REVIEW

Breakdown Mechanisms in Sulphur-Hexafluoride

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ABSTRACT

The well known breakdown theories, Townsend's generation mechanism and the streamer mechanism, are reviewed and applied to the results of breakdown in the strongly electronegative gas, sulphur-hexafluoride. Experimental results reported in the literature on the breakdown behavior of sulphur-hexafluoride are examined in the light of these theories. The breakdown theories are used for the estimation of the breakdown voltages in pure SF_6. Other factors that may affect the breakdown characteristics of SF_6 have been discussed. Further areas of work have been proposed in order to obtain a better understanding of the breakdown mechanism.

1. INTRODUCTION

It has been known for a long time that heavy gases belonging to the seventh group of the periodic table, e.g., fluorine, chlorine, etc., have a considerably higher dielectric strength compared to air under similar experimental conditions. The high breakdown strength depends mainly on their capability of taking up free electrons, thereby forming heavy negative ions. Gases having these properties are called electronegative. Of the many available electronegative gases, sulphur hexafluoride, SF_6, has especially gained importance in recent years because of its chemical stability in addition to its high breakdown strength. Therefore, it is being used increasingly in high pressure, high voltage systems as insulation. Due to its effectiveness in the extinction of arcs it is used effectively in circuit breakers and switchgear with a pressure in the range of 200 to 600 kPa.

Due to the increasing interest in SF_6 as high voltage insulation, many experimental and theoretical investigations have been reported in the literature describing the breakdown behavior of SF_6 under direct, alternating and impulse voltages. In this review, the experimental results are discussed in the light of the theoretical statements. We also have outlined possible areas of further investigations to clarify the breakdown mechanisms and the discharge phenomenon in compressed SF_6.

2. THE BREAKDOWN MECHANISMS IN SF_6

A gas is normally an almost perfect insulator. However, some free electrons and ions are always present due to ionization. Under the influence of an applied electric field, free electrons may gain sufficient energy to ionize a neutral gas molecule on collision. The number of electrons produced in the path of a single electron travelling a distance of one centimeter in the direction of applied electric field is known as the Townsend first ionization coefficient α. Several types of ionization processes in SF_6 have been suggested [1]. One possibility is

$$SF_6 + e \rightarrow SF_5^+ + F + 2e \tag{1}$$

In SF_6 negative ions are formed when a low energy electron attaches itself to the neutral gas molecule resulting in either a direct attachment

$$SF_6 + e \rightarrow SF_6^- \tag{2}$$

or to one of the constituents of the molecule after disassociation.

$$SF_6 + e \rightarrow SF_5 + F^- \tag{3}$$

This later reaction is known as disassociation attachment. The attachment processes are described by the electron attachment coefficient η, which is the number of attachments produced in the path of an electron travelling a unit distance under the influence of the applied field. Both coefficients, α and η, are strongly dependent on the applied electric field. As a result of the combined ionization and attachment processes the increase dN in the number of electrons along the path dx in the direction of applied electric field is given by:

$$dN = N(\alpha - \eta)\, dx \tag{4}$$

where N is the initial number of electrons. For $\alpha > \eta$, equation (4) leads to an exponential growth of the electron population, eventually resulting in the breakdown of the insulation.

Two types of breakdown mechanisms are generally used to describe the breakdown processes in gases. According to the "Townsend mechanism", a succession of electron avalanches initiated at the cathode causes breakdown of the gas. However, in the "streamer mechanism" a single electron avalanche can lead to a breakdown. Details of these mechanisms are given in most textbooks on gas discharges. Pedersen [2,3] has given short summaries of the Townsend and streamer theories.

In an electronegative gas under non-uniform field conditions, the prebreakdown current I compared to the initial photoelectric current I_0 can be written as [3]

$$\frac{I}{I_0} = \frac{1 + \int_0^d \exp[\int_0^x (\alpha-\eta)\, dx]\, \alpha dx}{1 - \gamma \int_0^d \exp[\int_0^x (\alpha-\eta)\, dx]\, \alpha dx} \tag{5}$$

where the secondary ionization coefficient γ is the number of secondary electrons produced per primary electron as a result of ionizing processes such as electron emission from the cathode by positive ion bombardment or photoelectric emission from the cathode and photoionization in the gas caused by photons released from excited atoms or from recombination processes. From equation (5) the Townsend criterion for breakdown in non-uniform fields is derived as

$$\gamma \int_0^d \exp[\int_0^x (\alpha-\eta)\, dx]\, \alpha dx = 1 \tag{6}$$

Equation (6) implies that an infinite amount of current will flow as a result of breakdown of the dielectric medium. A limit to the current flow is dictated by the parameters of the electric circuit. Equation (6) can be modified for applications to uniform fields as

$$\frac{\gamma\alpha}{\alpha-\eta} (\exp[\alpha\ \eta]\ \alpha - \eta) = 1 \tag{7}$$

The Townsend breakdown criterion (equation 6 or 7) is of little use to the high voltage design engineer because the secondary ionization coefficient γ is a very sensitive function of the electrode surface conditions and gas purity. γ is well known only under carefully controlled test conditions. Moreover, measurements of γ have so far been possible only at pressures below 3.4 kPa [4] and such values are not valid for pressures of technical importance. It is therefore difficult to apply the Townsend criterion in a meaningful way to engineering problems. Furthermore, the Townsend mechanism is unable to explain the breakdown under steep voltage surges.

In the streamer mechanism it is assumed that the growth of a single electron avalance becomes unstable before reaching the anode. This results in the formation of fast moving streamers from the avalanche head. These streamers form a highly conducting channel across the gap, which ultimately causes the collapse of the applied voltage. The basic mechanism behind the formation of these streamers is assumed to be photoionization in the gas. However, a satisfactory quantitative theory for streamer formation has not been formulated. In spite of the criticism of the streamer theory in the literature, it is necessary to assume a single avalanche mechanism to explain the breakdown characteristics in non-uniform field gaps subjected to steep fronted impulse voltages [5]. Meek [6] developed the following equation for the breakdown of a non-uniform field gap

$$(\alpha-\eta)_x \exp[\int_0^x (\alpha-\eta)\, dx] = k\, E_x \left[\frac{x}{p}\right]^{0.5} \tag{8}$$

In this equation x denotes the avalanche length at the moment when streamers are formed. In a non-uniform field, x is only a fraction of the gap length d. $(\alpha-\eta)_x$ is the apparent Townsend first ionization coefficient at the avalanche head, ρ is the gas density while k is a constant. A similar equation was proposed independently by Raether [7] who suggested that a critical number of charges, $\simeq 10^8$, is necessary to transform an avalanche into a streamer. This number is believed to be independent of the gas pressure.

Meek's equation was modified by Pedersen [2,3] to obtain the semi-empirical streamer criterion:

$$\int_0^x (\alpha-\eta)\ dx = k \tag{9}$$

Values of k equal to 18 and 10.5 have been reported in the literature [3,8,9].

3. MEASUREMENTS OF DISCHARGE PARAMETERS

In the absence of detachment and secondary processes, the current flowing in a uniform field gap can be expressed as

$$\frac{I}{I_0} = \frac{\alpha}{\alpha-\eta} (\exp[(\alpha-\eta)\, d] - \frac{\alpha}{\alpha-\eta}) \tag{10}$$

Experimentally, the current in a uniform field gap at fixed values of E/p and variable gap length d is measured. Here E is the applied electric field intensity and p is the gas pressure. Values of α and η in equation (10) are obtained from semilogarithmic plots of I/I_0 against d.

Geballe and Harrison [10] and Bhalla and Craggs [4] measured values of α/p and η/p as a function of E/p in the range of $0.6 < E/p < 1.24$ V/cmPa with pressures varying from 0.66 to 26.66 kPa. They concluded that up to pressures of 54 kPa, the breakdown in SF_6 is caused by the Townsend build-up mechanism. Dutton et al [11] reported a strong pressure dependence of α/p and η/p for pressure up to 53.32 kPa and $E/p = 0.88$ V/cmPa. They suggested that at such pressures one or more attachment processes operate which depend on p^2. However, Boyd et al [12] who carried out similar measurements over a range of $0.86 \leq E/p \leq 1.5$ V/cmPa ruled out any pressure dependence of α/p and η/p in the pressure range of $0.66 \leq p \leq 53.32$ kPa. According to them, the previous conclusions [11] concerning the occurrence of three-body attachment processes may be in error, and α/p and η/p are linear functions of E/p only. More recently Maller et al [13] also did not observe any pressure dependence of α/p and η/p in the range of $0.82 \leq E/p \leq 7.5$ V/cmPa with gas pressure varying from 133.3 to 1333 Pa at 20°C. Results of the various investigations are in reasonable agreement with each other. Bortnik et al [14] measured α/p_o and η/p_o equal to 333.3, 653.2, 2133, and 4266 Pa in the range of $0.75 \leq E/p_o \leq 1.5$ V/cmPa. Here p_o is the gas pressure normalized to 0°C. Their results show a fair agreement with those of Bhalla et at [4].

The values of α/p and η/p can be approximated by the following linear relations in the vicinity of the point of intersection of the two curves

$$\begin{aligned} \alpha/p &= 23\ (E/p) - 12.34\ \text{cm}^{-1}\ \text{kPa}^{-1} \\ \eta/p &= -4\ (E/p) + 11.35\ \text{cm}^{-1}\ \text{kPa}^{-1} \end{aligned} \qquad (11)$$

Thus a reasonable correspondence with the data over a wide range of values is obtained by using the empirical expression

$$\frac{\alpha-\eta}{p} = k\ \{E/p - (E/p)_{crit}\}\ \text{cm}^{-1}\ \text{kPa}^{-1} \qquad (12)$$

where $k = 27$ and $(E/p)_{crit} = 877.5$ V/cm^{-1} kPa^{-1}

Here E [kV/cm] denotes the electric field strength and p [kPa], the SF_6 pressure referred to a temperature of 20°C.

It has been suggested that in order to obtain reasonably accurate values of α and η from the prebreakdown current measurements the variations in the field strength between the electrodes must be less than 0.1% while the accuracy in setting the gap distance d must be better than 0.1% [8,12,15]. According to Boyd et al [12] a pressure of about 100 kPa sets the upper limit in such investigations. Karlsson et al [8] gave an upper limit of less than 100 kPa cm for prebreakdown ionization current measurements of α and η. Thus while values of α and η are very important at pressures of technical importance, we may not be able to determine these values accurately at such pressures [12,8].

Values of Townsend's second ionization coefficient γ have been reported by Bhalla et al [4], Boyd et al [12] and Maller et al [13] in the range of $0.75 < E/p < 4.5$ V/cmPa for pressures below 3.33 kPa. These values strongly depend on the gap separation. For example, with an increase in the gap length from 0.1 to 8 cm for a virtually constant field strength gap, γ decreases by a factor of 10^9. This weakening of the secondary ionization processes is a consequence of the effect of photon absorption in the gas medium. This effect is enhanced by an increase in the gap length [16].

Measured values of α and η in equation (11), are used in calculating breakdown voltages based on streamer or Townsend theories. All these values have been obtained at relatively low pressures and it is generally assumed that these results can be applied to higher pressures of technical importance. However, the validity of such an assumption has not been verified. Similarly, values of γ which have been obtained under laboratory conditions may not be applicable to practical cases.

4. MEASUREMENTS OF DISCHARGE VOLTAGES IN UNIFORM FIELDS

The maximum discharge voltage for any gaseous insulation can be obtained when the electrodes are designed for uniform field distribution in the gap. In high voltage SF_6 insulated equipment, one of the main conditions for obtaining minimal insulation spacing is, wherever possible, to use uniform or slightly non-uniform field gaps in which the ratio of the average field strength to its maximum value is greater than 0.2. Therefore, uniform field discharge data are of considerable importance from a theoretical as well as a practical point of view.

Uniform field breakdown studies can best be represented by obtaining the Paschen curve and the ranges in which Paschen's law is valid. Paschen's law states that the breakdown voltage V_d of a gas in a uniform electric field field gap is a simple function of the product pd at constant temperature. Paschen curves for SF_6 reported in the literature were not always measured under the same test parameters and in many cases the test conditions were not fully described. Therefore, only a limited comparison of these results is possible, especially in the pd range above 100 kPa cm. For SF_6 direct voltage breakdown data is available for pd values up to about 300 kPa cm [4,13,17-25]. The Paschen curve for direct voltage is shown in Fig. 1. The minimum of the curve occurs at about 3.5×10^{-2} kPa cm and is near 500 V as given by George et al [18]. A considerable amount of information is needed to complete the curve at both ends, i.e., at high as well as at low values of pd. Deviations from Paschen's law are observed by Maller et al [13] for small spacings with pd values near Paschen's minimum and by Dutton et al [17,27] and Chalmers et al [20] at higher pressures.

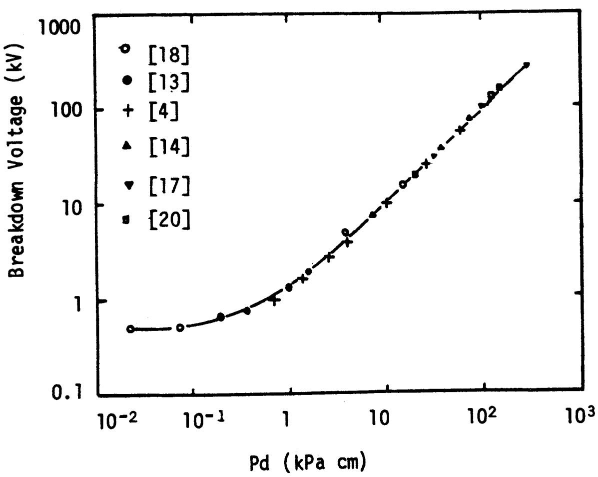

Fig. 1: Paschen curve for SF_6 for direct applied voltages.

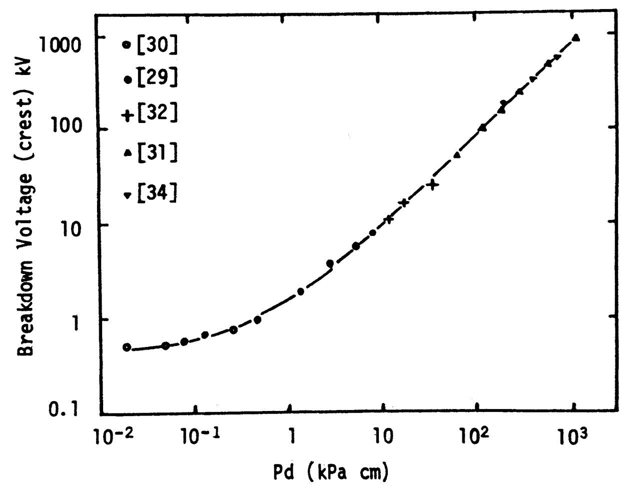

Fig. 2: Paschen curve for SF_6 for alternating (50 or 60 Hz) applied voltages.

TABLE 1

ac Breakdown Voltages for SF_6 In Uniform Field Gaps [25]

Temperature = 25°C

pd kPa cm	50 Hz Crest Breakdown Voltage kV												
	Distance mm												
	1	2	3	5	8	10	15	20	25	30	40	50	60
10	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
40	26.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5
80	42.5	55.5	64.5	70.5	70.5	70.5	70.5	70.5	70.5	70.5	70.5	70.5	70.5
100	50.0	60.0	74	89	89	89	89	89	89	89	89	89	89
200	98.0	103	120	150	168	170	170	170	170	170	170	170	170
300		144	155	190	217	240	253	253	253	253	253	253	253
400		177	185	220	250	275	303	310	310	310	310	310	310
500			216	248	275	305	356	385	385	385	385	385	385
600			250	278	305	340	395	440	455	455	455	455	455
800				335	370	390	450	500	535	580	580	580	580
1000				395	430	450	505	555	595	635	730	730	730
1200					485	505	562	610	650	685	750	805	870
1400					535	565	620	668	715	748	808	865	(920)
1600					585	618	678	725	768	(805)	(865)	(920)	(970)
1800						680	733	(785)	(825)	(862)	(925)	(975)	(1025)
2000						735	(790)	(840)	(880)	(920)	(975)	(1025)	(1075)

Figure 2 contains the Paschen curve for alternating applied voltages (50 or 60 Hz) [25,26,29-35]. In this Figure, results are included of investigations with values falling within the range for which Paschen's law is valid. In this range two rough limits are observed for *pd*, i.e., $p \leq 200$ kPa and $d \geq 0.3$ mm. Other test conditions and parameters being the same, the Paschen curves for alternating and direct applied voltages almost coincide. Under carefully controlled test conditions there is an extremely small scatter in the values of breakdown voltages and the influence of different electrode materials, e.g., aluminum, silver, nickel, stainless steel, and copper is negligible [25]. At higher pressures the breakdown voltage depends on the type of voltage as well as electrode material. With aluminum electrodes, breakdown voltage can be up to 20% lower than with stainless steel electrodes. For this reason, it is necessary to take the well defined test conditions into account when comparing results of different investigations.

Table 1 gives alternating breakdown voltages for SF_6 in uniform field gaps. The values within brackets are extrapolated. The values below the heavy line lie outside the range for which Paschen's law holds. No test results are available for direct voltage breakdown values for electrode spacings larger than 2.5 cm.

Departures from Paschen's law, which seem to be unique for each gas, are observed notably for quite high pressures and small spacings. The reasons for the limitations of Paschen's law have not yet been fully clarified. However, it is interesting to note that Paschen's law fails when the electric field strength exceeds 200 kV/cm (crest). The threshold for these deviations, which give breakdown voltages departing from the Paschen curve, is variable, depending on the electrode material and surface conditions and the presence of fine particles in the gas. These and other factors are discussed in subsequent sections.

5. ESTIMATION OF MINIMUM DISCHARGE VOLTAGE

The estimation of minimum discharge voltage, i.e., corona inception or breakdown voltage is of considerable importance from engineering point of view. A method capable of predicting discharge voltage with reasonable accuracy can save considerable amount of money required in testing new SF_6 equipment and can provide some insight in the breakdown mechanism itself. As the discharge phenomenon in compressed SF_6 is not fully understood, there is yet no general model which can be used successfully to determine discharge voltages in SF_6 insulated equipment. Existing methods can broadly be classified into two categories: those based on streamer theory and those based on concept of critical field strength.

The streamer criterion, as given in equation (9), offers a very promising approach for the solution of engineering problems. This criterion states that streamers are formed when a critical number of ions is developed in SF_6. These result in partial or total breakdown of the insulation depending on the degree of non-uniformity of the electric field in the gap. In a uniform field gap, streamer formation will directly lead to a breakdown while in a non-uniform field it may not cause breakdown. While calculating the terms on the left hand side of equation (9), the field distortion caused by space charge in the avalanche head is generally neglected. Because of the relatively rapid variation of $\alpha-\eta$ with field strength, equation (9) is satisfied even for a very small increase in field strength above the value corresponding to $\alpha-\eta = 0$. The essential result is that in non-uniform field gaps, like rod-plane configuration, the critical avalanche length x is a very small fraction of the total gap length.

The streamer criterion has been extensively studied [2,2,9,36-46] and has been used to estimate discharge voltages for fields having varying degrees of non-uniformity. It has been used successfully by Pedersen [9,38,47] and other [40-42,45] to explain some of the effects such as anomalous edge breakdown observed in SF_6 in uniform field electrodes and the reduction in breakdown voltage due to electrode surface roughness. The major limitation, at present, is the lack of adequate knowledge of ionization and attachment coefficients for the range of pressures used in high voltage SF_6 insulated equipment [36]. The streamer breakdown criterion may give reasonable agreement between the theoretical and experimental results at relatively low pressures. However, at higher pressures the experimental and theoretical results differ substantially [39,40]. In a recent paper [44] Rein et al have proposed a theoretical model for the impulse breakdown in SF_6 using a statistical approach to the streamer breakdown criterion. Their calculations agree with the experimental results for different electrode configurations covering a wide range of pressures and electrode areas.

The streamer breakdown criterion, equation (9), can also be expressed as

$$\int_0^x (\alpha-\eta)\, dx = \ln(N_c) \qquad (13)$$

where N_c is the critical number of ions in the avalanche when streamer formation starts. A constant value of k in equation (9) gives a constant value of N_c independent of pressure. Recently Khalifa et al [48,49] have developed a method for computing the discharge threshold voltage in SF_6 at pressures up to 1200 kPa. In this method, the size of the primary avalanche at the onset of discharge does not coincide with the streamer criterion given in equation (9) having values of $k = 18$ or 10.5. Its calculated size depends on the gap geometry [50]. In the uniform as well as non-uniform field gaps of positive polarity, there is a critical pressure above which the field emission from the cathode surface has been taken into account. This method predicts the discharge threshold voltages for uniform and non-uniform field gaps and explains the dependence of these voltages on pressure.

In 1953 Geballe and Reeves [51] proposed a special condition of self-sustaining discharge for electronegative gases on the basis of Townsend theory. In case of uniform fields with large values of *pd* this criterion for self-sustaining discharge is

$$\alpha = \eta \qquad (14)$$

which is satisfied at a threshold value of the field intensity. This value of the field intensity is generally referred to as the critical field intensity E_{crit}. Its value for SF_6 at normal atmospheric pressure is about 87 kV/cm. For $\alpha < \eta$, electron avalanche should not grow in electronegative gases and thus

$\alpha = \eta$ sets the threshold condition for the growth of electron avalanches. In a practical case an electron avalanche will grow when α is slightly greater than η. Thus, for uniform field gaps, breakdown gradients should have a limiting value given by

$$E_{crit} = 877.5\ p\ \mathrm{V\ cm^{-1}} \quad (15)$$

where p is pressure in kPa. However, anomalous breakdown below this limiting value of E_{crit} has been observed [4,14,21,22]. This has been attributed [38,47] to the field enhancement at the curved edges of the electrodes with breakdown taking place outside the uniform field region of the gap. This "edge sparking" is observed to occur for electrode separations well within the maximum designed gap spacings.

The concept of threshold field intensity was modified by Howard [52] to obtain the discharge voltage for non-uniform field gaps. According to Howard, discharge inception takes place when α becomes equal to η at points having maximum stress in the gap. Using this approach the discharge voltage can be expressed as

$$V_d = \xi\ d\ E_{crit} \quad (16)$$

Here $\xi = E_{av}/E_{max}$ is the field utilization factor [34,53-57]. Takuma et al [58] suggested a correction term H in the above expression to obtain a better agreement between the calculated and measured breakdown voltages. The modified expression for the minimum discharge voltage is

$$V_d = \xi\ d\ (E_{crit} + H) \quad (17)$$

Using this empirical expression, the calculated values of the discharge voltage were found to be in reasonable agreement with measured values even for highly non-uniform field gaps having $\xi = 0.02$. This means that breakdown in SF_6 is closely related to the maximum field strength in the gap, at least as far as non-uniform field configurations are concerned. This may explain the relatively flat nature of the flashover voltage as a function of gap length for long non-uniform field gaps insulated with SF_6 [59,60].

Although the above-mentioned methods may give reasonable correspondence between the theoretical and experimental breakdown voltages in some cases, a general agreement has not yet been reported in the literature. None of these criteria account for the simultaneous influence of factors like pressure, voltage waveform, polarity, electrode material, area and surface condition, and gas purity. These methods only give the corona inception voltages in cases where the breakdown voltage is substantially higher than the corona onset voltage due to the stabilizing action of the positive ion cloud surrounding the highly stressed electrode [61]. Furthermore, ionization and attachment coefficients used in all these calculations are average values and the statistical nature of the breakdown phenomenon is not taken into consideration. In our view, a considerable amount of work is required in this area to understand the breakdown phenomenon in SF_6, especially at higher pressures.

6. FACTORS AFFECTING DISCHARGE VOTAGE IN SF_6

6.1. Foreign Particles

It is now well known that any metallic particles present in the gas can lower the corona onset and breakdown voltages considerably [62-71]. The breakdown voltage in contaminated SF_6 can be as low as 10% of the values in clean gas. The breakdown voltage depends on the particle shape, size, material, location and motion, gas pressure and nature of the applied field as shown in Figure 3 [69]. The effects of these parameters have been studied by various authors to gain an understanding

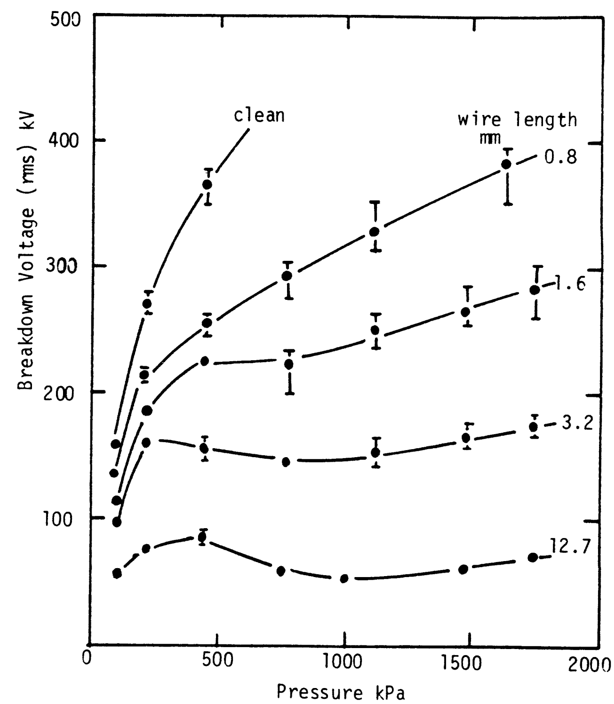

Fig. 3: Breakdown in SF_6 initiated by free copper wire particles in a 150 mm/250 mm coaxial electrode system: wire diameter is 0.4 mm [69].

of the particle initiated breakdown in SF_6. However, in compressed gases where particles play a dominant role, a mechanism has not yet been proposed which gives a satisfactory explanation for this complex phenomenon. It has been observed that gas breakdown usually occurs when metallic particles are at or very near the electrodes. According to the existing literature the breakdown starts at the particle tip as a result of the high pulsed field which appears there when the particle approaches an electrode and creates a microdischarge. Insulating particles such as glass, lucite, etc., have little or no effect on the breakdown voltage [63-65,68]. However, dust particles can lower the breakdown voltages by as much as 30% [65]. Ikeda et al [67] have reported that the effect of dust particles is particularly pronounced when alternating voltages are applied. Thus whereas very small quantities of gaseous impurities or insulating particles do not cause any appreciable reduction of the discharge voltage, free metallic or dust particles can reduce the breakdown voltage in SF_6 considerably.

6.2. *Electrode Material*

For low value of *pd* ie, the range in which Paschen's law is valid, the electrode material has practically no influence on the breakdown characteristics of SF_6 [72]. However, the electrode material definitely affects the breakdown gradients when the field strength exceeds about 200 kV/cm. Figure 4 shows uniform field breakdown gradients in SF_6 as a function of pressure for different electrode materials [73]. In the case of parallel plane electrodes at gas pressure up to 800 kPa the dielectric strength of SF_6 was found to be a function of the mechanical strength of the electrode material, its melting temperature and work function [72]. At higher pressures, similar dependence of breakdown voltage on electrode materials have reported in other gases and their mixtures with SF_6 [24,65,74]. While in parallel plane electrodes, the breakdown voltage depends on the electrode material, no such effect has been observed in non-uniform fields such as coaxial arrangement for pressures up to 400 kPa [75].

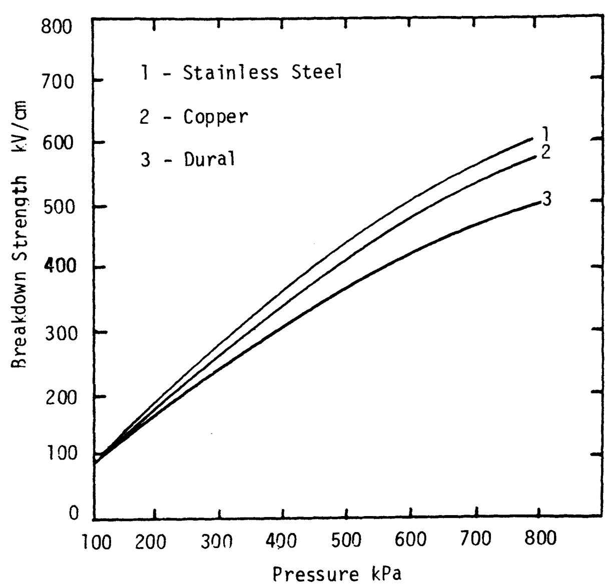

Fig. 4: Dielectric strength of SF_6 as a function of gas pressure for various electrode materials [78]

The breakdown voltage primarily depends on the cathode material and the influence of material increases with pressure and field strength. Although the anode is usually considered to have no influence on breakdown, an anode effect has been reported under certain conditions [65]. MacAlpine and Cookson [76] showed that an insulating film on the anode affects the breakdown voltage in compressed SF_6. Similarly an increase in the breakdown voltage results if the cathode is covered with a thin insulating film [77]. In general, insulated coverings markedly increase the breakdown strength. With uniform field conditions they enable Paschen's law to be obeyed for fields up to 130 kV/cm [76].

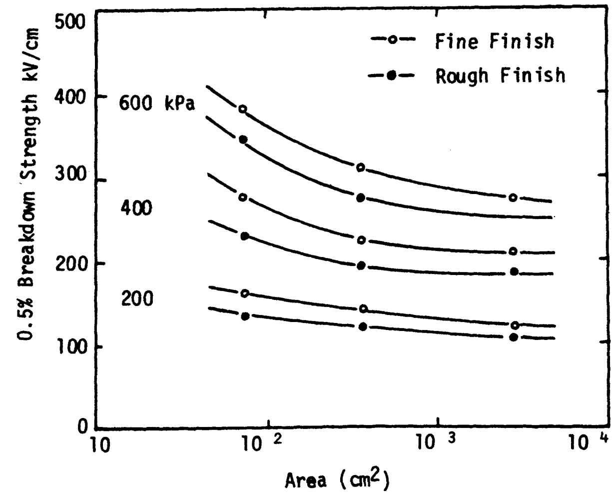

Fig. 5: Minimum breakdown field strength as a function of electrode area and gas pressure [78].

6.3 *Electrode Area*

The breakdown voltage in SF_6 decreases with increasing electrode area when the field strength in the gap exceeds about 100 kV/cm [65]. Figure 5 shows the 0.5% breakdown strength as a function of the electrode area and pressure [78]. The influence of the electrode area is more pronounced at higher pressures and therefore at higher gradients. Similar results have been recently reported by Rein et al [44]. The effect of electrode area also depends on the waveshape and polarity of the applied voltage. The negative switching impulse breakdown gradients are less influenced by the electrode area as compared to the power frequency breakdown gradients because of the relatively short duration of the impulse voltages.

In SF_6 the breakdown voltage at higher pressures obeys the extreme value distribution. This means that the breakdown is governed by the weakest points in the gap, which have statistical properties in nature. The model value of the distribution of breakdown strength of the irregular gap may be higher than that of the ideal gap. However, the irregular gap is the dominant gap for large electrode areas at higher pressures, since the characteristic of the gap is quite sensitive to the number of weak points. This number is expected to increase with the area of the electrodes. Weak points of the gap are destroyed by breakdown sparks, and thus the breakdown voltage changes by a "conditioning effect". The number of conditioning sparks and the relative increase in breakdown voltage become larger as the electrode area is increased [65].

6.4 *Electrode Surface Conditions*

Electrode surface roughness can cause a large reduction of the threshold for breakdown in SF_6 insulated apparatus [9,31,41,42,45,46,65,78]. Surface roughness can lead to the existence of localized microscopic regions in the gas near the electrode with a field strength much higher than the macroscopic average field.

Depending on gas pressure, such regions of enhanced field strength can result in a large reduction of the breakdown voltage. This may be one of the reasons that sometimes breakdown gradients in SF_6 are in the region where α is less than η.

Pedersen [9] has studied the influence of the electrode surface roughness using streamer breakdown criterion. He has shown that the surface roughness will not affect the threshold of breakdown if

$$pR_{max} < 0.4 \text{ kPa cm} \tag{18}$$

where R_{max} is the maximum roughness height, assuming a semispherical protrusion. Figure 6 shows the results of his caluclations. Cook [42] suggests that the breakdown voltage decreases when the product of gas pressure and the protrusion height above a flat electrode exceeds 0.8 kPa cm. Detailed investigations have been carried out to understand the effect of pressure, shape

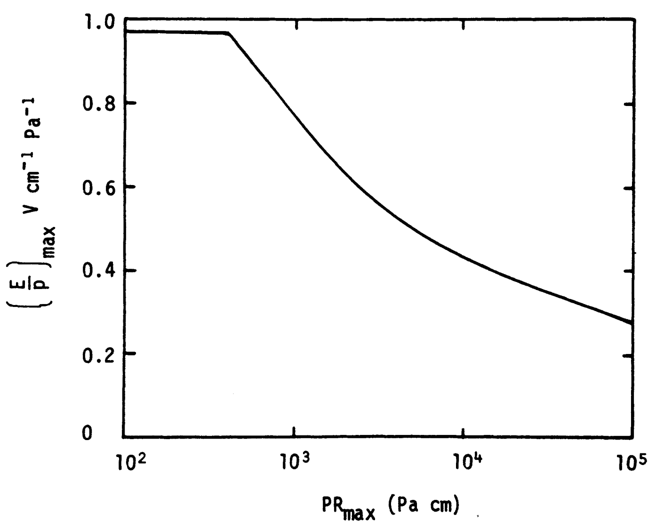

Fig. 6: Breakdown limitations in SF_6 from surface roughness. $(E/p)_{max}$ is the threshold value of E/p. R_{max} is the maximum surface roughness and p is the gas pressure [9].

and size of electrode surface protrusion and the field configuration on the discharge characteristics of SF_6. Experimental observations generally support these theoretical findings [9,40-42]. Kawagachi et al [31] did not find any distinct effect of wavy unevenness of up to 30 μm, caused by lathing, on the breakdown voltage of a coaxial system for pressures to about 500 kPa.

With the increase in electrode surface roughness, the number of conditioning sparks increase many times that required for smooth electrodes of the same area. Moreover, with an increase in surface roughness, deviations from Paschen's law occur at lower values of *pd*.

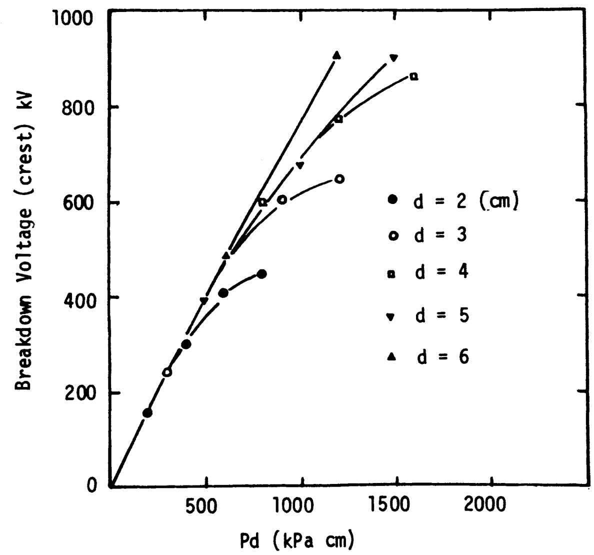

Fig. 7: Breakdown voltage between 43 cm diameter Rogowski profiled electrodes as function of pd (corrected to 20°C) [31].

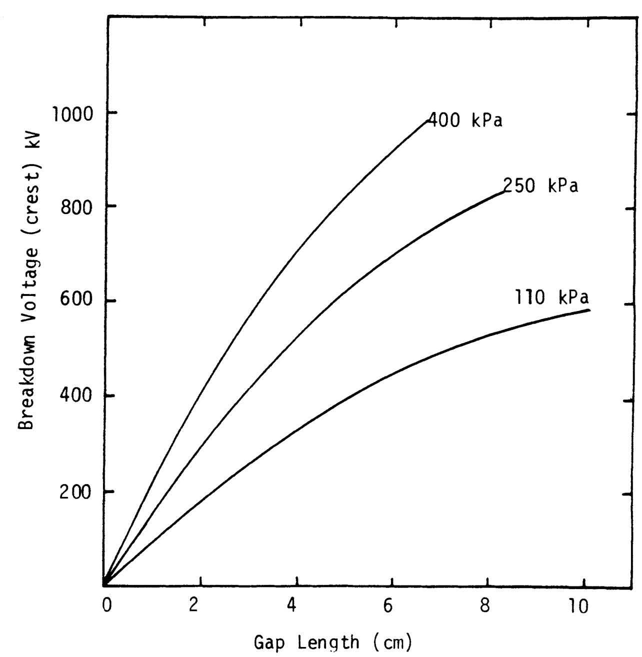

Fig. 8: 60 Hz breakdown voltage of SF_6 in long gap region as a function of gap length when electric field is uniform [80].

6.5 Other Factors

Other factors such as pressures, gap length, field configuration, voltage waveform and polarity greatly affect breakdown voltage of SF_6 [79]. For uniform field gaps, usually the variation due to pressure and spacing can be combined togehter as in Paschen's law. In the range of pressure and gap spacing where Paschen's law holds, any decrease of one of these factors can be compensated by an increase in the other if their product is kept constant. However, at higher pressures where Paschen's law fails, an increase in pressure at constant gap length usually results in a saturation tendency in the breakdown voltage versus pressure curve, Figure 7 [31]. Figure 8 gives the breakdown voltage of SF_6 in long gaps as a function of gap length when the electric field is uniform. This illustrates a similar saturation caused by varying the gap length [80]. For uniform fields the ratio of V/pd or E/p for breakdown is not constant, but it decreases with increasing gap length towards an asymptotic value [25,51,79]. This limit is reached when the attachment coefficient η equals the ionization coefficient α.

In non-uniform fields, the effect of pressure and spacing depends also on the polarity of the highly stressed electrode. For example, in the case of positive rod-plane gap, the breakdown voltage expressed as a function of pressure exhibits a maximum. This maximum depends on the gap spacing, radius of curvature of the rod and the waveform of the applied voltage [18, 37,81-84]. For negative rod plane gaps, the breakdown voltage is a linear function of pressure for smaller gap spacings. However, negative slopes of breakdown voltage versus pressure curve have been observed when the gap is sufficiently long [50,59,60,64]. Therefore, one has to be careful in using test data for design purposes, as results obtained under one set of conditions may not be applicable to a different set of conditions.

REFERENCES

[1] D. Kind, Trans. of SA Institute of Electrical Engineers, vol. 65, part 12, 1974.

[2] A. Pedersen, IEEE Trans. on P.A.S., vol. PAS-86 no. 2, 1967, pp 200-206.

[3] A. Pedersen, IEEE Trans. on P.A.S., vol. PAS-89, no. 8, 1970, pp 2043-2048.

[4] M. S. Bhalla et al, Proc. Phys. Soc., vol. 80, 1962, pp 157-160.

[5] A. Rein, Electra, no. 32, 1974, pp 43-60.

[6] L. B. Loeb, J. M. Meek, "The mechanism of electrical spark", Stanford, California, Stanford University Press, 1941.

[7] H. Raether, "Electron Avalanches & Breakdown in Gases", London, England, Butterworth, 1964.

[8] P. W. Karlsson et al, IEEE Trans. on P.A.S., vol. PAS-91, no. 4, 1972, pp 1597-1601.

[9] A. Pedersen, IEEE Trans. on P.A.S., vol. PAS-94, no. 5, 1975, pp 1749-1754.

[10] L. B. Loeb, "Basic processes of gaseous electronics", California University Press, 1955, pp 415.

[11] J. Dutton et al, Nature, vol. 227, August 1970, pp 702-703.

[12] H. A. Boyd et al, Proc. IEE, vol. 118, no. 12, 1971, pp 1872-1877.

[13] U. N. Maller et al, Proc. IEE, vol. 123, no. 12, 1976, pp 107-108.

[14] I. M. Bortnik et al, Soviet Physics - Technical Physics, vol. 16, no. 4, 1971, pp 571-575.

[15] A. Pedersen et al, IEEE Trans. on P.A.S., vol. PAS-90, no. 5, 1971, pp 2175-2180.

[16] A. S. Perlin, Soviet Physics - Technical Physics, vol. 17, no. 5, 1972, pp 813-817.

[17] J. Dutton et al, Proc. IEE, vol. 118, no. 5, 1971, pp 732-733.

[18] D. W. George et al, Brit. J. Appl. Phys., vol. 2, Ser. 2, 1969, pp 1470-1471.

[19] H. A. Boyd et al, Proc. IEE, vol. 119, no. 2, pp 275-276.

[20] I. D. Chalmers et al, Proc. IEE, vol. 118, no. 12, 1971, pp 1893-1894.

[21] P. R. Howard, Proc. IEE, vol. 104, Part A, no. 13, 1957, pp 123-238.

[22] E. Kuffel et al, Proc. IEE, vol. 113, no. 11, 1966, pp 1863-1872.

[23] D. F. Binns et al, Proc. IEE, vol. 116, no. 11, 1969, pp 1962-1968.

[24] E. H. Cohen, Proc. IEE, vol. 103, Part A, no. 7, 1956, pp 57-68.

[25] T. W. Dakin et al, Electra, no. 32, January 1974, pp. 61-82.

[26] G. Oppermann, "Uber Die Gultigkeit des Paschen-Gesetzes Fur Schwefelhexafluorid Bei Gleich, -Wechsel-und Stoss-Spannungen". Ph.D. Dissertation, 1974, Technical University of Berlin.

[27] J. Dutton et al, 1970 International Conference on Gas Discharges, IEE Conf. Publication, no. 70, pp 544-548.

[28] A. M. Zalesskii et al, Elektrichestvo, no. 12, 1967, pp 6-9,

[29] C. N. Works et al, Annual Report 1964 Conf. on Elect. Insul., pp 69-72.

[30] S. Schreier, IEEE Trans. on P.A.S., vol. PAS-83, 1964, pp 468-471.

[31] Y. Kawaguchi et al, IEEE Trans. on P.A.S., vol. PAS-90, no. 3, 1971, pp 1072-1078.

[32] W. A. Wilson et al, Journal of Applied Physics, vol. 21, March 1950, pp 203-205.

[33] G. Camilli et al, Trans. of AIEE, vol. 74, Part I, Nov. 1955, pp 637-642.

[34] S. Menju et al, IEEE Trans, on P.A.S., vol. PAS-93, no. 5, 1974, pp 1706-1712.

[35] G. Camilli et al, Trans. of AIEE, vol. 71, Part II, 1952, pp 348-357.

[36] J. Blackett et al, 1970 International Conference on Gas Discharges, IEE Conf. Publication No. 70, pp 293-297.

[37] R. Hazel et al, IEEE Trans. on P.A.S., vol. PAS-95, no. 1, 1976, pp 178-186.

[38] A. Pedersen et al, IEEE Trans. on P.A.S., vol. PAS-93, no. 6, pp 1820-1826.

[39] T. Nitta et al, IEEE Trans. on P.A.S., vol. PAS-90, no. 3, 1971, pp 1065-1071.

[40] I. M. Bortnik et al, IEEE Trans. on P.A.S., vol. PAS-91, no. 5, 1972, pp 2196-2203.

[41] S. Berger, IEEE Trans. on P.A.S., vol. PAS-95, no. 4, 1976, pp 1073-1079.

[42] C. M. Cook, IEEE Trans. on P.A.S., vol. PAS-94, no. 5, 1975, pp 1518-1523.

[43] W. Mosch et al, Elektrichestvo, no. 5, 1974, pp. 50-54.

[44] A. Rein et al, IEEE Trans. on P.A.S., vol. PAS-96, no 3, 1977, pp 945-954.

[45] S. Berger, IEEE Paper No. A75 494-5, IEEE PES Summer Meeting, San Francisco, Calif., July 20-25, 1975.

[46] S. Berger, IEEE Trans. on P.A.S., vol. PAS-96, no. 4, 1977, pp 1179-1189.

[47] T. M. Nielson et al, Proceedings of Second International Conference on Gas Discharges, London, England, Sept. 11-15, 1972, pp 323-325.

[48] M. Khalifa et al, IEEE paper No. F-76-324-4, PES Summer Meeting, Portland, Oregon, July 18-23, 1976, pp 343-348.

[49] M. Khalifa et al, Proceedings of International High Voltage Symposium, Zurich, Sept. 9-13, 1975, pp 343-348.

[50] Abdel-Salam, Discussion, IEEE Trans. on P.A.S., vol. PAS-96, no. 3, 1977, pp 952.

[51] R. Geballe et al, Phys. Rev., vol. 92, no. 4, 1953, pp 867-868.

[52] P. R. Howard, Proc. IEE, vol. 104, Part A, no. 13, 1957, pp 139-142.

[53] Y. Kawaguchi et al, IEEE Trans. on P.A.S., vol. PAS-90, no. 3, 1971, pp 1079-1085.

[54] V. N. Borin, Elektrichestvo, no. 9, 1976, pp 51-53.

[55] W. Mosch et al, Elektrie, vol. 28, H-3, 1974, pp 152-156.

[56] W. Mosch et al, Elektrie, vol. 26, H-9, 1972, pp 250-253.

[57] W. Houschild et al, Elektrie, vol. 26, H-7, 1972, pp 198-202.

[58] T. Takuma et al, Electrical Engineering in Japan, vol. 90, no. 4, 1970, pp 26-33.

[59] T. Takuma et al, Electrical Engineering in Japan, vol. 90, no. 6, 1970, pp 227-234.

[60] T. Takuma et al, Electrical Engineering in Japan, vol. 90, no. 3, 1970, pp 166-176.

[61] C. N. Works et al, Trans. of AIEE, vol. 72, Part I, 1963, pp 682-687.

[62] A. H. Cookson et al, IEEE Trans. on P.A.S., vol. PAS-91, no. 4, 1972, pp 1329-1338.

[63] H. C. Doepken, IEEE Trans. on P.A.S., vol. PAS-88, no. 5, 1969, pp 364-369.

[64] A. Diessner et al, IEEE Trans. on P.A.S., vol. PAS-89, no. 8, 1970, pp 1970-1978.

[65] A. H. Cookson, Proc. IEE, vol. 117, no. 1, 1970, pp 269-279.

[66] H. Kuwahara, IEEE Trans. on P.A.S., vol. PAS-93, no. 5, 1974, pp 1546-1555.

[67] E. Ikeda et al, Electrical Engineering in Japan, vol. 91, no. 5, 1971, pp 67-74.

[68] H. W. Graybill et al, IEEE Trans. on P.A.S., vol. PAS-89, no. 1, 1970, pp 17-23.

[69] A. H. Cookson et al, IEEE Trans. on P.A.S., vol. PAS-92, 1973, pp 871-876.

[70] H. C. Doepken, Annual Report 1969 Conf. on Elect. Insul. & Dielectric Phenomenon, NAS. Pub. No. 1764, 1970, pp 7-11.

[71] C. M. Cook et al, IEEE Trans. on P.A.S., vol. PAS-96, no. 3, 1977, pp 768-777.

[72] I. M. Bortnik, Elektrichestvo, no. 12, 1974, pp. 20-27.

[73] B. A. Goryunov, Soviet Physics - Technical Physics, vol. 20, no. 1, 1975, pp 66-67.

[74] G. D. Trump et al, Electrical Engineering, vol. 69, 1950, pp 961-964.

[75] Y. Kawaguchi et al, Electrical Engineering in Japan, vol. 90, no. 5, 1970, pp 197-204.

[76] J.M.K. MacAlpine et al, Proc. IEE, vol. 117, no. 3, 1970, pp 646-652.

[77] D. J. Chee-Hing et al, IEEE Trans. on Elect. Insul., vol. EI-10, no. 4, 1975, pp 119-124.

[78] T. Nitta et al, IEEE Trans. on P.A.S., vol. PAS-93, no. 2, 1974, pp 623-629.

[79] P. Narbut et al, Trans. of AIEE, vol. 78, Part III, 1959, pp 545-551.

[80] K. Itaka et al, IEEE Trans. on P.A.S., vol. PAS-89, no. 8, 1970, pp 1986-1994.

[81] A. A. Azer et al, IEEE Trans. on Elect. Insul., vol. EI-8, no. 4, 1973, pp 136-141.

[82] D. Berg et al, Trans. of AIEE, vol. 77, Part III, 1958, pp 820-823.

[83] T. R. Foord, Nature, vol. 166, 1950, pp 688-689.

[84] H. C. Pollock et al, Phys. Rev., vol. 56, July 1939, pp 170-175.

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High Speed Photography of Surface Flashover in Vacuum

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ABSTRACT

The method and results of high speed streak photography of surface flashover in vacuum are presented. It is shown that the bright phase of the flashover arc bridges a 12.5 mm gap in 0.15 ns. The streak records indicate that the flashover arc is preceded by an intense electron burst from the cathode-insulator junction.

INTRODUCTION

In any system using vacuum as electrical insulation there must be at some point a solid insulator separating and supporting the conductors. The surface of such a solid is a weak point in the insulation and therefore its characteristics are of technical importance. The insulation fails by the development of an arc along the vacuum-solid interface. This type of failure is referred to as surface flashover. It has been reported that the flashover is a very fast process [1,2,3,4], and in an earlier study at this laboratory we showed that the high luminosity phase of the flashover between uniform field electrodes bridged by a cylinder of alumina propagated at a speed greater than 10^7 m/s; that is, beyond the limit of resolution of the camera available at that time. This paper describes a successful attempt to measure the rate of arc propagation using a camera with much higher speed.

EXPERIMENTAL PROCEDURE

The photography of arcs under dc stress at high voltages involves problems in coincidence and protection. With a breakdown under dc stress the event time cannot be predicted and yet the camera operation must coincide with the initial stage of the arc that lasts less than one nanosecond. In earlier work [3], the coincidence was achieved by triggering both the arc and the camera from a spark but with the camera used in this study (Imacon 600) a more convenient method of obtaining the coincidence is available. The camera is an electronic image converter camera, used in this study in the streak mode, with a streak rate of 20 mm/ns. The camera will start operation with a small time delay after the arrival of a trigger signal. That time delay is 28 ns for the camera speed used in this study, the time increasing as the speed of the camera is reduced. If the trigger is obtained from the