltage to the left of the minimum.

It is worth noting that if the density is fixed, breakdown to the left of the minimum occurs more readily (i.e. at lower voltages) along longer distances. If the gap spacing is fixed also, the electron trajectory may nevertheless be lengthened by applying a magnetic field to the gap, and this accounts for the lowering of breakdown voltage which is caused by magnetic fields.

3.1.2. *Phenomena at high pressures*

Electrode material does not effect breakdown at atmospheric pressure, but becomes important if the pressure is increased sufficiently. Trump[2] obtained significantly higher breakdown voltages between stainless steel than between aluminium electrodes at as little as 5 atm, and at 28 atm the breakdown gradients were 1170 and 770 kV/cm respectively.

Another high-pressure phenomenon is that if the voltage is supplied from a low-energy source, then the breakdown value increases on successive

flashovers, until a constant value is reached. The electrodes are then said to be conditioned. This increase in voltage is ascribed to the burning off by sparking of microscopic irregularities or impurities which may exist on the electrodes. At sufficiently high pressures (normally above 10 atm) even this constant breakdown voltage is less than that obtained at the same *pd* value at a lower pressure: in other words, Paschen's law fails. Increasing the pressure results in an increase of breakdown voltage even in these circumstances,[1, 3–5] except that in nitrogen the breakdown voltage has been found to be virtually independent of pressure for gaps of 1 to 2 mm above 30 atm.[3]

These phenomena can be accounted for by field emission, which is known to depend on the smoothness and composition of the cathode surface. Field emission results in a current which distorts the electric field, and Paschen's law fails because it applies to uniform fields only.

Paschen's law fails for similar reasons at very low pressures, as will be seen in Chapter 4.

3.1.3. *Temperature effects*

The discussion given so far has ignored temperature variations. However, it has been shown in the discussion of Fig. 3.1 that pressure affects breakdown by affecting density. A more general statement of Paschen's law is therefore $V = f(\rho d)$ where ρ is the density; this takes into account the effect of temperature. The validity of Paschen's law has been confirmed experimentally[6] up to 1100°C. Further increase in temperature must ultimately result in failure of Paschen's law because of thermal ionization (above 2000°K),[7] or thermionic emission, or simply due to distortion of the electrodes by heat.

Hot spots may exist on electrodes, for example after an arc has burned in a circuit breaker. Their effect is almost the same as if the whole gap were at the temperature of the hot spot.[6] The reason for this is that the electric strength is lowered near the hot spot, and once ionization occurs there, the field becomes distorted and this tends to cause a complete flashover.

3.1.4. *Breakdown characteristics*

Gaps of more than 10^{-2} cm at n.t.p. have ρd values well to the right of Paschen's minimum, and the breakdown voltage increases roughly in proportion with ρd up to the limits of validity of Paschen's law. In air the exact formula for the voltage is[8]

$$V = 24{\cdot}22\frac{293p}{760T}d + 6{\cdot}08\sqrt{\left(\frac{293p}{760T}d\right)}$$

where p is the pressure in mmHg, T is the temperature in °K, d the spacing in cm, and V the voltage in kV. Note that even in a uniform field, at constant pressure and temperature, the electric strength is not constant; with $p=760$ and $T=293$

$$E = 24{\cdot}22+\frac{6{\cdot}08}{\sqrt{d}}\ \text{kV/cm}$$

which tends to 24 kV/cm in long gaps; the value of 30 kV/cm, which is sometimes quoted as the electric strength of air applies only for

$$\frac{293p}{760T}d = 1,$$

i.e. for a 1-cm gap at 760 mmHg and 20°C.

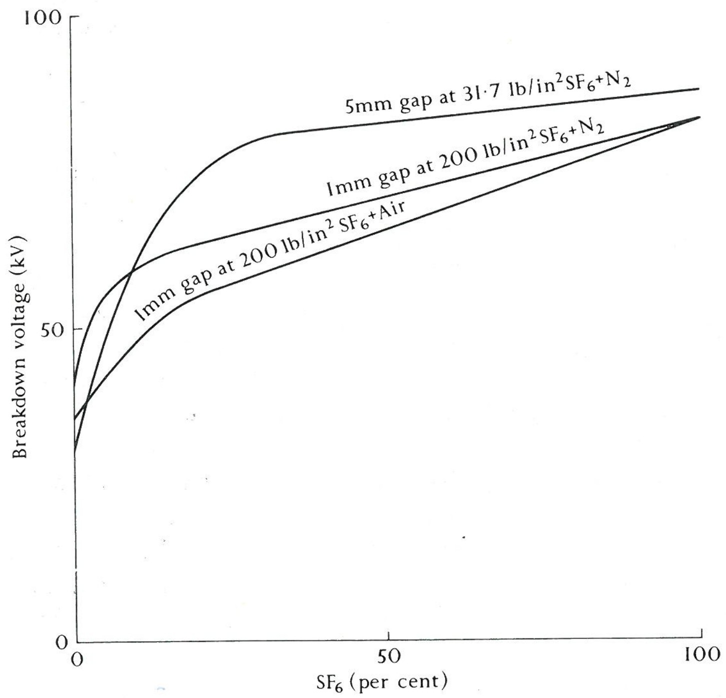

FIG. 3.2. Dependence of breakdown voltage on SF_6 content for mixtures of SF_6 with air and nitrogen. The abscissa is the partial pressure of SF_6 expressed as a percentage of the total pressure of the mixture. From data by Howard[4] and Cohen.[3]

The ratio of breakdown voltages in different gases at a given ρd depends on the value of ρd; however, the ratios given in Table 3.1 are typical to the right of Paschen's minimum.

The most commonly used high-strength gas is SF_6, a characteristic of which is that it maintains a high electric strength even if diluted with another gas (see Fig. 3.2). Vapours of higher strength are known, but most of them liquefy at atmospheric pressure and room temperature.[9] C_5F_8, which was discovered recently by a group under Professor Tatlow at Birmingham University, has a boiling point of 25°C at atmospheric pressure.

TABLE 3.1

Relative electric strengths

Air	1
Nitrogen	1
SF_6	2·5
30% SF_6+70% air (by volume)	2
C_5F_8	5·5
Hydrogen	0·5

3.2. Phenomena in non-uniform fields

If the maximum stress in a gap is less than above five times the mean stress, phenomena are very similar to those in a uniform field. In more divergent fields, however, a new phenomenon occurs: at voltages below breakdown, ionization may be maintained locally, in the region of high stress. This ionization is termed corona.

The stress required for the onset of corona in the vicinity of a cylinder depends upon its radius, as shown in Table 3.2.

TABLE 3.2

Corona inception stress in air of relative density δ ($\delta=1$ *at 760 mmHg and 20°C*)

Configuration	E_i (kV/cm)
Concentric cylinders, inner cylinder radius r	$31\delta\left(1+\frac{0{\cdot}308}{\sqrt{\delta r}}\right)$
Parallel cylinders of radius r	$30\delta\left(1+\frac{0{\cdot}301}{\sqrt{\delta r}}\right)$

These relations were obtained by Peek,[10] from experiments in which δ had values up to about 1; they require confirmation at higher densities.

It will be seen from the table that the stress increases as r decreases. The reason for this is that electrons must be accelerated over a finite distance to cause avalanches. The smaller r, the more rapidly does stress fall with distance, and therefore the higher the stress required at the electrode. The corona inception voltage can be calculated for cylindrical configurations by using the stress given in Table 3.2, and the appropriate formula from Table 1.1.

The similarity relations[1] can be used to show that for any configurations of the same shape and different sizes, the corona inception voltage in a given gas is given by $V=f(\rho d)$ where d is the gap spacing and ρ the density. This is of the same form as Paschen's law, but in a non-uniform field all dimensions must be varied in proportion with the spacing.

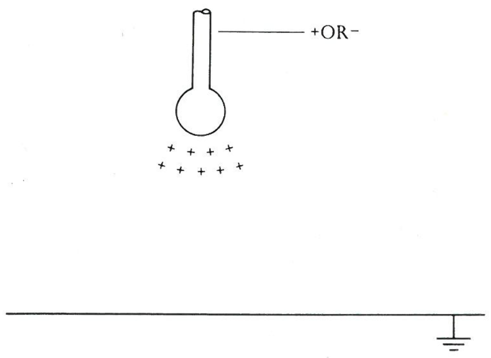

FIG. 3.3. Space charge in sphere–plane gap.

Once corona starts, the electric field becomes distorted by space charge, and the dependence of the breakdown voltage on the electrode configuration is much more complex than the dependence of the corona inception voltage. However, several qualitative generalizations can be made, and they will now be discussed with reference to a sphere–plane gap. With this, as with any other asymmetrical gap, the value of the breakdown voltage in air depends upon polarity. Experiment shows that if the field is sufficiently divergent for corona to occur, the voltage required for breakdown is smaller if the sphere is positive than if it is negative. This polarity effect may be explained as follows. When avalanches occur, the electrons move quickly to the anode, leaving behind a positive space charge in the region of high stress, i.e. near the sphere (see Fig. 3.3). If the sphere is positive the space charge acts as an extension of the electrode, but if the sphere is negative, the space charge acts as a screen which decreases the stress between it and the other electrode, and so tends to prevent flashover.

Because of this polarity effect, characteristics obtained with the sphere positive are usually more important for practical applications, and Fig. 3.4

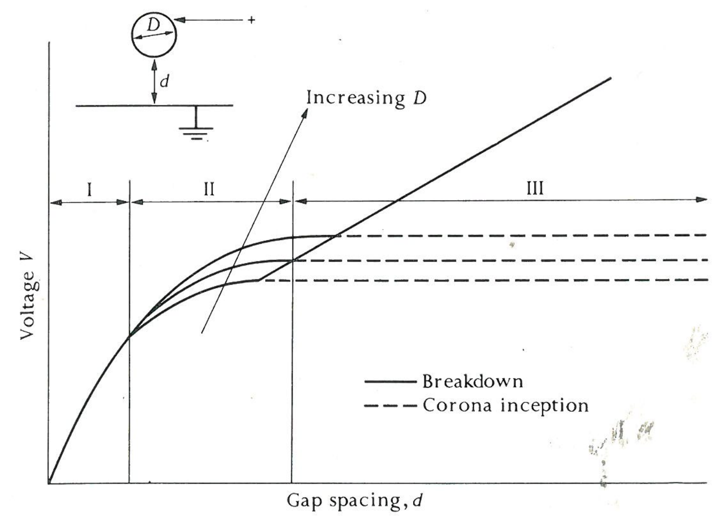

FIG. 3.4. Sketch of breakdown and corona inception characteristics for spheres of different diameters.

illustrates the dependence of the voltage on the gap spacing and sphere diameter. There are three main regions, viz:

(I) At small spacings the field is nearly uniform, even with spheres of relatively small diameter. The voltage depends mainly on the spacing.
(II) At moderate spacings (up to about 2 sphere diameters) the field is non-uniform. The voltage therefore increases with the sphere diameter, as well as with the spacing. The effect of spacing on stress decreases as the spacing increases.
(III) At large spacings, breakdown is preceded by corona. The maximum stress and therefore the corona inception voltage are controlled mainly by the sphere diameter, though the spacing also has some effect. The breakdown voltage depends only on the spacing.

Actual breakdown characteristics are given in Fig. 3.5 and in Ref. 11.

The dependence of voltage on sphere diameter for a system of fixed overall dimension, Y, is shown in Fig. 3.6; this characteristic follows readily from Fig. 3.4, if it is borne in mind that an increase in diameter causes a decrease in spacing. It will be seen that a decrease in diameter may increase the breakdown voltage at the expense of the corona inception voltage. This characteristic is sometimes used in practice, by creating regions of high stress in a moderately divergent field in order to raise the flashover voltage. Unfortunately this increases the corona level, which has undesirable chemical effects. To illustrate quantitatively the relation between voltage and sphere diameter at fixed Y, data obtained in sphere–

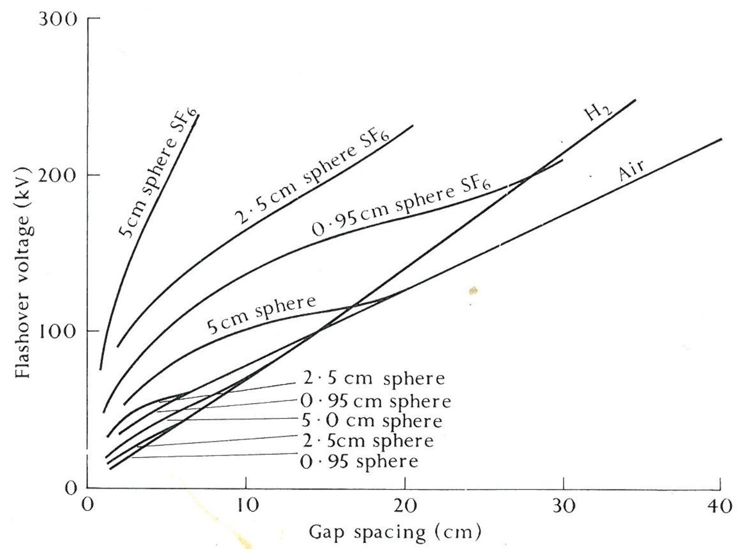

FIG. 3.5. Flashover characteristics in air, hydrogen, and sulphur hexafluoride (reproduced by courtesy of A. Reyrolle & Co.).

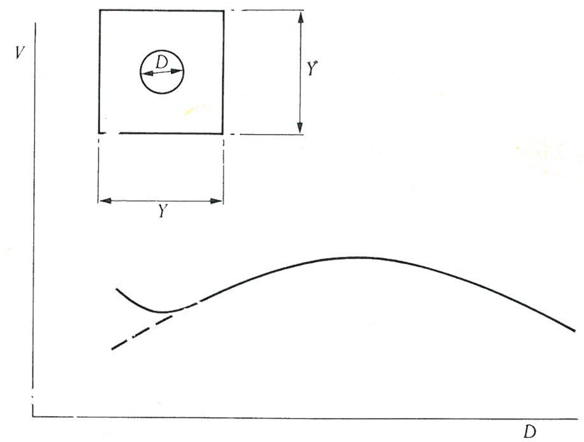

FIG. 3.6. Sketch of corona and breakdown characteristics as function of sphere diameter for a container of fixed dimensions.

plane experiments have been replotted in Fig. 3.7 for fixed values of the distance, $Y/2$, between the sphere centre and the plane.

The effect of pressure,[4,5,12] is illustrated in Fig. 3.8 for electronegative gases, which include oxygen (and therefore air), SF_6, and Freon. Increasing

the pressure increases the corona inception voltage. The breakdown voltage also increases initially, but reaches a maximum (at some 100 p.s.i. in air)

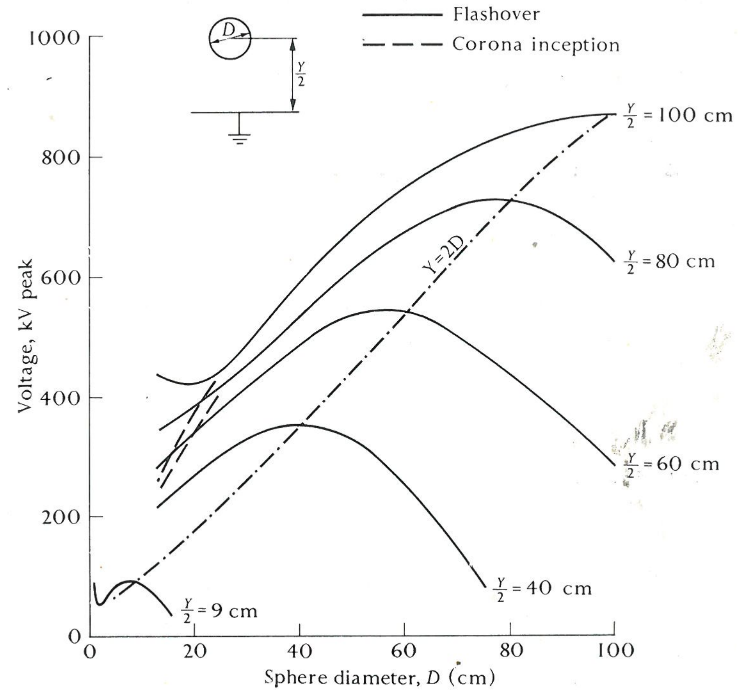

FIG. 3.7. Characteristics of sphere–plane gap in air. From analysis of data given in Ref. 11 and from data reproduced by courtesy of A. Reyrolle & Co.

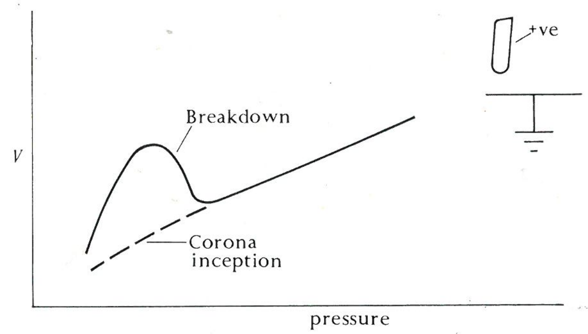

FIG. 3.8. Dependence of breakdown and corona, inception voltage on pressure in a non-uniform field.

and then falls down to the corona inception voltage. Increasing the pressure may therefore decrease the breakdown voltage. In pure nitrogen, which is not electronegative, breakdown is not preceded by corona at any pressure.[12]

It is worth noting that hot spots on the electrodes have a much smaller effect than in uniform fields.[6] A hot spot in the sphere of a sphere–plane gap decreases the electric strength locally and lowers the corona inception voltage; however, if the field is sufficiently non-uniform the hot spot has little effect on breakdown (presumably because there is in any case considerable corona before breakdown). If the hot spot is in the plane, it has no effect unless the lowering of electric strength due to the hot spot is sufficient for breakdown to start from the plane instead of from the sphere: this requires a hot-spot temperature equal, to a first approximation, to

$$(\text{ambient temperature}) \times \frac{(\text{stress at sphere})}{(\text{stress at plane})}$$

For example, a 1200°C hot spot in either electrode lowers the breakdown voltage by less than 20 per cent in a gap consisting of a 2·5-cm sphere 8 cm away from a plane.

3.3. Surface flashover

If a piece of solid insulation is inserted in a gas so that the solid surface is perpendicular to the equipotentials at all points, then the voltage gradient

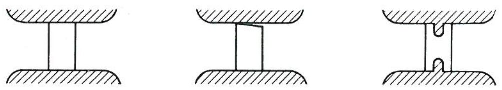

FIG. 3.9. Sketches illustrating the discussion on surface flashover.

is not affected by the solid insulation. An example of this is a cylindrical insulator in a uniform field (see Fig. 3.9(a)). If the insulator is clean and conforms accurately to cylindrical shape, its insertion does not affect the breakdown voltage, but if these conditions are not fulfilled a substantial lowering of the breakdown voltage can occur, as will now be explained.

3.3.1. *Imperfection of shape*

Field intensification results if solid insulation departs even in detail from the cylindrical shape. In particular, if the edges are chipped, or if the ends of the cylinder are not quite perpendicular to the axis (see Fig. 3.9(b)) then an air gap exists next to an electrode, and the stress there can reach up to k times the mean stress in the gap (where k is the dielectric constant of the cylinder). Discharges may therefore occur at a voltage approaching $1/k$ times the breakdown voltage in the absence of cylinder and these discharges can precipitate a breakdown. A possible method of reducing the stress in the air gap is shown in Fig. 3.9(c); with this technique, the breakdown

voltage can easily be maintained within 30 per cent of that obtained in the absence of the cylinder.

3.3.2. *Effect of moisture*

The effect of ambient humidity is illustrated in Fig. 3.10 for perfect cylinders.[13] It will be seen that if the humidity is sufficiently high, the breakdown voltage falls—due to the formation of conducting paths on the

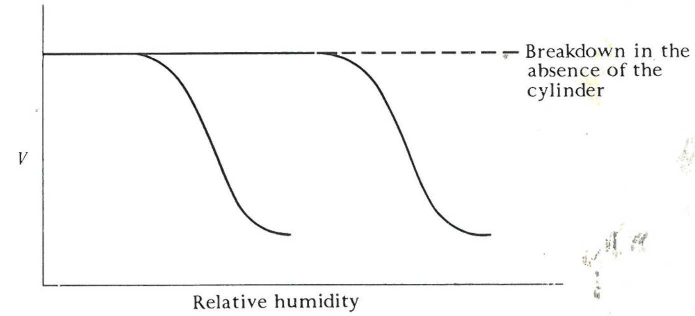

FIG. 3.10. Surface flashover characteristics for two cylinders of different materials.

surface of the cylinder. The value of relative humidity at which the voltage collapses depends on the cylinder surface; it is much greater for perspex and cast resin than for glass or porcelain.

3.3.3. *Heavy pollution*

Outdoor insulation, such as overhead line insulators, can become heavily polluted, and its consequent flashover constitutes one of the most difficult high-voltage problems.[14] The mechanism of flashover is as follows. Pollution becomes deposited on the surface; this pollution may be industrial in origin, or it may be salt in coastal areas. It does not affect the performance of the insulation significantly unless it becomes moist, for example due to fog or dew deposition. The pollution then becomes conducting, and causes considerable field distortion. Sparkover occurs in regions of high stress, and discharges burn along small portions of the insulator. These discharges are maintained by current flowing through the polluted but discharge-free portions of the insulator. Now, the discharges dry the pollution near their roots, and dry pollution does not conduct; to maintain conduction, therefore, the discharge roots must travel along the insulator to a region which is still moist. The voltage required to maintain conduction along the insulator surface equals the sum of the voltage drops along the discharges, and along the discharge-free surface in series with them. As the discharges elongate, the voltage required to maintain conduction varies, and it can exceed the supply voltage: under these conditions flashover clearly cannot occur.

An analysis[15] based on these considerations has shown that if the polluted surface has a resistance $r\ \Omega$ per unit length, and a total length L cm, then flashover cannot occur if the supply voltage, V, is less than $10{\cdot}5Lr^{0{\cdot}43}$ volts; the maximum leakage current in the absence of a flashover is $233(V/L)^{-1{\cdot}31}$ A. These conclusions are pessimistic, in that phenomena which were ignored in the analysis may also prevent a flashover; however, under suitable conditions the discharges elongate until they span the electrodes, and flashover then occurs.

3.4. Dielectric recovery

Immediately after the current flowing through an arc is interrupted, the gas is ionized and at high temperature, and consequently its electric strength

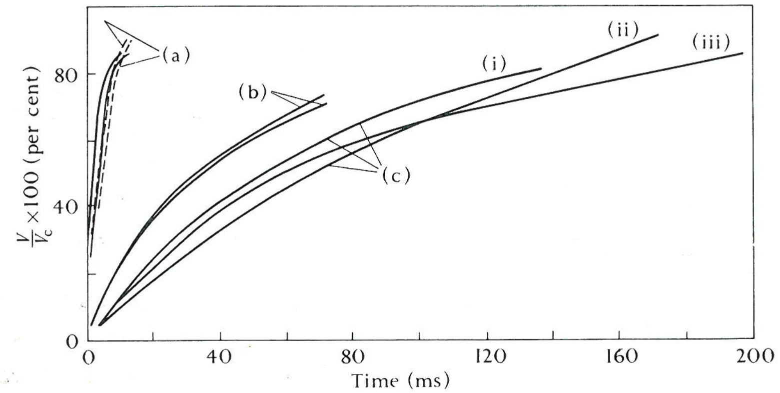

FIG. 3.11. Comparison of dielectric recovery curves. V = flashover voltage; V_c = value of V in un-ionized air.

(a) Surge-current arcs.[16] Envelopes of curves obtained with surge currents 1–20 kA (peak), 20–1000 μs duration.

- - - - - 11-in rod-gap, $V_c = -238$ kV.
——— 6-in rod-gap, $V_c = -130$ kV.
Negative polarity throughout.
Flashover on the tail of the voltage wave.

(b) Power-frequency arcs.[17] Current of 700 A for 0·7 s. Rod-mesh gap. Mesh earthed.

Top curve: V positive; $V_c = +250$ kV.
Bottom curve: V negative; $V_c = -340$ kV.
Flashover on the tail of the voltage wave.

(c) Power-frequency arcs.[18] Current of 300 A (peak) for 1/120 s.

(i) 3-in rod-gap, $V_c = 83$ kV.
(ii) 6-in rod-gap, $V_c = 129$ kV.
(iii) 11-in rod-gap, $V_c = 192$ kV.
Flashover on the tail of the voltage wave.

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is low initially. However, the strength increases as the gas de-ionizes and cools, until it reaches the value which it had before the arc-over. This ability to recover electric strength is characteristic of gases and is illustrated in Fig. 3.11; it will be noted that it is much more rapid after short duration arcs than after power-frequency arcs, even though the latter carried smaller currents.

Solids clearly cannot recover their insulating characteristics, while in liquids impurities produced by the arc usually remain dissolved or in suspension and cause a permanent reduction of the electric strength. It should be noted that even in gases damage caused by the arc to the electrodes may distort the field so that a permanent lowering of the breakdown voltage results; this effect is much more marked in uniform fields than in non-uniform fields in which the field is intensified at the electrodes even before the flashover.

3.5. References

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