# Review of high-voltage gas breakdown and insulators in compressed gas

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*Indexing terms:* *Breakdown and gas discharges, Arcing, Insulators and insulation*

**Abstract:** In the past ten years there have been significant advances in the theoretical and experimental analysis of high-voltage gas breakdown and surface flashover of insulators in compressed gases. This has probably been fostered by the recent growth in the design and application of gas-insulated high-voltage equipment. The review describes the characteristics of compressed-gas breakdown, including the effects of failure of Paschen's law; conditioning; electrode area; material and surface; breakdown-voltage distribution; particle contamination; voltage waveform; temperature; and gas mixtures. The insulator-flashover characteristics are then described, including the effects of insulator-electrode interface; insulator material; insulator shape; voltage waveform; charge generation; particle contamination; surface contamination; conditioning; flashover distribution; and dependence on type of gas. The various mechanisms proposed for gas breakdown and insulator flashover are reviewed and discussed in relation to the experimental characteristics. Future theoretical and experimental work is suggested to clarify the gas-breakdown and insulator-flashover mechanisms, and which would also help bring about the design of improved high-voltage gas-insulated systems.

## 1 Introduction

In the past ten years there has been a tremendous increase in the interest in the electrical-breakdown characteristics of compressed gases. This has been fostered by the advances in equipment such as gas-insulated circuit breakers, substations, transmission lines, cables, current transformers, voltage transformers, and high-voltage generators.

The objective of this review is to describe the general characteristics of gas breakdown and insulator flashover in compressed gases in uniform or quasiuniform fields, and to discuss the various proposed mechanisms of breakdown. This review concentrates primarily on the advances since the previous review published in 1970 [1]. Although the Figures are selected for $SF_6$ systems, for convenience and consistency, the text is intended to be general for all compressed gases.

## 2 Electrical breakdown in compressed gases

### 2.1 Breakdown characteristics

*2.1.1 Deviations from Paschen's law:* Paschen's law, that the gas breakdown voltage $V_s$ in a uniform field is only a function of the product gas density $\rho$ and electrode separation $d$, is satisfied by most gases at pressures below atmospheric when the field $E$ is low [1]. As the pressure is increased so that the breakdown field correspondingly increases, it is observed that deviations occur from the characteristic curve of $V_s$ as a function of $\rho d$ (Fig. 1) [2]. Usually the gas pressure $p$ is used instead of $\rho$, which is valid as long as the experimental conditions (temperature, pressure) ensure a proportionality between $p$ and $\rho$. These deviations generally begin to occur at fields of the order of 10 MV/m to 20 MV/m for electrodes prepared under standard laboratory conditions. These deviations are strongly dependent on the conditions of the electrode surface and gas cleanliness. The relationship has been verified to fields of 100 MV/m, if extreme conditions of cleanliness and surface preparation are taken, or with dielectric-coated electrodes or single crystal electrodes [1–3].

*2.1.2 Conditioning effects:* A 'conditioning' effect is defined as the increase in the breakdown voltage by the test procedure.

Paper 1291A, presented in original form at IEE 6th International Conference on Gas Discharges and their Applications, 8th–11th September 1980

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The most common observed effect is 'spark conditioning' [1, 4], where the breakdown voltage increases with the number of breakdowns, usually to a 'plateau' value (Fig. 2) [4]. The first breakdown is usually low, particularly for freshly prepared electrodes [1, 4]. Spark conditioning becomes significant when the field exceeds 10 MV/m to 20 MV/m for all gases. The amount of spark conditioning is a function of the electrode surface area, electrode surface roughness, and dust. Usually, the number of sparks for conditioning and scatter in the breakdown values increase with the stored energy [5], but some tests have indicated otherwise. Usually it is the cathode that controls conditioning, although an anode effect has also sometimes been detected.

Another form of conditioning is termed 'stress conditioning' where the applied voltage is raised in steps (ranging from

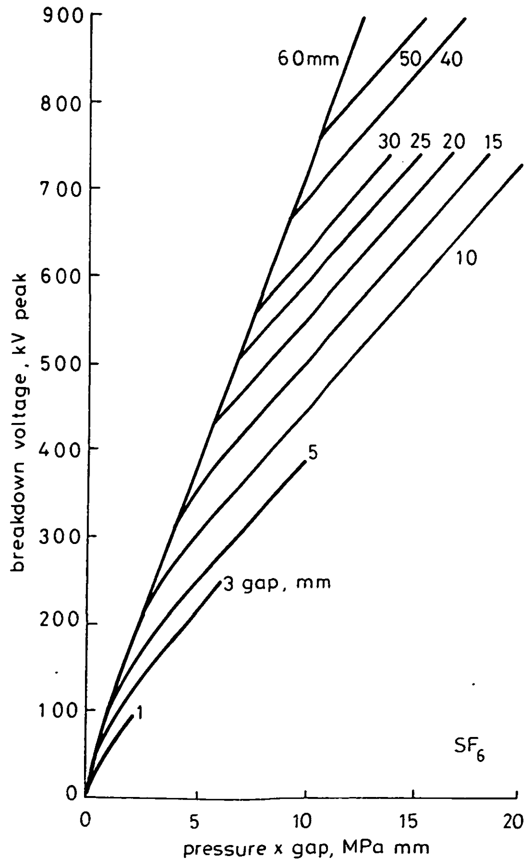


**Fig. 1** *Paschen plot for AC uniform field breakdown in clean $SF_6$ [2]*



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minutes to hours). Usually the first breakdown value can be increased compared with spark conditioning, but the final conditioned values will be less than for the spark-conditioned system. Stress conditioning is now often used in testing practical gas-insulated systems to elevate and move conducting particle contaminants into 'particle traps' where the particles are deactivated [6] (see Section 2.1.4).

The spark-conditioning process is probably the progressive destruction of electrode protrusion sites, oxide layers or larger particles that initiate breakdown (Section 2.2). Stress conditioning is attributed to the destruction of the protrusions or emission sites by ion bombardment and could also be due to movement of contamination out of the highly stressed areas.

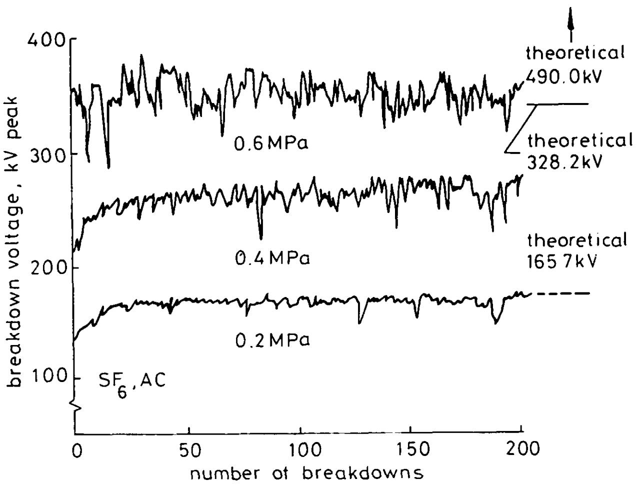


**Fig. 2** *Spark conditioning in $SF_6$ for 132 mm/152 mm diameter coaxial electrodes, 116 mm long with ± 0.5 μm finish [4]*

*2.1.3 Electrode effects:*

(*a*) *Electrode material:* The effect of electrode material is complex. The general listing of cathode materials in the order of decreasing breakdown voltage and increasing scatter of breakdown results [1] is as follows: stainless steel, copper, iron, carbon-steel, brass, silver, zinc, aluminum, nickel, carbon. However, this refers to the spark-conditioned breakdown value. If one refers to the first breakdown voltage, results may indicate relatively small dependence on the electrode material. Spark conditioning is observed to produce metallic dust which is strongly dependent on the stored energy and on the anode and cathode materials. This dust then can initiate subsequent breakdowns.

(*b*) *Electrode surface finish:* The surface finish of the electrodes (usually the cathode) has a strong influence on the breakdown voltage [1, 7–9]. Experimental and theoretical analysis have shown that the deviations from Paschen's law are a function of the product of gas pressure $p$ (or density) and the height $h$ of the surface protrusion. For $SF_6$ deviations begin when $ph$ is of the order 4 kPa mm; in air, deviations begin when the $ph$ value of the order ten times larger.

This effect of surface protrusions is reflected in the surface-finish importance. Thus, very highly polished surfaces generally give a better finish than sandblasted surfaces [1, 10, 11]. Etching can give even better 'first' and conditioned breakdown values than polished or sandblasted electrodes [11].

Studies on single-crystal cathodes of tungsten and molybdenum have been reported to enable Paschen's law to be verified in high-pressure nitrogen (3 MPa) to fields of 100 MV/m [1].

(*c*) *Electrode coatings:* Controlled insulating coatings on the electrodes, particularly the cathode, can significantly increase $V_s$ by 25% to 50% so that Paschen's law can be satisfied to higher pressure and fields than for bare electrodes [1, 12, 13].

Evidence for the effect of resistivity and permittivity of the coating is conflicting [1]. Generally, the coating thickness is not critical unless the layer is of adequate thickness to withstand the voltage after breakdown of the gas. Oxide layers have given generally erratic results with high and low values. Coatings can also sometimes prevent particle movement.

Dielectric-coated electrodes can increase the gas breakdown voltage by

(i) effectively shielding electrode protrusions from the gas, and preventing emission currents and subsequent ionisation

(ii) preventing, or delaying, particle movement to higher fields and delaying the particle-initiated breakdown process.

(*d*) *Electrode area effect:* There is extensive experimental verification that the breakdown voltage in all gases is strongly dependent on the electrode area [1, 4, 14], even at pressures as low as atmospheric, and for fields as low as 7 MV/m. This effect becomes more pronounced with increasing pressure and electrode area (Fig. 3) [14].

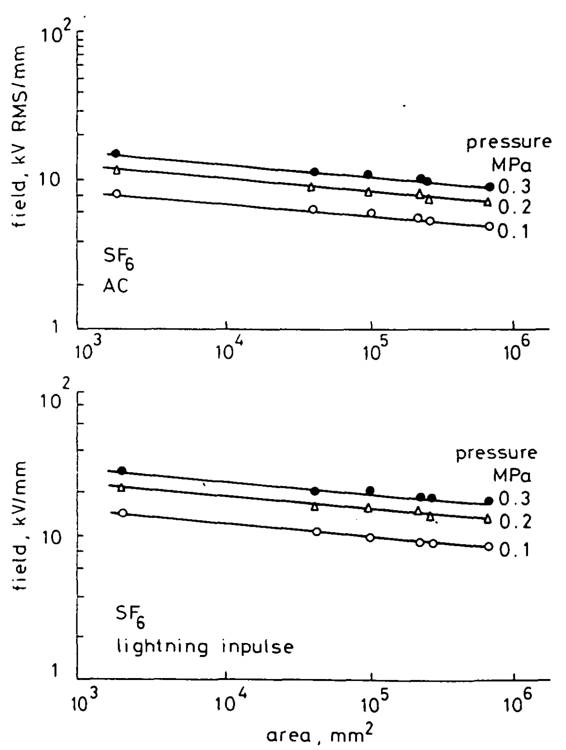


**Fig. 3** *Breakdown field in $SF_6$ as function of equivalent electrode area [14]*

The area effect is related to the extreme-value breakdown distribution (Section 2.1.4) relating breakdown initiated at a 'weak point' on an electrode surface.

Nitta *et al.* [4] proposed an extreme-value distribution of the form:

$$P(A) = 1 - \exp\left\{-\lambda A\left(\frac{E - E_o}{E_d}\right)^m\right\} \qquad (1)$$

Where $P(A)$ is the cumulative probability of breakdown, $A$ is the electrode area, for which the breakdown field is $E$, and $E_d$ is the theoretical breakdown field. $E_o$ is the minimum breakdown field for very large electrode area at a particular pressure, dependent only on the gas and pressure: $\lambda$ is a constant dependent on the gas, surface roughness and pressure; $m$ is a constant dependent on the gas, but independent of pressure or surface roughness, being equal to 7.4 for $SF_6$. Their results suggested a minimum value of $E_o$ independent of surface roughness. Other studies have not shown a minimum value of $E_o$ with increasing area and have used a modified Weibull distribution [14].

(*e*) *Electrode separation:* The breakdown field in a compressed gas generally decreases with increasing electrode separation [1, 15], particularly at high pressures and fields. This can result in a saturation effect of the breakdown voltage; i.e. increasing the gap may have little effect on the breakdown voltage.

In low-pressure gases, this effect is due to ionisation over the gap, requiring a lower value of net ionisation coefficient for a critical value of the avalanche size (or chain). In compressed gases, the effect is enhanced by the breakdown being controlled by processes on, or very close to, the electrode surface (e.g. ionisation at protrusions).

(*f*) *Effect of electrode geometry:* This review is limited to uniform or quasiuniform fields, defined as where there is negligible corona before breakdown. This corresponds to geometries having a ratio of maximum to minimum field of the order less than five to ten.

Comparing uniform-field and nonuniform-field geometries (e.g. coaxial electrodes of diameter ratio of approximately 3), under these conditions the cathode field is usually the most critical, i.e. it determines breakdown. For the coaxial geometry or sphere-sphere geometry, the breakdown is usually lower when the inner, or highest stress, electrode is negative. However, sometimes for coaxial breakdown the characteristics cross over at a critical pressure with the positive highly stressed electrode giving the lowest breakdown voltage [1].

*2.1.4 Breakdown voltage distribution:* When Paschen's law is satisfied, the breakdown voltage distribution is normal with a standard deviation of less than 1%. When deviations from Paschen's Law begin to occur, there is increasing evidence that the distribution becomes abnormal [1, 4, 11]; standard deviations of 3% or more may become typical. The issue is further complicated by the distribution changing with spark conditioning or stress conditioning.

Most of the mechanisms proposed for compressed-gas breakdown voltages less than the Paschen law value have initiation at a 'weak link' on the cathode surface. Weibull distributions were originally developed specifically for these conditions assuming a weak link or flaw.

Nitta *et al.* [4] have shown that once Paschen's law has not been satisfied, the accumulated breakdown probability $P(A)$ satisfies eqn. 1, assuming a minimum breakdown field $E_o$ at very large values of electrode area.

Other studies [14] have indicated a better fit with experimental results for a zero value of $E_o$ (i.e. no limiting minimum value of breakdown field for very large electrodes).

*2.1.5 Particle contamination effects:* The influence of particulate contamination has received quite intensive [16–18] study as a consequence of the application of higher pressures and operating fields in gas-insulated equipment.

Testing has shown that the most deleterious type of particles are longer, metallic particles (Fig. 4). Under the influence of the field, the particles become elevated. For AC conditions the particles tend to hover near the lower electrode, and the 'bounce height' of the particle increases with voltage. In a coaxial geometry, for example, breakdown can occur when the particles cross the gap to the inner conductor and the field there is sufficient to initiate breakdown.

Under DC conditions [13, 17] the particles can cross the gap as soon as they are elevated. They can hover near the cathode and form 'fireflies'. For a coaxial geometry, the breakdown voltage can be lower than the AC value.

Under lightning and switching impulses, the particles do not have time to move until after the impulse has been applied, so the large particles are not as harmful as under AC and DC conditions, unless they have already moved onto an insulator.

In practical systems, particle traps are used to create zero, or very low, fields where the particles are deactivated. A conditioning voltage, usually AC, is used to elevate any particles and move them into the trapping regions [6, 17, 19, 20].

*2.1.6 Voltage waveform effects:* The effect of the different voltage waveforms on breakdowns is due to statistical and formative time lags of the breakdown mechanisms.

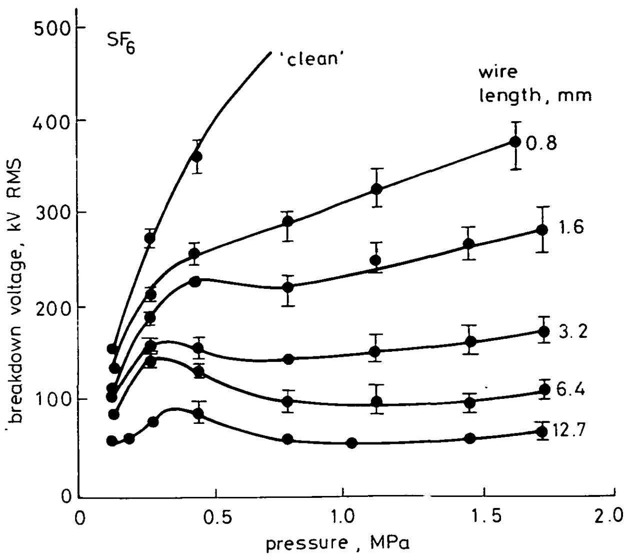


**Fig. 4** *Breakdown initiated by free copper wires, 0.4 mm diameter, in 150 mm/250 mm diameter coaxial geometry [16]*

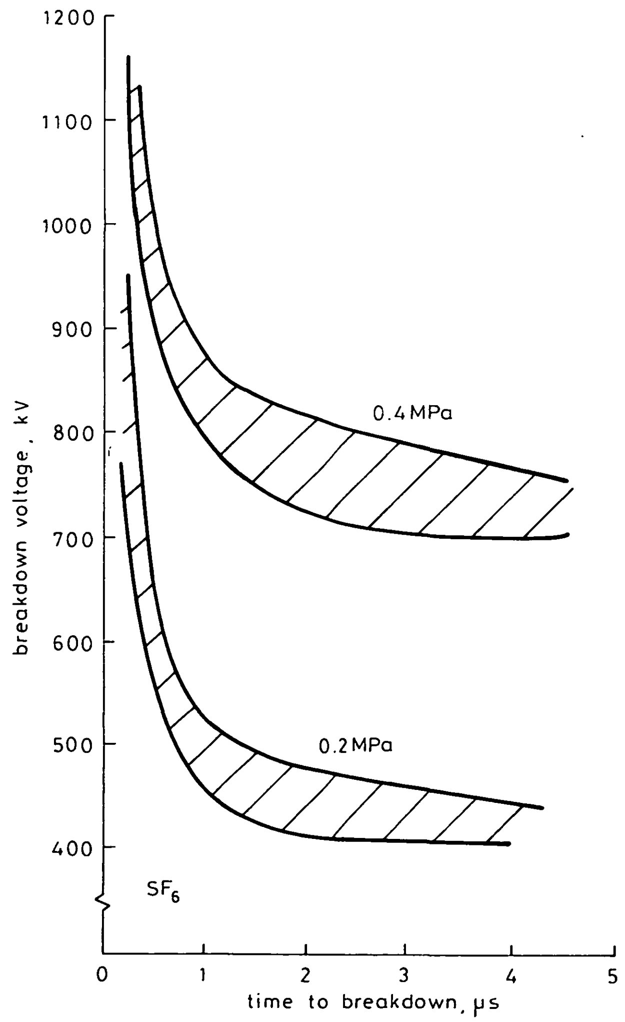


**Fig. 5** *Voltage/time characteristic for 90 mm diameter, negative sphere-plane gap of 40 mm [21]*

For impulse breakdown, it is essential to consider the statistical and formative time lags. The statistical time lag $t_s$, the time for the initiary electron to appear, can vary between milliseconds and seconds for unirradiated conditions [1]. This is usually attributed to 'field emission' being able to provide the initiatory electrons at the higher field. The formative time lag can be interpreted as the sum of two parts; the time $t_c$ for the electron avalanches to form or reach a critical value, and the time $t_f$ for the highly conducting spark channel to be formed by thermal ionisation for the voltage collapse. The total time lag $t_z$ is the sum of $t_s$, $t_c$, and $t_f$. These time lags are now being measured and calculated to determine the voltage/time-to-breakdown characteristics for compressed gases [21–23, 60].

A typical $V/t$ characteristic [21] is given in Fig. 5. Generally, the results indicate, for $SF_6$ and other compressed gases, that the upturning at short times is more pronounced for negative than positive impulses, and the upturn decreases with increasing pressure, increasing field and less field nonuniformity. With very nonuniform fields a minimum can occur at times of the order 10 $\mu$s. With rough electrodes or surface imperfections a minimum can occur at times of the order several hundreds of microseconds.

Comparing the AC and DC performance in compressed gases, under clean conditions the crest AC and DC breakdown values are almost identical. However, cleanliness is more severe under DC conditions as particles are more active, and then the DC value can be 20% lower.

An important parameter in practical systems is very long time $V/t$ characteristics corresponding to thousands of hours. In $SF_6$ a typical decrease in gas breakdown field is 3% per decade of time [24]. This decrease is attributed to statistical effects of the conditions at the electrodes (e.g. protrusions, dust, oxide).

*2.1.7 Temperature effects:* Paschen's law, that $V_s$ is a function of $pd$, is satisfied over a wide temperature range depending on the gas. Deviations occur when the gas decomposition, or ionisation, or attachment processes, are modified, or if the electrode emission or secondary ionisation coefficients are modified.

In $SF_6$, deviations begin to occur at about 453 K, and are attributed to a temperature dependency of the attachment processes [1]. In other, more temperature-stable gases (e.g. nitrogen, A, He), departures only occurred at temperatures of 1000 K to 2000 K when intense thermionic emission results in a lowering of the breakdown voltage [1, 25].

At the other temperature extreme, lowering the ambient temperature to 4.5 K in dense helium has shown that Paschen's law is satisfied until densities exceed 15 kg/m$^3$. The breakdown field then increases rapidly or reaches a limiting value [26].

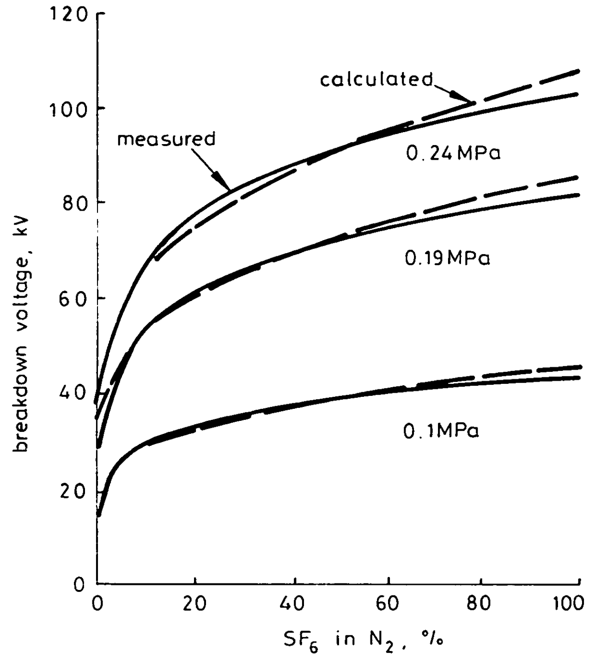


**Fig. 6** *Breakdown in $SF_6$-$N_2$ mixtures for 10 mm uniform field gap [28]*

*2.1.8 Gas mixtures:* There have been intensive investigations recently on gas mixtures mainly in an effort to develop gases or gas mixtures with superior characteristics to $SF_6$, presently used in gas-insulated equipment [1, 27].

Typically, the results for binary mixtures with a 'high-strength' gas, such as $SF_6$, and a 'low-strength' gas, such as nitrogen, are as given in Fig. 6 [28], where there is a saturation effect, i.e. for about 50% of the high-strength gas, 85% of the breakdown voltage is obtained, corresponding to 100% of the low-strength gas. Recent mixture studies have concentrated on multicomponent mixtures in an effort to blend mixtures which have electron-collision cross-section at low energies that 'complement' each other [27].

Experimental and theoretical studies in gas mixtures on the effect of electrode surface roughness have generally shown that surface imperfections have a similar effect on the mixture as for the component gases [29].

### 2.2 *Breakdown mechanisms in compressed gases*

*2.2.1 Failures of simple Townsend and streamer mechanisms:* When an electron leaves the cathode and moves to the anode at separation $d$, ionisation occurs in the gas in the applied field $E$ such that exp ($\alpha d$) electrons arrive (on average) as an electron avalanche at the anode. Here $\alpha$ is the first Townsend ionisation coefficient. The simple Townsend criterion is then

$$\gamma \exp(\alpha d) = 1 \tag{2}$$

where $\gamma$ is the second Townsend ionisation coefficent.

If electron attachment occurs to form negative ions, then the breakdown criterion is

$$\gamma[\exp\{(\alpha - \eta)d\} - 1] = 1 - \eta/\alpha \tag{3}$$

where $\eta$ is the attachment coefficient. Usually ($\alpha/p$) and ($\eta/p$) are functions of ($E/p$), where $p$ is the gas density. Paschen's law, that the breakdown voltage $V_s$ is only a function of $pd$, can be derived from the above equations. Usually the gas density $p$ is proportional to the gas pressure $p$ at moderate pressures. However, for some gases such as $SF_6$, deviations from this linearity can occur at moderate pressures.

An alternative breakdown mechanism is that one electron avalance can reach a critical size for the local field to be distorted sufficiently by the space charges of electrons and positive ions in the avalance head for initiation of a 'streamer'. The streamer breakdown criterion is when the critical avalanche size reaches approximately $10^8$ electrons. Pedersen [30] developed a streamer criterion for $SF_6$ of the form

$$\int_0^{z_o} \bar{\alpha}(z)dz = K \tag{4}$$

Where $\bar{\alpha}$ is the effective ionisation coefficient ($\alpha - \eta$), $z$ is line element in the field direction, and $z_o$ is the critical avalanche length, i.e. the length of the avalanche at the time of streamer formation. There is some controversy over the value of $K$, the discharge constant. This may vary between gases; a value of 10.5 is most frequently used, but values up to 18.6 are also used in some analyses.

At high pressures and fields when Paschen's law is apparently no longer valid, typical values of $\alpha d$ calculated from the nominal field conditions are too low (e.g. of value even less than ten) to satisfy either criteria (eqns. 2 and 3). Several mechanisms have been proposed to explain breakdown with these apparently low values of $\alpha d$.

*2.2.2 Breakdown due to enhanced ionisation at electrode protrusions:* Electrode surfaces always have surface imperfections such as microscopic scratches and projections. As the pressure is increased then at a particular value of $E/p$, the average distance between ionising collisons $(\alpha)^{-1}$ decreases. When it becomes comparable to the height of these electrode projections, significant additional ionisation can occur in the gas as a result of the field enhancement near the projection.

For this projection to have an effect, the initiatory electron must be produced at or near the projection. 'Field emission' is attributed for initiating electrons at the negative protrusions, but this is a general term to describe electrons appearing at high fields. For some gases, electron detachment from negative ions or impurities in the gas or on the cathode surface may be possible. Electron emission and subsequent current growth have been associated with cathode projections. These phenomena need further study to be clarified.

Calculations have been made of the reduction in breakdown voltage due to the ionisation at these projections, and with the streamer breakdown criterion eqn. 4 [1, 8, 9, 29–32]. The value of projection height ($h$) at which deviations begin to occur from the theoretical 'intrinsic' breakdown value, depends on the projection shape (Fig. 7) [31]. For $SF_6$ it typically begins for $ph \geqslant 4$ kPA mm, assuming the usual value of $K = 10.5$.

Some analyses indicated a 'limiting' value for breakdown voltage as a function of $ph$ below which breakdown could not occur. Recent analyses have shown that, if the electrode surface curvature is taken into account, there is no minimum value [32].

It is of interest to note that the criteria for projection-initiated breakdown by streamer may be interpreted as the corona-onset voltage, rather than the breakdown voltage. Some measurements have indicated that this may occur with small ($\sim 10\,\mu$m) projections. Future analysis must take this into consideration.

Other breakdown mechanisms which previously had been proposed for 'smooth' electrodes without projections may also be relevant for the case with projections [1]. These include enhanced $\gamma$ effect at the high-field sites; high local density, resulting in enhanced ionisation; and the space-charge field in the gas increasing the field at the cathode and increasing ionisation in the gas.

*2.2.3 Breakdown due to enhanced emission at cathode:* Earlier-proposed mechanisms have suggested enhanced electron emission at the cathode initiating breakdown [1]. These were considered occurring at a cathode with no consideration of projection-enhanced ionisation in the gas. In one mechanism, the positive ions, produced by ionisation, drift to the cathode area, and increase the cathode field sufficiently to increase electron emission. This results in an emission-ionisation runaway mechanism leading to breakdown.

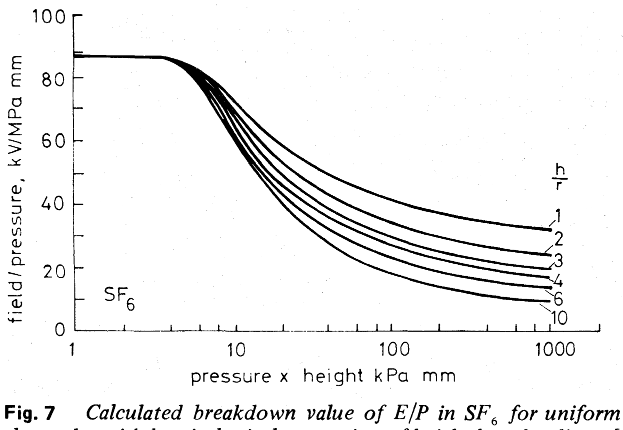


**Fig. 7** *Calculated breakdown value of $E/P$ in $SF_6$ for uniform field electrodes with hemispherical protrusion of height h and radius r [31]*

Another criterion was based on positive ions returning to the cathode to reside on a tarnish or oxide layer to further increase the electron emission from this layer, either by increasing the field across this layer, by initiating a trigatron type of breakdown, or by initiating an intense burst of emission ('emission blitz') for a streamer breakdown. These mechanisms may be playing a secondary role with the electrode projection, in addition to the probable primary mechanism of enhanced gas ionisation occurring at the projection tip.

*2.2.4 Particle-initiated breakdown mechanisms:* Testing has shown that, for the larger free particles ($\sim$ mm), the breakdown values are not the same as when the particle is simply fixed on the conductor, and so additional mechanisms must exist.

As the particles move in the field and approach an electrode, microdischarges are observed at the particle/electrode interface because they have opposite charges. For spherical particles, one can calculate this critical distance, and then calculate the breakdown voltage, assuming a lengthened particle with a streamer criterion for breakdown [33]. This gives good agreement with the experimental results. The microdischarge may also be playing a role in the breakdown mechanisms.

For wire-shaped particles it is more complex. Ionisation can occur at the particles which will affect its charge level and even polarity. At the instance of the microdischarge at the particle/electrode interface, the field at the tip facing the main gap suddenly changes, and initiates breakdown without permitting corona stabilisation. No comprehensive theoretical model yet exists.

*2.2.5 Breakdown in gas mixtures:* Recent theoretical studies on gas mixtures have concentrated on being able to predict which gas mixtures would have a high breakdown strength, and on being able to calculate the breakdown level.

An experimental approach to the calculation of the breakdown voltage in gas mixtures has been by interpolating the ionisation and attachment coefficient from the constituent gases according to their partial pressures [28, 34]. Calculation of the breakdown voltages from eqn. 4, using these interpolated coefficients, gives good agreement with the measured values for $SF_6$-$N_2$ mixtures (Fig. 6). However, there is increasing evidence that this interpolation will not work for all gases [35, 36]. Only for $SF_6$-$N_2$ and $SF_6$-He gases has there been an attempt [36] to calculate the coefficients from actual basic data. Further studies of this basic data and its application to the calculation of breakdown in mixtures are required.

## 3 Surface flashover characteristics of insulators in compressed gases

### *3.1 Introduction*

A critical part in the development of gas-insulated equipment has been the support insulator. Improved insulator materials and electrical stress analysis and control techniques have played a significant part in developing practical insulator systems which are able to withstand electrical stresses similar to those in the gas alone.

### 3.2 *Insulator flashover characteristics*

*3.2.1 Failure of Paschen's law:* If the flashover voltage of an insulator is measured as a function of increasing pressure, then eventually flashover will occur at a lower voltage than in the gas alone without the insulator. This will be a strong function of the insulator shape, insulator material, electrode/insulator interface, contamination and the voltage waveform. Unlike the gas breakdown case, the conductor material and surface finish may not be critical. Usually these deviations will begin at pressures of a few atmospheres when fields are of the order 10 MV/m. The subsequent reduction in gas breakdown voltage may be even up to 60% for poor insulator configurations. With special care, the critical field may be doubled, or even trebled, for well designed, clean systems.

For the nominally clean insulator without obvious surface defects or interface irregularities, there has been good agreement for calculating the flashover voltage based on equating the maximum resultant insulator surface field to the conductor field for gas breakdown at the same pressure [38, 39]. This has been shown to be valid even for the case where Paschen's law has failed in the gas breakdown case. The critical resultant field can occur at the insulator surface in a midgap region, and not necessarily at an electrode.

*3.2.2 Insulator/electrode interface:* The insulator/electrode interface can be critical for initiating flashover, such as might occur if there were imperfections [1, 37, 40, 41]. Studies with narrow (0.5 mm) gas gaps underneath the insulator [40, 41] at the insulator edges have shown that discharges occurring here can lower the flashover voltage by a factor of two or three (Fig. 8). This effect becomes more pronounced with increasing field and pressure, and becomes significant at fields above about 5 MV/m.

For insulators under AC or impulse-voltage conditions, the discharge at the interface is dependent on the capacitively graded voltage distribution. Fields in these gaps will increase with increasing value of the relative permittivity $\epsilon$. For DC insulators the short-term stress in the interface gap will be dependent on $\epsilon$, but for the long term, the stress enhancement will be a function of the material resistivity. This is discussed further in Section 3.2.5.

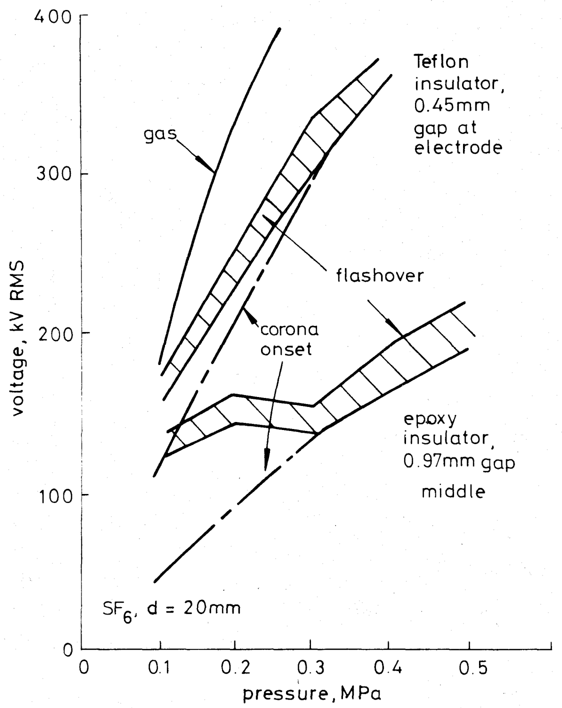


**Fig. 8** *Effect on insulator flashover in uniform field of gap at electrode interface or in middle of spacer [40]*

Insulator development has concentrated on reducing this interface effect by either:

(i) casting the insulator directly onto the conductor or a metal insert to eliminate interfacial voids

(ii) using shielding electrodes mounted on the conductors external to the insulator

(iii) shaping the insulator to reduce the field underneath the insulator and at the insulator-edge/conductor interface

(iv) metallising the insulator surface to be in contact with the electrode surface.

*3.2.3 Insulator-material effects:* The influence of the insulator material depends on the type of voltage application for the insulator.

Under AC and impulse conditions, the voltage distribution along the surface and inside the insulator is dependent on the relative permittivity $\epsilon$. Generally, the reduction in the flashover voltage correlates with increasing value of $\epsilon$ [1]. This is due to the increase in field in gaps at the interface, at surface imperfections, or at any particle contaminants on the insulator surface.

For DC operation of insulators, the situation is more complex than for AC or implulse conditions. The initial voltage distribution for DC will be determined by the capacitance grading, whereas the long-term distribution will be determined by the resistivity. Consequently, as described in Section 3.2.5, static charges can be formed at the insulator surface which can subsequently initiate flashover.

Variations in the insulator material consistency, e.g. due to filler settling in cast expoxy insulators, have little effect on the AC or impulse-voltage performance, but can result in big reductions in the DC flashover voltage [42]. This is because the consistency variations may have a bigger effect on material resistivity than permittivity, and these variations result in field-enhanced areas on the insulator surface.

*3.2.4 Insulator shape:* One can almost make the statement that there are as many 'optimised' insulator shapes as there are investigators in the field. This clearly demonstrates the lack of agreement on the critical parameters for insulator flashover. There are presently two basic types of insulators:

(i) where the insulator is cast directly on a conductor, a conductor insert, or on a semiconducting rubber coating on the conductor

(ii) where the insulator is made separately, usually of a polymeric material (e.g. polysulfone, polypropylene, polycarbonate) or a low value of dielectric constant $\epsilon$, and the insulator is then fitted onto the conductor system.

*Cast epoxy insulators:* For the epoxy materials (Fig. 9) there are basically post, cone and disc insulator designs. The post acts as a simple support insulator [38, 39, 43–46, 49], with

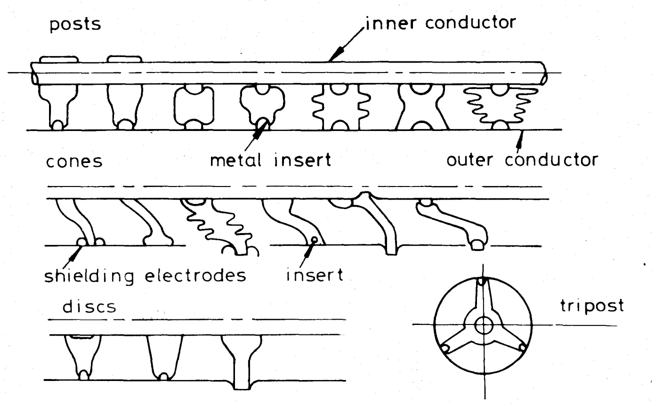


**Fig. 9** *Various cast-epoxy insulator designs*

advantages of low cost, low surface fields and low surface area for contamination to collect. Several designs have been used, with and without corrugations. Where there is a cast metallic insert on the conductor, care is needed not to produce excessive fields inside the insulator. The various post designs reflect alternative approaches to minimise the fields inside and on the surface of the posts.

The epoxy cone and disc insulators can also act as gas barriers [46–50]. The cones have lower surface fields, which tests have shown may be better than discs under contaminated conditions. Recesses in the conductor are sometimes used to further reduce the interface field [50]. Field plots have been used to attempt to optimise the angle of the cone and the shape of the cone at the conductor [47, 48, 50]. The conical/disc insulators are designed to be either mounted inside the enclosure conductor, or to be captured between flanges (Fig. 9). The field both at the inner and outer conductor is critical, and the alternative designs show shielding at both electrodes.

The evidence for using corrugations with insulators is conflicting. Under clean conditions the corrugations can reduce the flashover voltage [1, 39]. Under contaminated conditions they have been reported both to increase the flashover voltage and to have no effect [39, 52–54].

*Low-dielectric-constant insulators:* The second type of insulator is where the insulator is premoulded, and later fitted on to the conductor. It is preferable to use a low-dielectric-constant material in order to minimise the stress enhancement underneath the insulator at the conductor interface.

The various designs rely on shielding the interface (Fig. 10). Some designs use external and internal metallic shielding rings [1, 49]. Some insulators may have a conducting layer on the insulator surface at the interface [4]. This will not be necessary if the insulator is sufficiently thin with the external shielding rings, although obviously this then will be mechanically weaker. Alternatively, by using long extensions to the thin-disc insulator to give an I-shaped cross-section, the field increase underneath can be kept very low [55], typically only 10%. If the insulator has many cut outs, the critical field can also be reduced, although in this case there will again be a loss in the mechanical strength [56].

Recent advances in insulators have used a configuration where there are multiple conductors which fit around the insulator [57–59], as shown in Fig. 10. These result in a low field along the insulator surface, typically 40% lower than that in the gas at the equivalent simple '*e*-ratio' coaxial conductor. The field at the conductor/insulator interface is also very low, eliminating interface discharges. However, the penalty paid is a higher conductor field near the insulator. Because of the low insulator-surface and insulator-volume fields, these new designs offer potential advantages over the cast epoxy insulators.

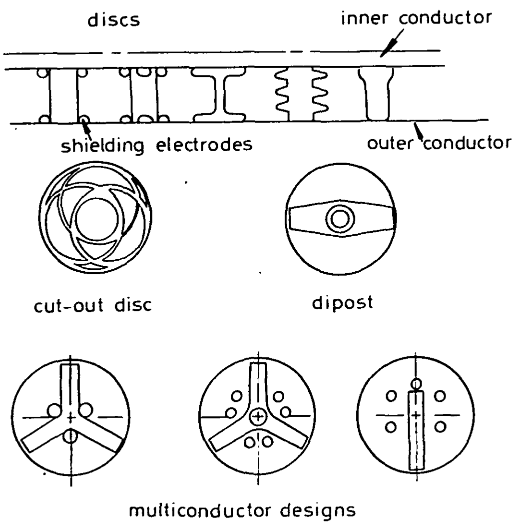


**Fig. 10** *Insulator designs with low-dielectric-constant material*

*3.2.5 Voltage waveform effects: AC and impulse characteristics:* The effect of the voltage waveform on flashover for insulators is similar to the breakdown in the gas for AC and lightning, and switching impulses. Typically (e.g. for $SF_6$) the crest 60 Hz and negative-switching impulse values are similar, the positive-impulse flashover values are 20% higher than the negative values for lightning impulses and 35% higher for switching impulses.

These ratios will be strongly dependent on the type of insulator and the cleanliness. If the insulator has a poor interface with the conductor such that corona discharges, or contamination occur, this will affect the ratio [41].

The voltage/time-to-breakdown characteristics of insulators are similar to the gas, with a marked upturn at small times ($\leqslant 2\,\mu s$) for negative impulses, and a smaller upturn for the positive values [60]. This has been calculated empirically for those cases where breakdown occurred in the gas from a conductor-shielding electrode adjacent to the insulator [61].

*DC Characteristics:* As described earlier, the voltage distribution for insulators under long-term steady-state conditions for DC is controlled by the resistivity. However, when the voltage is initially applied, the insulator voltage grading is controlled by the capacitance. The long-term DC bulk charging of the insulators must be considered.

The resistivity $r$ for most insulator materials is related to the temperature $T$ and field $E$ by the relationship

$$r = r_o \exp\left(\frac{A}{T} - BE\right) \tag{5}$$

Here $A$ and $B$ are the temperature and stess coefficients, respectively. Typical values are $A \simeq 5 \times 10^{-3}$ K, and $B \simeq 75 \times 10^{-3}$ mm/kV.

Charge accumulation in the bulk can occur as a result of a resistivity or conductivity gradient in the same direction as the field, due to the field dependency of the resistivity, or due to inhomogeneities in the material [62, 63].

The above effects can result in a changing voltage distribution along the surface, and inside the insulator over a period of several hours. As a result, depending on the insulator shape and the insert design, an insulator may fail after several hours with DC by flashover (Fig. 11), after having initially withstood higher voltages in the short term [63].

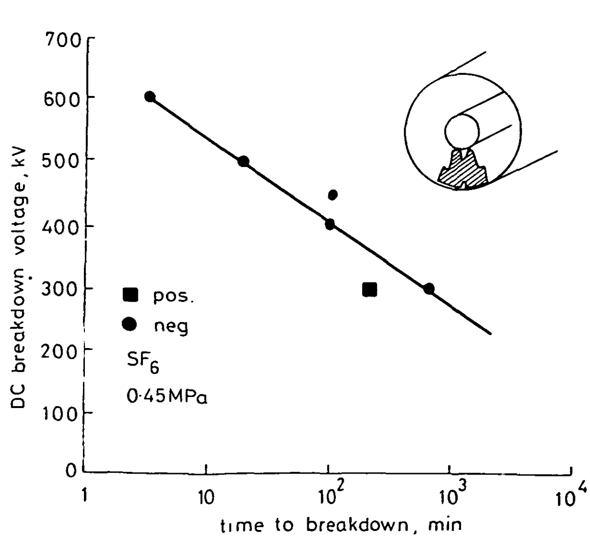


**Fig. 11** *Time to DC breakdown for corrugated-post insulator [63]*

In the nonuniform field geometries under practical conditions, then as a result of the $T$ dependency, stress inversion might occur with an insulator under DC conditions, e.g. in a coaxial geometry the maximum field is shifted from the inner to the outer conductor. In a paractical geometry (e.g. gas cable) there is a field distribution which will tend to slightly compensate with the field dependent resistivity, but the temperature dependency will be dominant.

*3.2.6 Paricle contamination effects:* Particles can be moved onto the insulators by the electric field and can, subsequently, initiate breakdown [1, 17, 51, 52, 60, 64–66]. The insulator flashover characteristics with particles are very similar to the particle-initiated gas breakdown characteristics. The most critical position for the long wire particles with disc insulators has been shown to be where the tangential field is a maximum rather than the resultant field [60]. With conical insulators, the most critical position is the inside corners where the insulators meet the conductor or the enclosure [51].

Fine metallic dust can reduce the flashover voltage by a factor of two or three. Insulating fibers are generally not deleterious but if there is any metallic dust present, the fibers will act as metallic wires.

The insulators can be more susceptible to particles than the gas alone. In the gas the particles may move to the high-field region; this may not be possible under impulse conditions. However, particles already moved onto the insulator, e.g. by an AC field, may then be in the worst position to cause flashover when an impluse occurs.

There have been very few fundamental studies of particle-initiated flashover. In one uniform field study in $SF_6$, high-speed image intensifier analysis followed the progress of the streamer from the particle leading to complete suface flashover [65].

*3.2.7 Surface contamination effects:* The surface of the insulator can be contaminated with other materials apart from particles, such as oil, grease, moisture or gas-decomposition products. Clean oil on the clean insulator surface has been reported to have little effect on the AC or lightning impluse breakdown, but can reduce the DC level by 25% [66].

Moisture condensing in the liquid form on the insulator surface can result in a reduction of the flashover voltage [51, 67] by a factor of five. This is obviously of interest for practical systems. Typically this equipment must have a moisture content below 300 ppm, and below 50 ppm is a common level. Interestingly, if the water is frozen on the insulator surface, the flashover performance can be hardly affected.

If very heavy arcing occurs in $SF_6$ in the presence of moisture, this can result in reduction of the flashover voltage of epoxy insulators [68, 69]. This has been attributed primarily to the $SF_4$ gas produced by arcing reacting with moisture to produce HF and reacting with the silica filler to reduce the surface resistivity. Alumina filler is not affected as much as silica filler. Practical systems prevent this problem occurring by using dry gas, absorbent to remove the moisture and any decomposed gas, and by suitable formulation of the epoxy.

*3.2.8 Conditioning effects:* Spark conditioning can occur with insulators if the insulator material is formulated to be able to withstand the sparkover energy without surface tracking. After a flashover has occurred, charges are trapped on the surface [62, 63] but these do not necessarily result in flashover at the same site. Spark conditioning can remove particles already on the surface. It may also remove or neutralise areas on the insulator already charged, perhaps from an opposite-polarity voltage application; these initial charges may have concentrated the field at critical areas on the insulator.

Stress conditioning can also occur, again by particle removal or charging the insulator to neutralise previous charges. Under DC conditions long-term stress conditioning may allow equalisation of the charges in the bulk of the material.

*3.2.9 Flashover distribution:* There have been few studies of the distributions of flashover voltages for insulators [70, 71].

Where the flashover is due to initiation from a highly stressed conductor region, for example a shielding electrode, an extreme value distribution is assumed to hold as for the gas breakdown case [4],

For the conditions where flashover occurred acorss an insulator, probably due to particle contamination [70], or initiated at a high-field area on the insulator, the experimental measurements have not been able to distinguish between a normal or an extreme value distribution.

*3.2.10 Dependence on type of gas:* Generally, the relative performance of flashover voltage of different insulators is independent of the type of gas. Deviations from the 'gas breakdown' values may occur at different pressures depending on the field levels reached, which is a function of the gas dielectric characteristics.

Some differences might be expected for the insulator where corona occur due to imperfect electrode interfaces or where metallic particle contamination is present.

Thus, insulators with deliberate poor interface tested in $SF_6$-$N_2$ mixtures have shown certain mixture ratios which have a higher flashover voltage, probably dependent on the corona characteristics [41].

### *3.3 Insulator flashover mechanisms*

There has been very little progress in determining the mechanism of insulator flashover.

There are several possible mechanisms:

(i) corona occurring at an imperfect insulator/electrode interface or at a surface imperfection will result in charges being sprayed onto the surface, which can act as a nonuniform field projection or even a microdischarge for a trigatron type of breakdown

(ii) corona occurring at a particle, with resultant charging of the insulator to enhance gas ionization and initiate flashover

(iii) sufficiently high field at the insulator surface, not necessarily at an electrode, for ionisation to begin. This assumes that the initiatory electron will be available either from a negative ion in the gas, or perhaps from an ion or impurity trapped on the insulator surface. The increased field could be due to the insulator shape, and, for the DC case, also affected by internal charging phenomena.

The flashover channel may then develop in a manner similar to Lichtenberg figures and, as shown for nonuniform field, flashover along insulating materials [1]. It would be expected that secondary ionisation processes from the insulator surface and trapped charges would play a role.

## 4 Conclusions and future work

### *4.1 Gas breakdown*

Although significant advances have been made in the past ten years to clarify the mechanism of electrical breakdown in compressed gases, there are still many areas where further studies are required.

The effect of electrode surface roughness is now much better understood, but the calculations must be developed further to include the case where some form of corona stabilisation may be present. Here it will be necessary to link to nonuniform-field breakdown studies and mechanisms.

Microscopic examination of the electrode surfaces and the correlation with prebreakdown current growth, both transient and 'steady state', will be of interest. Analysis of the transient breakdown processes using high-speed imaging techniques will be important to help clarify the mechanisms. Electrode effects (finish, material, impurities) still need to be clarified.

Another obvious deficiency is the lack of data available on the fundamental ionisation, attachment and collision cross sections and the $\alpha$ and $\eta$ coefficients at higher pressures. Presently the data taken at low pressures, in most cases at one atmosphere or below, are assumed to apply at the higher pressures. This is particularly critical for calculations of ionisation at electrode projections. Similarly, it will be necessary to extend electron and ion mobility measurements, diffusion and photon absorption measurements to higher pressures, particularly if there is to be correlation with the nonuniform-field breakdown mechanisms.

This absence of fundamental data is particularly felt when trying to 'tailor' gas mixtures to have desired breakdown characteristics. The limitations of the technique of interpolating ionisation and attachment coefficients from the constituent gases are now becoming apparent. Promising preliminary calculations are being made with fundametnal cross-section data to predict ionisation, attachment and breakdown in the mixtures, and this work should be extended [35, 36]. For these mixtures it will be possible to include by calculation the effect of electrode roughness, contamination etc. to determine the 'practical' breakdown voltages.

Application of extreme-value statistics to compressed gases has been particularly rewarding [1, 4]. However, there is still disagreement on the mode of extreme-value statistics that should be applied; i.e. is there a minimum breakdown field value $E_o$? This work should be extended to include surface finish, electrode coatings, and gas mixtures.

Similarly, the calculation of the voltage/time-to-breakdown characterisitcs should be extended to higher pressures and to include the effect of electrode protrusions and contamination.

Further studies are needed to determine the origin of the initiatory electron resulting from 'field emission' or proposed electron detachment from negative ions in the gas.

The effects of particle contamination are now better understood. For spherical particles there is good agreement of the theoretical analysis with experimental results for particle movement and breakdown. However, for irregular 'practical' wire-shaped particles, the picture is not clear. The theoretical analysis must be extended to include the impulsive field change and microdischarges occurring with the particles. Obviously, this is another area where a link must be made with the nonuniform-field breakdown analysis and mechanisms.

### 4.2 *Insulator flashover*

There has been extensive work on the development of new insulator configurations for gas-insulated systems, but relatively little on the mechanisms of insulator flashover. The criteria for onset of flashover appears to be the same for the insulator as for gas breakdown, but the progress of the streamers across the insulator leading to flashover is still incompletely understood. The effect on onset criteria and flashover is still incompletely understood. The effect on onset criteria and flashover mechanism of the insulator material, insulator shape, insulator coatings and surface contamination still needs to be clarified. Valuable information can be obtained using high-speed sensitive imaging techniques to examine the flashover mode, as well as from the transient measurement of the prebreakdown and breakdown currents.

The effect of charges generated and trapped inside the insulator and on the insulator surface has only recently started to be examined. This may be critical in determining the critical flashover criteria as well as the flashover mechanism, and should be studied further.

The investigation of statistical analysis of the flashover values has been neglected compared with the gas breakdown area. It should be extended to confirm the preliminary results that the distribution is probably normal rather than extreme value.

There are several areas where information is needed. For example, there has been no theoretical analysis and relatively little experimental work on the voltage/time characteristics for insulator flashover. Similarly, additional information is needed on the mechanisms of particle-initiated insulator flashover and the precise role of any corona charge deposited on the surface. Also, the relative importance of the tangential and normal components of the applied field on the insulator surface must be determined.

Future practical gas-insulated systems will undoubtedly operate at higher fields to reduce the size and cost of the equipment. This means that it will be even more critical that we have a detailed, comprehensive knowledge of the fundamental mechanisms of gas breakdown and insulator flashover. This will then enable prediction of the performance of these systems and lead to optimisation of the gaseous and insulator dielectric designs.

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