Electrical insulation characteristics of high pressure gaseous gaps.

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LA THÈSE A ÉTÉ MICROFILMÉE TELLE QUE NOUS L'AVONS RÉCU
ELECTRICAL INSULATION CHARACTERISTICS OF HIGH PRESSURE GASEOUS GAPS

by

ROY SAMUEL

A thesis presented to the University of Windsor in partial fulfillment of the requirements for the degree of Master Of Applied Science in The Department Of Electrical Engineering

Windsor, Ontario, 1984

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ABSTRACT

It has long been recognized, that the insulating strength of gases in a uniform field, increases with pressure. The electrical breakdown and prebreakdown characteristics of gases at atmospheric pressure and below have been widely investigated, and there is reasonable agreement on the mechanisms involved - however, the breakdown mechanism in compressed gases have not been fully understood.

Whenever mention is made of high pressure gaseous insulation in the literature, it often refers to pressures well above 1 bar, but usually below 6 bar. This research project attempts to extend these studies to pressures up to 16 bar, with electric field values close to 50 MV/m.

A review of investigations carried out in the past, in compressed gases, has been included. To ensure accuracy in measurements, it was necessary to adopt several procedures, which included preventing gas leakages, reducing corona losses, adequate shielding of measuring equipment, among several others.

Breakdown and prebreakdown studies were conducted to observe the effects of conditioning, electrode separation, gas pressure, electrode material, the type of gas used, and
the source of power on the insulation characteristics of compressed gases. Based on these investigations several conclusions have been drawn.
ACKNOWLEDGEMENTS

It is with pleasure, that I acknowledge my supervisors Dr. Reuben Hackam and Dr. G. R. Govinda Raju, whose valuable guidance, expertise, and constructive criticism, have helped me during the course of this work.

I also appreciate the advice and suggestions of Dr. Alan Watson and Prof. P. H. Alexander, as members of my Master's committee.

I would also take this opportunity to thank Mr. Alan Thibert, and the members of the Central Research Workshop for their cooperation and kind help rendered, over the past two years. It warms my heart to think of my colleagues and friends, with whom I have had the pleasure of associating.

I am very grateful to my parents and family, whose unwavering love, support and guidance have seen me through thick and thin. And all praise be to God, through whom all these things have been made possible.
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Chapter I
INTRODUCTION

It is characteristic of the breakdown phenomenon, that the voltage between electrodes drops by a process which produces very high conductivity between the cathode and the anode. This takes place in a very short time, thereby preventing the gap capacity from being reloaded quickly. Thus, when a potential difference is established between electrodes in a gas, the gas behaves as an insulator unless the potential exceeds a certain definite value, which is called the 'sparking' or 'breakdown' potential.

The superior dielectric strength of compressed gases, their low dielectric loss, their low dielectric constant, and the fact that they are self healing, make their use as insulating media, an attractive prospect. Compressed gas insulation has been used in precision capacitors where low dielectric loss is essential, in electric power cables where low dielectric constant is of considerable importance, and in entire substations termed as 'Gas Insulated Substations' (GIS).
It has long been recognized, that the insulating strength of gases in a uniform field, increases with pressure. The classical analysis of the voltage breakdown mechanism and its dependence on pressure and other properties of the gas, was made by Townsend in 1903. This was based on the ionization of the inter-electrode gas by electron collision - a process which Townsend showed would become cumulative, when the positive ions produced by the electrons moving towards the anode, under the influence of a field, become capable, by their ionizing collisions, of producing an even greater number of electrons. Since that time, Townsend's second ionization coefficient ($\gamma$), has been reinterpreted to include various other mechanisms which generate charged particles in the interelectrode space. Among these are photoelectric emission, secondary electron emission due to positive ion impact at the cathode, photoionization in the gas, ionization by excited atoms and multiple collisions, thermionic emission and field emission.

The electrical breakdown and prebreakdown characteristics of gases at atmospheric pressure and below have been widely investigated, and there is reasonable agreement on the mechanisms involved. However, breakdown in compressed gases is not yet fully understood, and often apparently similar investigations produce varying results. It is important to note that any explanation of high
pressure breakdown must also take into account the several processes of ion removal, and the important influence of space charges, in modifying the electric field. Recognition of these various field modifying mechanisms, has clarified the general picture of breakdown in high pressure gases, but at the same time has shown it to be too intricate for full quantitative description. Hence, knowledge of gaseous insulation continues to depend to a large extent on the experimental determination of the breakdown strength and the prebreakdown behaviour as a function of parameters such as pressure, electrode spacing, type of gas, temperature, supply voltage, electrode geometry, electrode material and area, and conditioning effects.

1.1 SCOPE OF THIS RESEARCH PROJECT

Very few attempts have been made in the past to study the insulation characteristics of high pressure gases. Whenever mention is made of high pressure gases in the literature, it often refers to pressures well above 1 bar, but usually below 6 bar. This research project attempts to extend these studies to pressures up to 16 bar, with electric field values close to 50 MV/m.

There are several factors influencing the breakdown mechanism when compressed gas insulation is used. One of the
primary objectives of this work is to attain a level of understanding of the characteristics of very high pressure gaseous insulants. The use of high pressures entails several additional complications, hazards, and expenditure, and hence it is essential to determine the advantages and disadvantages of this type of insulation. Modern cities cannot afford to have high voltage sub-stations occupying large spaces, and exposing expensive equipment to the numerous corrosive contents of city air. Hence it is imperative to decide as to whether compressed gas insulation would provide us with a viable, efficient and effective alternative to conventional types of insulation.

A concise outline of the experimental studies conducted during the course of this research project, is given below:

1. Studies on the effect of conditioning on the insulation strength of compressed gas insulation, were conducted using Rogowski profile electrodes, under uniform field conditions.

2. The dependence of the insulation strength, on the type of gaseous insulant used, the electrode material, electrode separation, and pressure were studied under AC, and DC voltage stresses. These tests were conducted using small gaps (between 1mm. and 30mm.), with pressures being varied up to 16 bar. The gases used were air, nitrogen, helium, and argon.
3. The growth of prebreakdown currents across the gap was investigated to determine whether it was in agreement with the Fowler-Nordheim field emission, or the Schottky-Richardson thermionic field emission.

1.2 Thesis Organization

Chapter II attempts to outline briefly the salient features of the results obtained by earlier investigators. Since, some of the information has been highly condensed, it may be necessary to go back to the references for greater details. This chapter has been compiled by systematically classifying all information available, in sections - each section dealing with one particular factor affecting the breakdown or prebreakdown characteristics of compressed gas insulation.

Several precautions were taken in order to ensure accuracy in the measurements. A brief description of the apparatus used, and the precautions taken to ensure accuracy, are provided in Chapter III. These experimental procedures and techniques, play an important role in interpreting the results obtained, since the experimental conditions greatly influence the breakdown and prebreakdown mechanism.
The results obtained have been presented in the form of graphs, and tables in Chapter IV, along with a discussion of these results.

Chapter V lists the conclusions drawn from this project, and probable interesting extensions which could be carried out in the future.
Chapter II
AN OVERVIEW OF THE LITERATURE

At high gas pressures, and in large systems of practical interest, where electric stress in the gap reaches high values, breakdown occurs at levels significantly below calculated values. In addition, substantial variation and scatter can occur. These 'departures' from theoretical expectations may be due to unaccounted changes in the ionization process at higher pressures or voltages, electrode surfaces or other reasons.

This chapter aims at reviewing briefly, the investigations carried out in the past, by other researchers for determining the breakdown and prebreakdown characteristics of uniform field systems in compressed gases. Listed below are results of some of these investigations, arranged topically for convenience.
2.1 **BREAKDOWN CHARACTERISTICS AT HIGH PRESSURES**

2.1.1 **EFFECT OF ELECTRODE SEPARATION**

The breakdown field for compressed gases, decreases with increasing values of electrode separation, even though the rate of decrease has been found to vary with the electrode separation\(^{(30)}\). Hence, it is essential, when quoting a breakdown field strength, that the electrode separation be specified.

2.1.2 **CONDITIONING EFFECTS**

The initial value of the breakdown voltage for a freshly cleaned electrode system used at high pressures is lower than the subsequent breakdown voltage readings. Cookson\(^{(3)}\) has shown that in compressed \(N_2\), the breakdown voltage is nearly doubled after a hundred sparks. It is essential to note that the breakdown voltages quoted in the literature are invariably the conditioned values. But in devices of practical interest, using compressed gases, the first breakdown is critical. A common problem with conditioned voltage values, is the possibility of some low erratic breakdown values, which may be way below the conditioned value. Howell\(^{(8)}\) verified that conditioning is
an electrode effect, and that electrodes conditioned at one pressure need further conditioning, when the pressure and therefore the field is increased. He explained that sparking presumably burned off the irregularities, which were the cause for the reduction in breakdown voltage for unconditioned electrodes. Goldspink & Lewis⁶, have shown experimentally that the spark conditioning characteristic at high pressure were affected by factors such as the area of the electrode, dust particles between electrodes, material of the electrode, the surface condition of the electrode, and the exposure of conditioned electrodes to the atmosphere.

2.1.3 INFLUENCE OF ELECTRODE MATERIAL

Earlier investigations conducted by Skilling⁹ indicated no difference in breakdown voltages for iron, copper and zinc as electrode materials, up to pressures of 20 bar. Later investigations, however, have yielded results indicating, that when \(|E|\) is of the order of 10-20 MV/m, the electrode material and the surface preparation influences breakdown voltages in compressed gases. Cookson⁶ has given a tabulation of the list of cathode materials in diminishing order of breakdown voltage in compressed gases. Similar results were obtained by Goldspink & Lewis⁶.
Sysoev et al. following their investigations with impulse voltages, have concluded that the electric strength of air at pressures up to 25 atmospheres were:

1. negligibly dependent on the electrode material in the absence of any preliminary spark treatment - the material effect increasing with natural electric spark treatment at power frequency voltage.

2. for a special thorough preparation of electrode arrangement and test apparatus, the dependence of $V_b$ (breakdown voltage), on electric spark treatment was negligible.

Breakdown is determined primarily by the cathode, and the influence of the material increases with the field. Although the anode is usually considered to have no influence on breakdown, an anode effect, which is attributed to the anode material sputtering on to the cathode during conditioning, has been found under certain conditions.

Coates et al. have observed, contrary to conclusions drawn by Cookson, that stainless steel had the lowest value of $V_b$, compared to aluminium and titanium. However, he noticed that a continuous layer of fine dust was deposited on the stainless steel electrodes during sparking. He concluded that there was a need for complete specification of surfaces including metallurgical details, when assessing their suitability for high field conditions.
The preparation of electrode surfaces has a very strong influence on the breakdown characteristics of the electrodes. Polishing and thorough degreasing of the electrodes increases \( V_b \), reduces the amount of conditioning and decreases the prebreakdown emission current.

2.1.4 **EFFECT OF SURFACE ROUGHNESS**

Several investigators have demonstrated that, surface roughness on the electrodes of compressed gas insulated systems, can cause a sharp reduction in the breakdown voltage. As early as in 1939, Skilling\(^9\) observed that the breakdown voltage was extremely sensitive to the surface condition, and hence experiments in high pressure air indicated breakdown at different values of \( E \). Howell\(^8\) has observed that simply sanding the flat part of the electrode can reduce the breakdown voltage at higher pressures by a factor of three or four, and that the detrimental effect of roughness can be overcome by conditioning the electrodes.

Similar investigations were conducted with impulse voltages by Sysoev\(^11\), and the breakdown voltages were lower for electrodes with a high degree of surface roughness.Govinda Raju et al.\(^32\) observed a critical pressure effect when the electrodes were stressed with...
positive or negative polarity impulses, with pressures varied up to 10 bar. Under positive polarity impulses, a critical pressure effect was observed up to gaps of 25.4 mm., after which it disappeared completely. On further increase in gap length to 76 mm. a slight critical pressure effect was observed which became very pronounced at 102 mm. They suggested that the first two behaviours were associated with different mechanisms of breakdown, and the third represents an intermediate stage between the two mechanisms. They suggested that under negative polarity impulses, field emission was a likely cause for the critical pressure effect. On coating the electrode with a thin layer of epoxy resin, they observed that the critical pressure effect disappeared - they suggested that this was due to the suppression of field emission by the insulating film.

Chalmers et al. (7) observed that even when well sparked electrodes were used, increasing the gas pressure at a constant 'pd' necessitates further conditioning before the plateau level is reached. This, they attributed to the fact that when the pressure is increased (and therefore the effective gap decreased to maintain a constant value of 'pd'), the field strength around certain asperities increased well beyond the threshold for field emission. Hence these asperities must be removed by sparking in order to avoid abnormally low flashover voltages.
Avrotskii et al. \(^{(12)}\) made investigations with the purpose of determining whether it was possible to make analytical calculations for electric field strength of gaps at elevated gas pressures, due to electrode surface irregularities. They arrived at an expression which when analysed, indicates that for a given scatter in the effective microprojection, the corresponding spread in the initial voltages is greater, the greater the gas pressure. They also noted that at the time of discharge or immediately before it, bright points appeared on the cathode, these points being the location where intense ionization processes were taking place. Berger\(^{(13)}\) applied the streamer theory of electrical discharges to investigate the influence of surface roughness on the breakdown voltage in air and SF\(_6\). He observed that these measurements should be made on well conditioned electrodes, since they provide more knowledge about the role of surface roughness in the onset of breakdown. His investigations showed that the height and shape of the protrusions influence the onset of breakdown.

Saha et al. \(^{(15)}\) investigated the variation of the breakdown field strength of compressed SF\(_6\) in a concentric cylinder system, and presented a model which could predict insulation strengths for this form of surface. McAllister et al. \(^{(14)}\) have expressed suspicion over the validity of this model, since it cannot be used to predict the breakdown
voltage of an actual system. Cooke\(^{16}\) attached small protrusions of well defined dimensions, to the center conductor of a moderately sized coaxial electrode system, and the deterioration in electrical performance resulting from spark damage to steel and aluminium protrusion tips, was correlated to the resultant surface irregularities. A general relation showing effects of these irregularities on insulation performance was then developed. The curves derived from experimental data appeared to agree reasonably well with the calculated values. These experiments were conducted both for negative and positive polarity DC voltages, and the general experience for non-uniform fields was that the positive polarity breakdown exceeded that for negative polarity DC voltage.

2.1.5 EFFECT OF ELECTRODE AREA

The differing results obtained in several investigations under apparently identical conditions can often be attributed to the electrode area effect. Hence great care should be taken, to ensure that optimistic values of \(V_b\) are not used in the design of large practical insulating systems, as a result of incorrectly extrapolating the breakdown values with electrodes of a smaller area.
The breakdown field in a compressed gas decreases with increasing electrode area when the electric field is greater than 10 MV/m. Mitta et al.\textsuperscript{(18)} have shown that the electrode area effect on the breakdown of the gas presents a statistical behaviour which may be described by a Weibull type of extreme distribution - their research work has given important results, using basic electrode configurations such as sphere-plane, parallel plane and coaxial cylinders. Masseti et al.\textsuperscript{(17)} have experimentally confirmed that the electrode area effect on the breakdown of the insulating gas presents a statistical behaviour which may be satisfactorily represented by a Weibull distribution. They have also attempted to extend these fundamental considerations to some electrode geometries typical of cable installations. Mitta et al.\textsuperscript{(19)} have suggested that the decrease of the breakdown field with time is not caused by deterioration of insulation, but by weak points (such as microscopic protrusions or conducting particles) existing in the system already. The electrode area effect of breakdown in compressed gas insulation has been related to the spatial distribution of these weak points. Hence the probability of the appearance of a weak point reduces the value of the breakdown field, $|E|$. Experiments showed $|E|$ to decrease with the increase in area, and conditioning effects were more pronounced in electrodes of smaller areas.
2.1.6 EFFECT OF DUST

Dust affects gas breakdown in compressed gases, resulting in a reduction of the initial and conditioned breakdown voltage, and an increase in the amount of conditioning required. When precautions were taken to exclude dust, the readings indicated conformity with the linearity of the Paschen curve, for higher values of pressure than before.

The dielectric properties of dust particles have a significant influence: conducting particles and airborne dust reduce $V_b$ in compressed gases, but glass and acrylic particles have no effect. Doepken and Trump\(^5\) studied the movement of particles between coaxial electrodes in compressed gases under the influence of an electric field. Metallic particles in the inner negative electrode could cause bursts of corona. Metallic particles landing on the inner positive electrode could initiate breakdown. Dakin and Hughes\(^5\) noted a similar effect with uniform field electrodes, in atmospheric air. The current has also been found to increase with the square of the applied voltage for a fixed value of pressure and electrode separation.
2.1.7 **EFFECT OF TEMPERATURE**

Although Paschen's law has been verified at atmospheric pressure for temperatures up to 1373 Kelvins by Alston et al.\(^{31}\), this is not the case always for compressed gases. Investigations by several authors\(^{5}\) have revealed that for a constant value of 'pd' deviations from the Paschen curve occurred at a lower field when the temperature was higher. This reduction was considered to be due to the intense field-assisted thermionic emission from the cathode initiating breakdown at lower voltages.

2.2 **FAILURE OF PASCHEN'S LAW**

Several investigators have shown conclusively that for most gases at atmospheric and lower pressures, the breakdown voltage \(V_b\) is a function of the product of the gas density\(^{9}\) and the uniform field electrode separation\(d\). This is known as Paschen's law, and although the pressure '\(p\)' is often used instead of the gas density, it must be remembered that the simple proportionality between the pressure and the gas density may not be true at higher pressures.

For values of |E| of the order of 10-20 MV/m in compressed gases, Paschen's law is no longer satisfied and \(V_b\)
is lower than expected. The value of $|E|$ at which deviations from Paschen's law commence depends on the electrode material, electrode separation, the area of the electrode; and the dust content of the gas — hence different readings are observed at different laboratory conditions. Several investigators\(^5\) have found that the failure of Paschen's law was associated with the intense burst of electron emission in compressed gases like methane and hydrogen. In hydrogen, the current was observed to increase sharply at a pressure of 21 bar, within a few nanoseconds, to cause a breakdown with an emission blitz. Since the phenomena occurring in the gas gap at higher pressures do not adhere to the theory postulated by Townsend, it is to be expected that there would be a failure in Paschen's law. Several suggestions have been made in the past as to the breakdown mechanism in compressed gases. We will now try to study these different suggested mechanisms.

2.3 **Suggested Breakdown and Prebreakdown Mechanisms**

2.3.1 **Failure of Townsend and Streamer Theories**

As the voltage applied across a uniform field increases, the current increases according to the equation:
\[ I = \frac{I_0 \times \exp(\alpha d)}{1 - (\exp(\alpha d) - 1)} \]

where, 
\( \alpha = \) Townsend's primary ionization coefficient \\
\( \gamma = \) Townsend's secondary ionization coefficient, \\
and \( d = \) the electrode separation.

The current increases until there is a sudden transition from the Townsend dark current to a self-sustained discharge. This transition is accompanied by a sudden increase in the current in the gap. For the current 'I' to become very large, in the above expression, the denominator has to vanish. Thus Townsend's criterion for breakdown in uniform fields is given by the expression:

\[ (\exp(\alpha d) - 1) = 1 \]

On the average, one electron leaving the cathode grows to \( \exp(\alpha d) \) electrons at the anode. If the ionization coefficients are expressed functions of \( E \), the field strength and the pressure, then

\[ \frac{\alpha}{P} = P_1 \left( \frac{E}{P} \right) \]
and \[ \frac{\gamma}{P} = P_2 \left( \frac{E}{P} \right) \]

and the threshold equation for the spark is given by:

\[ \sqrt{x \exp(\alpha d)} = 1. \]

Since \( Ed = V \) for a uniform field, the threshold equation mentioned above, can be rewritten as:

\[ P_2 \left( \frac{V}{pd} \right) \times \exp(pd \times P_1 \left( \frac{V}{pd} \right)) = 1 \]

Hence \( V_b = F(pd) \)
Thus we arrive at the conclusion that the breakdown voltage is a function of the product of the pressure and the electrode separation which is the statement of Paschen's law. The presence of space charges can alter the ionization coefficient $\alpha$, since it is a function of the field gradient. Raether\textsuperscript{(1)} has studied the effect of space charges of an avalanche, on its own growth, and he observed that when the number of ions were between $10^6$ and $10^8$, the avalanche growth was weakened, due to the reduction in the applied field, created by the positive ion space charge field. When the number of ions exceeded $10^8$, the avalanche current was followed by a steep rise in current, after which breakdown followed. Raether\textsuperscript{(1)} suggested that the positive ion space charge have acquired a sufficiently high value to initiate a streamer. A good explanation of the streamer mechanism of a spark can be found in reference \textsuperscript{(1)}. Thus, according to Raether, the criterion for streamer formation is reached when $\exp(\alpha d) = 10^8$.

But several investigators have observed that at pressures above 30 bar there can be an abrupt decrease in the value of $\alpha$, and hence a decrease in the product $\alpha d$. This fall is to be expected at higher pressures, because the electron avalanches which dominate the theories of breakdown at lower pressures, become progressively less significant as the energy gained by the electrons between their frequent collisions with atoms or molecules, becomes
insufficient to cause ionization\(^{(4)}\) At these higher pressures, typical values of the product \((\alpha)d\) ranges between 2 and 3\(^{(5)}\), and hence the streamer mechanism fails to explain the phenomenon any longer. Therefore it has become necessary to look for some new explanations for the breakdown mechanisms in compressed gases.

Suggestions have been made in the past by numerous investigators as to the mechanism of breakdown. Although interrelated, these suggestions can be generally classified into basic types, as dealt with below.

2.3.2 **BREAKDOWN BY FIELD EMISSION ALONE**

Though it is known that Paschen's law does not hold good for compressed gases, there have been conflicting observations with regard to the mechanism. The Schottky-Richardson or the Fowler-Nordheim emission mechanisms can possibly take place at locations of field enhancement, possibly like at the sites where the work function of the material is low, or in the vicinity of asperities. Minute cracks in electrodes created when the electrode-oxide layers crack owing to compressive forces produced by high applied fields, crystal dislocations and inclusions, dust particles, and asperities have been observed to be potential emission sites\(^{(5)}\)
It has been suggested by List\(^5\) that chains of avalanches released by the cathode, and produced by field emission and positive ion secondary ionization processes, finally led to the breakdown of the gaseous insulation. Sharbaugh and Watson\(^5\) were of the opinion that because the current density of field emitted electrons at high pressures was very high, a narrow filament of gas could be heated up sufficiently to reduce gas density along this filament, cause ionization, and thereby create an instability in the current, causing breakdown.

Other investigators have proposed enhanced secondary ionization processes at around 15 bar, but these processes cannot increase the secondary ionization coefficient\(\gamma\), by more than a factor of ten, and hence cannot explain breakdown at values of gamma, effectively reduced by \(10^3\) or more, when compared with their values at lower pressures.

2.3.3 **BREAKDOWN BY FIELD EMISSION AND SPACE CHARGES**

The positive ions produced in compressed gases, can enhance the field at the cathode to force field emission. This increases the ionic space charge, and each ion becomes more effective in increasing the electron current until breakdown follows. Boyle and Rislink\(^20\) developed a breakdown criterion, which was a function of \(E/p\) and \(E\),
assuming a Fowler-Nordheim type of field emission with no additional ionization near the high field cathode. But Sharbaugh and Watson\(^5\) considered that the positive ion space charge only increased ionization in the gas and did not affect field emission. They developed a breakdown criterion based on the Schottky-Richardson type of field emission, where the product \(\alpha d\) became a decreasing function of \(E^{1/2}\).

Both the above criteria indicated close agreement with some gases, but poor agreement with others. A breakdown criterion similar to that proposed by Howell\(^6\), which combines both the above mentioned mechanisms is also possible.

2.3.4 Breakdown by Field Emission and Charge Collection

Positive ions drifting towards the cathode can create an intense field around a dust particle, oxide, or tarnish layer and cause field emission. Sharbaugh and Watson\(^5\) considered that when positive ions were formed at a cathode layer at a rate faster than the leakage of ions, then field emission from this layer increased continually to cause breakdown. Again, a Fowler-Nordheim type of field emission was assumed with no additional ionization near the high field site.
Others have suggested\(^5\) that positive ions effectively enhanced gamma by factors of the order of \(10^4\) to \(10^5\), thus creating a Townsend breakdown at low values of the product \((\alpha d)\). Muller\(^5\) suggested that there was an intense burst of electrons from a small area of the cathode, so that a modified streamer breakdown took place.

Goldspink et al.\(^{21}\) proposed that a charged layer of dust particles or ions either at the anode or the cathode, could create an electric field across the electrode oxide layer, to cause a small discharge and hence initiate a trigatron type of breakdown. Calculations indicate that the conditioned breakdown voltage is halved due to a 1 microjoule discharge on the electrode surface in nitrogen at a pressure of 26 atmospheres. However, it is unlikely that the first gas breakdown could have been initiated by a trigatron type of breakdown, since the number of positive ions present would be small. But when the number of positive ions reach large values, breakdown at this stage may be reasonably assumed to undergo the mechanism indicated above.
Chapter III
EXPERIMENTAL TECHNIQUES AND PROCEDURE

3.1 DESIGN OF THE HIGH VOLTAGE LABORATORY

Existence of nearby electrical networks, radio stations, and discharges from electrically free objects, can cause electromagnetic disturbances. These disturbances enter either capacitively or inductively into the test circuit, and get transmitted to the measuring circuit. Hence, when making breakdown or prebreakdown measurements, the high voltage laboratory has to be adequately shielded. Water and drainage pipes, rails and other metallic structures have been carefully screened, and metallic objects in the vicinity have been grounded. A wire mesh is embedded in the plaster of the walls, with the joints and knots of the mesh carefully welded together. A similar mesh is provided in the floor, and is connected to the shielding in the walls.
3.2 APPARATUS USED

3.2.1 TEST CHAMBER

A sectional view of the test chamber used is given in Fig. (3.1). The cylindrical wall of the pressure vessel has a shell thickness of 0.750 inches, and a head thickness of 0.687 inches, and is rated for a maximum allowable pressure of 38 bar. The high voltage bushing is a General Electric Air Blast Circuit Breaker bushing with an insulation rating of 401 kV. A conductor passes through the bushing to electrically connect the upper electrode to the high voltage supply. This bushing is filled with SF₆, at a pressure of 2 bar.

The pressure vessel has a volume of 330 litres, with provision for three viewing ports. Two of these are temporarily sealed, while the third one is used to observe the phenomena occurring between the electrodes. The electrodes were of the Rogowski profile, details of which are given in the next section. The upper electrode remained fixed, while the lower electrode was made movable, to help vary the electrode separation 'd'. The electrode separation could be measured correct to 0.01 mm.
fig(3.1). A cross sectional view of the pressure chamber (drawn to scale).
Extreme care was taken to ascertain that the pressure vessel was leakproof. The upper lid of the pressure vessel was systematically bolted down. The viewing ports, which could be another source of leakage, were also carefully sealed. The vessel was then pressurized slowly, and locations of leakage were spotted using a soap solution. These locations were then treated with sealing wax, to prevent further leakage. On testing, the pressure vessel was found to have an average leakage rate of about 0.2 bar in 48 hours. An inlet and an outlet, are provided to pressurize or depressurize the pressure vessel. A pressure gauge, was used in conjunction with the pressure vessel, with each division in this gauge representing 0.7 bar.

One of the problems inherent with high voltage connections, is corona. Adequate care had to be taken to prevent excessive corona losses. A corona ring as indicated in Fig. (3.1), was installed to reduce corona losses at the connection of the high voltage line to the pressure vessel. It was noticed that another site of field intensification was some sharp points on the edges of the bolts holding down the lid of the pressure vessel. Glass jars were made to cover these bolts, to prevent a direct flashover path from the high voltage side to these intense field locations. Moreover, the diameter of the hollow conductor connecting the supply to the pressure vessel, was increased to three inches to prevent corona along its length.
3.2.2 **ELECTRODE PROFILE**

While studying breakdown characteristics assuming uniform fields, great care should be taken in the manufacture of the electrode, since edge effects play an important role in making the field uniform or non-uniform. The radius of curvature near the edge of the plane electrodes must be decreased gradually, so that at no point does the field become greater than it is in the center of the plane position.

Rogowski extended the Maxwell's analysis of the electrostatic field due to a finite plane plate, to an infinite plane plate. He plotted the electrostatic field between two electrodes, and observed that for a particular equipotential surface\(^{(22)}\) the field was at no point, greater than it is for the uniform region between the plates. So if this equipotential surface was made as the surface of the electrode, the breakdown at the gap would take place at exactly the same voltage as for a uniform field. The details of determining the profile of the electrode can be found in reference \(22\).
3.2.3 **HIGH VOLTAGE POWER SUPPLIES**

One of the objectives of this research was to test the dependence, if any, of the breakdown and prebreakdown characteristics of high pressure gaseous gaps on the source of supply. Hence tests were made with AC and DC voltages, and this section gives a description of the power supplies used in these experiments.

3.2.3.1 **THE DC POWER SUPPLY**

The source of the DC supply was a Deltatron Model M-1000 power supply. The primary required a 208/240 volt, 60 Hz., single phase, 8 kVA supply, and the voltage delivered was 1 MV in air at 2 mA. The supply has a load regulation (typical) rating of 1000 V/ma, and a ripple (RMS) rating of 100V at 1 MV and 500 microamps load.

The Deltatron Model M-1000 DC power supply, essentially consists of a stack of 20 identical voltage producing decks in an insulating housing, and driven by a 81 kHz. source. Each deck consists of a primary and a secondary coil coupled to one another by a capacitance 'T' network. Within each deck is a Cockcroft-Walton voltage multiplier producing the high voltage output. Each deck is constructed as an integral unit with two external connections for the
positive and negative terminals. They are stacked one upon another, with an insulating layer in between. The decks are encapsulated to provide structural rigidity and to insulate their individual parts. A 24 inch diameter, laminated phenolic tube contains the entire assembly. Polarity reversal is achieved by reversing the polarity of the connections to the decks. \( S_F \) is circulated between and around the decks to provide cooling and insulation. An inner cylinder contains a spiral of 150 capacitor compensated 100 meg resistor. The voltmeter on the control panel is connected in series with this resistor. Also the error signal, used to drive the electronic stabilization circuit is derived from it.

3.2.3.2 AC SUPPLY

The AC supply, manufactured by Voltronics Universal Corp., requires a 208/230 volt, single phase, 50/60 Hz, 3 kVA (approx), 15 amp input and delivers a maximum of 150 kV RMS, with an RMS output current of 0 to 14 mA.

3.3 EXPERIMENTAL PROCEDURE

As mentioned earlier the high voltage lab was designed to facilitate accurate measurements, and eliminate the influence of electromagnetic interferences. All controls for
the various high voltage power supplies, are located inside a cage of copper mesh, which is well grounded. All metallic objects and wires in the vicinity were carefully grounded, and all measuring equipment were shielded to enhance accuracy in measurements.

A digital voltmeter, was connected to the high voltage side of the Deltatron M-100-DC supply, through a 1:10^4 resistance divider. This divider was initially calibrated by comparing the breakdown voltage reading of the digital voltmeter for 25 cm. dia sphere gaps, with their standard values in reference (4) - all the digital voltmeter readings were then corrected using this calibration curve.

The electrodes used were of the Bogowski profile, with a diameter of 115 mm. The surfaces of the electrodes were carefully machined and polished with a 600 grid sandpaper, and then given a mirror finish. It was then washed with acetone and distilled water. The electrodes were then subjected to a few hundred conditioning shots, before being used for measurements. The upper electrode was maintained stationary, and connected to the high voltage supply through a high voltage bushing. The lower electrode was made movable—this was made possible by an arrangement shown in Fig. (3.2). The dial is held from moving, by a set of screws, which prevent it from vertical motion. When this
dial is rotated the shaft which is threaded is forced to move vertically. This shaft passes through a bush into the pressure vessel. The movement of the shaft displaced a platform which is connected to the base of the shaft, through a similar distance, and this was monitored by a meter, which measured the electrode separation correct to 0.01 mm.

Whenever the upper lid of the chamber was lifted for replacing the electrodes, it was necessary to recalibrate the meter measuring the electrode separation. This calibration was found necessary in order to account for the slight manufacturing errors in the dimensions of the electrode, which could falsify the electrode gap measurements, using a setting calibrated for another set of electrodes. To do this, the electrodes were brought in contact, and the meter was set to read zero, at this position.

For breakdown measurements, the voltages were increased swiftly, to about 60% of the expected values of the breakdown voltage, and then slowly at an approximate rate of 30 kV/minute. Care was taken to prevent excessive losses due to corona, details of which have been dealt with earlier.
fig(3.2). Arrangement for movement of lower electrode.
A high voltage resistor was connected in series at the high voltage side, in order to limit current at breakdown, since high currents at breakdown could result in excessive erosion of the electrode surface. A schematic diagram of the experimental set up for breakdown measurements, is given in Fig. (3.3).

The pressure vessel was tested for leakage, and it was found to lose about 0.2 bar in 48 hours, on an average. Whenever the chamber was pressurized, breakdown measurements were made after a period of 20 to 30 minutes, in order to obtain consistent readings. All readings were referred to a temperature of 20 degrees centigrade, in order to facilitate comparison of the results obtained, with those obtained by other researchers.

Since the pressure at temperatures higher than 20 degrees centigrade would be higher than that at 20 degrees centigrade, a correction factor was required to ensure that the breakdown voltage values used in calculations were those higher values, which could be expected at 20 degrees centigrade. The equation used for this correction is:

\[ V_{\text{actual}} = \frac{273 + T}{273 + 20} \times V_{\text{measured}} \]

where \( T \) is the ambient temperature.
fig(3.3). A Schematic diagram of the Apparatus used.
An Edwards high speed rotary pump was used for evacuating the chamber. When a new gas had to be used, the chamber was first of all evacuated to a pressure of about 10 torr, and then flushed with the new gas. This is repeated about two or three times, before the chamber was finally pressurized for experiments.

Traces of the waveforms to be studied, were obtained using a Tektronix Type 549 Storage Oscilloscope. This oscilloscope uses a T5490 direct view, bistable storage tube, having a 6x10 cm. display area divided into two 3x10 cm. targets. The targets are independently controlled for split screen applications. An additional area, which does not store is provided to the left of the targets. The instrument is designed to perform to specifications in a laboratory environment, with an ambient temperature range between zero and 50 degrees centigrade.

A Sabtronics Model 2010A, Digital Multimeter was use for all resistance and voltage measurements.
Chapter IV

RESULTS AND DISCUSSION

This chapter provides a discussion of the investigations conducted, with regard to the breakdown and prebreakdown characteristics of uniform field systems, in highly compressed gases. These investigations were primarily of an experimental nature, and precautions were taken, as mentioned in the previous chapter, to ensure that these measurements were accurate - precautions to prevent leakages of the gas, reduce losses due to corona, shielding of measuring equipment, etc.

While several investigations of the insulating properties of compressed gases have been made, nearly all of them have dealt with pressures less than 5 to 6 bar. The work reported here, presents experimental data for gases, principally air, at pressures up to 16 bar, and voltages up to 400 kv.
4.1 Conditioning Effects

The breakdown voltage $V_b$, of a gas under uniform field conditions, at low pressures, is independent of the number of sparks. But, at higher pressures, a 'conditioning' effect is observed. Results for freshly polished electrodes in nitrogen are presented in Fig. (4.1). At a pressure of 39.65 psi there is almost a one hundred per cent increase in the breakdown voltage, after a mere 15 to 20 shots. This conditioning effect is due primarily to the existence of microscopic protrusions on the electrode surface - their effect becomes significant at higher pressures, since they are possible sites for field intensification. On sparking, these protrusions or craters are removed, hence increasing the insulation strength of the system. After a few sparks, it is noticed that the breakdown voltage fluctuates, but to a much lesser extent.

An electrode conditioned at a lower pressure, is observed to need further conditioning when the pressure is increased. This is in agreement with the observations of Philip(25), who stated that conditioning is primarily an electrode effect, and that electrodes conditioned at one pressure, need further conditioning, when the pressure, and therefore the field is increased. But note, however, that the conditioning required is much less than that required for a freshly polished electrode.
MEDIUM: NITROGEN
ELECTRODE SEPARATION: 1 CM.
SUPPLY: -VE DC
ELECTRODES: ALUMINIUM

fig(4.1). Curves indicating conditioning effect.
4.2 BREAKDOWN MEASUREMENTS

4.2.1 NEGATIVE POLARITY DC VOLTAGES

4.2.1.1 ELECTRODE SEPARATION AND PRESSURE

The variation of the breakdown voltage, with electrode separation, has been plotted in Fig. (4.2). It is observed that there is a linear increase in $V_b$ on increasing the electrode separation '$d$'. Observations made here used nitrogen as the gaseous insulant, with electrode separations up to 20 mm. In fact the increase in breakdown voltage with '$d$', is rather steep, and this increase becomes steeper with increase in pressure.

This statement can lead us to a conclusion that the insulation strength of gases improve steadily with pressure. However, when an increase in pressure is considered, there are several factors to be accounted for - factors like cost, dimensions of the enclosure which is to hold the compressed gas, efficiency, etc. A closer look at Fig. (4.2) indicated that the improvement in insulation strength with increase in pressure, was very good up to 6 or 7 bar, beyond which this improvement became less marked.
ELECTRODES: ALUMINIUM
MEDIUM: NITROGEN
SUPPLY: -VE DC

fig(4.2). DC breakdown voltage vs. electrode separation.
To study this more carefully, the difference in the breakdown voltage on varying the electrode separation from 5 mm. to 10 mm., was plotted against the pressure, and is shown in Fig. (4.3). The data for this plot was obtained from Fig. (4.2), and is tabulated in Table (4.1). It can be seen, that the slope of the curve in Fig. (4.3), decreases progressively from a high value to a low value as the pressure increases. When the pressure was between 6 to 7 bar, the slope attained a value of 1, and beyond this pressure, the slope decreased further.

A plot of the breakdown voltage versus pressure is shown in Fig. (4.4), for nitrogen, for different values of electrode separation. This plot as well as Fig. (4.3), indicate that the improvement in insulation strength becomes less marked after a certain threshold value of pressure.

Similar investigations were conducted for air, argon and helium, and the measurements obtained are plotted in Figures (4.5), (4.6), and (4.7). The trend of the variation of the electrode voltage with the electrode separation for air, argon and helium is similar to that observed in nitrogen.
### Table 4.1 - Increase in Breakdown Voltage, on Changing Gap Length from 9 mm. to 10 mm. at Different Pressures

<table>
<thead>
<tr>
<th>Pressure (Bar)</th>
<th>Increase in Breakdown Voltage (KV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.41</td>
<td>52</td>
</tr>
<tr>
<td>6.41</td>
<td>75</td>
</tr>
<tr>
<td>9.20</td>
<td>99</td>
</tr>
<tr>
<td>12.60</td>
<td>125</td>
</tr>
<tr>
<td>14.65</td>
<td>134</td>
</tr>
<tr>
<td>16.00</td>
<td>141</td>
</tr>
</tbody>
</table>

**Figure 4.3:** Increase in breakdown voltage, on changing electrode separation from 5 mm. to 10 mm. vs. pressure.
MEDIUM: NITROGEN
ELECTRODES: ALUMINIUM
SUPPLY: -VE DC

$V_B$ in Kilovolts

fig(4.4). DC breakdown voltage vs. pressure.
Figure 4.5: DC breakdown voltage vs. electrode separation for air.

KILOVOLTS

D in mm

1 bar

2.71 bar

4.41 bar

6.46 bar

9.19 bar

12.6 bar

16 bar

SUPPLY: ±5 DC

MEDIUM: AIR

ELECTRODES: ALUMINIUM

14.65 bar
fig(4.6). DC breakdown voltage vs. electrode separation, for Helium.

fig(4.7). DC breakdown voltage vs. electrode separation, for Argon.
Trump et al. (32) have conducted similar studies in air with stainless steel electrodes, under DC stresses. As seen in Fig. (4.8), there is reasonable agreement between the results obtained in this work, and those of Trump et al.

4.2.1.2 FAILURE OF PASCHEN'S LAW

Plotted in Fig. (4.9) is the Paschen curve for compressed nitrogen. Paschen's law states that the breakdown voltage is a function of the product of pressure and electrode separation. Though this law has been proved true for atmospheric and lower pressures, Fig. (4.9) indicates that this is not so under high pressure conditions - significant deviation from linearity occurs at a value of $(pd)$ close to 8 bar-cm.

It is also noticed that this deviation from linearity becomes more pronounced as the pressure is increased. At a pressure of 4.4 bar, the Paschen curve is very close to linear, whereas, at pressures around 9 bar, the deviation from linearity is clear.
SUPPLY: -ve DC
MEDIUM: AIR
ELECTRODES: STAINLESS STEEL

--- This work.

--- Trump et al

**fig(4.8):** Comparison of these breakdown studies, with those of Trump et al.
fig(4.9). Paschen curve for nitrogen.
Air, however shows a linear Paschen curve for higher 'pd' values than nitrogen, as seen in Fig. (4.10). Sysoev et al. (11), observed variations from linearity in air at 7 bar-cm, using plane stainless steel electrodes, with a diameter of 11 cms. Fig. (4.10) shows a linear Paschen curve up to a pressure of 8 bar, approximately.

Figures (4.11) and (4.12) show Paschen curves for helium and argon. Experiments were conducted up to a pressure of 16 bar, with electrode separations varying up to 30mm. for helium and 25mm. for argon. In helium, a marked deviation from linearity was observed at 10 bar-cm, whereas in argon a deviation from linearity was observed at around 8 bar-cm.

It was however, difficult to correlate the results obtained with those of previous researchers, since the value of \( V_b \) at which deviations from linearity begin, depends on factors like electrode material, area of electrodes, dust content, experimental conditions, etc.
fig(4.10). Paschen curve for air.
SUPPLY: -VE DC
MEDIUM: HELIUM
ELECTRODES: ALUMINIUM

fig(4.11). Paschen curve for Helium.
SUPPLY: -VE DC
MEDIUM: ARGÓN
ELECTRODES: ALUMINUM

fig(4.12). Paschen curve for Argon.
4.2.1.3 DEPENDENCE ON GASEOUS INSULANT

Dutton et al.\(^{26}\), observed that at pressures up to 1000 mm. of Hg., the current growth in air, nitrogen and hydrogen are of the same form. An experimental study was made, to compare the breakdown voltages of electrode systems, in compressed air and compressed nitrogen, the results of which have been plotted in Fig. (4.13).

It is noticed that the breakdown voltages, for a fixed gap, are higher for air than for nitrogen. Note that in measurements up to 6.46 bar in Fig. (4.13), the difference in insulation strengths between air and nitrogen is well within the range of experimental error of measurements (between 3% and 5%). At 9.19 bar, this difference becomes noticeable above electrode separations of 8mm., whereas at a pressure of 16 bar, this difference was noticeable at values of electrode separation higher than 5 to 6mm. This can be explained by the fact that air is more electronegative than nitrogen, due to its oxygen content. And the more electronegative the gas, the higher the breakdown voltage. It is also observed that the higher the pressure, the more marked the difference in insulation strength between air and nitrogen.
fig(4.13). Comparison of DC breakdown voltage variation with electrode separation, for air and nitrogen.
SUPPLY: -VE DC
ELECTRODES: 8 mm.
ELECTRODES: ALUMINIUM

fig(4.14). Comparison of breakdown voltages for different gases.
Considering the fact that there is a possible 3 to 5 per cent error in the breakdown voltage measurement, it can be suggested that air has a significantly higher breakdown voltage when compared to nitrogen, at pressures greater than 6.5 bar, with electrode separations greater than 4 mm. Fig. (4.14) gives a comparison of the breakdown voltages for air, nitrogen, argon and helium, at an electrode spacing of 8 mm.

4.2.1.4 DEPENDENCE ON ELECTRODE MATERIAL

Since Paschen's law is no longer obeyed at higher pressures, breakdown can no longer be explained by the usual gas collision theories, which have been proved true, time and again, for lower pressures. The Townsend-type mechanism, is assisted by a field dependent electron emission, and other mechanisms which are dependent on the cathode material.

Comparisons were made between the insulation strengths of aluminium and stainless steel electrode systems, in compressed air. Fig. (4.15) which is a plot of the breakdown voltage versus pressure, indicates little or no difference between the insulation strengths of stainless steel or aluminium electrodes at lower pressures. But beyond pressures of 2 to 3 bar, their insulation strengths begin to vary. However significant variations are observed at pressures above 40 bar.
The fact that the influence of the electrode material is rather limited at lower pressures (since the breakdown mechanism is primarily due to electron collision processes, with very little field-assisted electron emission from the cathode), could be a possible explanation for this phenomena. But, as the pressure, and hence the field increases, collision processes lose significance and the mechanism is mainly dominated by processes largely dependent on emissions from the electrode material.

Fig. (4.15) indicates a significantly better insulation strength for aluminium than stainless steel, at pressures around 4 bar and above. Before any conclusions could be drawn from this result, it has to be stated that the experimental conditions were not similar during data collection. The aluminium electrodes were highly conditioned since they had undergone several hundred sparks, whereas the stainless steel electrodes were conditioned with about 100 sparks before being used for this experiment. This could be a reason why, stainless steel indicates a lower breakdown voltage, in spite of the fact that it has a higher work function.
Coates et al.\(^{(10)}\) had observed that a layer of fine dust was deposited on stainless steel electrodes, during sparking. He conducted his experiments in nitrogen up to pressures of 12 bar. These dust particles could result in points of weakness on the electrode surface, thus creating possible sites of field emission. This could be an explanation of the observation in these results that stainless steel has a lower breakdown voltage when compared to aluminium — in spite of the fact that stainless steel has a higher work function.

Note however, that stainless steel shows a slightly higher breakdown voltage value when compared to aluminium, for an electrode separation of 10 mm. The breakdown voltage has been plotted against the electrode separation in Fig. (4.16), and this leads us to the same conclusions as mentioned above.
SUPPLY: -ve DC
MEDIUM: Air

fig(4.15). DC breakdown voltage vs. pressure for aluminium and stainless steel.
fig(4.16). DC breakdown voltage vs. electrode separation for aluminium and stainless steel.
4.2.2 AC VOLTAGES

One of the objectives of this research endeavour was to make a comparative study of the effects, if any, on the insulation strength, due to the type of supply used. The results obtained using AC voltages have been plotted in Fig. (4.17). It has been observed in the past, that when subjected to AC voltages, the insulation broke down at the peak of the positive half cycle. So, the breakdown voltages indicated in Fig. (4.17), are the peak values of the AC RMS breakdown voltage data.

This plot indicates a similar trend as observed in the DC measurements, with the breakdown voltage increasing linearly with the electrode separation, for different values of pressure. Also, the improvement in insulation strength with pressure, becomes less pronounced (for a constant electrode separation) as the pressure is increased.

The AC breakdown voltages have also been plotted against the pressure in Fig. (4.18). The steepest increase in insulation strength is observed in the low pressure range. One conclusion that can be drawn from this is that the increase in breakdown voltage with pressure, is by no means linear.
ELECTRODES: ALUMINIUM
MEDIUM: AIR

fig(4.17). AC breakdown voltage vs. electrode separation.
ELECTRODES: ALUMINIUM
MEDIUM: AIR

fig(4.18). AC breakdown voltage vs. pressure.
AC breakdown studies were also conducted with helium and argon as gaseous insulants, and the breakdown voltage data are plotted in Figures (4.19) and (4.20). Skilling et al.\(^{(9)}\) have studied the behaviour of compressed air, with steel sphere electrodes. Their results have been compared with those obtained in this work in Fig. (4.21). There is reasonable agreement in the results, the slight differences being due to the difference in the electrode material.

4.2.3 A COMPARATIVE STUDY

To compare the results obtained under AC and DC voltage stresses, a graph depicting the characteristics of the test electrode system under these different conditions was included. This is shown in Fig. (4.22). Comparisons were made of the flashover voltage characteristics with increasing pressure, at two values of electrode spacing. It was observed that the insulation system had a higher insulation strength under AC stress, while the breakdown occurred at slightly lower voltages under DC voltages. However, this difference is not significantly large, and could be well within the range of the experimental error of 3 to 5 per cent.
fig(4.19). AC breakdown voltage for helium, plotted against electrode separation.
ELECTRODES: ALUMINIUM
SUPPLY: AC
MEDIUM: ARGON

fig(4.20). AC breakdown voltage for argon, plotted against electrode separation.
SUPPLY : AC
MEDIUM : AIR
ELECTRODE SEPARATION : 1.25 mm.

---X--- : This work with aluminium electrodes.
--- --- : Skilling et al with steel spheres.

fig(4.21). Comparison of these breakdown studies (AC), with those of Skilling et al.
fig(4.22). Comparison of AC and DC breakdown measurements.
4.3 **PREBREAKDOWN MEASUREMENTS**

To understand the breakdown phenomena more clearly, the prebreakdown characteristics have to be analyzed. The circuit used to study the prebreakdown currents, is shown in Fig. (4.23). A very large resistance of 996 kiloohm, was used in the low voltage side of the electrode system, across which prebreakdown currents were measured. A protective circuit, was used to protect the measuring devices like the digital voltmeter and the oscilloscope, in case of an accidental flashover.

When field-emission currents were observed as a function of time, it is found that there are large fluctuations in the current which could be termed as 'noise'. Powell and Chatterton(29) have discussed in detail the effects of noise, temporal variations in emission currents, and curved Fowler-Nordheim plots, in vacuum. They were also able to show that this phenomena observed in field emission from gas covered electrodes, could be explained on the basis of the adsorption/desorption effects occurring during data collection.
fig(4.23). Circuit for prebreakdown measurements.
Typical examples of noise in field emission currents are shown in the oscillographic pictures in Figures (4.24), (4.25), and (4.26). Such rapid changes or fluctuations in emission, can greatly alter the character of the emitting sites, and investigators have reported difficulty in reproducing prebreakdown results.

But an effort was made to measure the dc component of the prebreakdown current, by connecting a large capacitance in parallel with the high resistance. The RC time constant of the entire current measuring circuit was 4.31 seconds. This helped in suppressing all pulses with a wavelength smaller than 4.31 seconds from affecting the prebreakdown current readings.

In order to ensure that the electrode surfaces were devoid of dust, it was subjected to a glow discharge, at an approximate pressure of 10 torr for a period of three hours, with glow discharge currents of the order of 15 to 20 milliamps.

The results obtained indicated that the dc component of the prebreakdown current was not in agreement with the Fowler-Nordheim equation (ie) when ln(I/V^2) was plotted versus 1/V, the curve indicated a positive slope, and not a negative slope, which is what one would expect if there was
agreement with the Fowler-Nordheim equation. \( \ln(I) \) was plotted versus \( V^{1/2} \), to check whether there was an agreement with the Schottky-Richardson equation — Refer to Fig. (4.27). The plot was a curved Schottky curve, with emission currents increasing with the field. These measurements were conducted at an electrode separation of 8 mm.

But it is to be noted that there are low frequency pulses generated in the gap in a compressed gas insulated system, and this attempt was made only to determine the trend of the dc component, of the emission current growth before the ultimate breakdown of the gap.
fig(4.24). Measurement of the voltage across a 99.6 k resistor, at 40% the breakdown voltage. Pressure = 74.65 psi
Vertical Scale: 1 Volt/cm
Horizontal Scale: 0.5 sec/cm

fig(4.25). Measurement of the voltage across a 995 k resistor, at 80% the breakdown voltage. Pressure is 74.64 psi.
Vertical Scale: 1 Volt/cm
Horizontal Scale: 0.5 sec/cm

fig(4.26). Magnified view of fig(4.25)
Vertical Scale: 1 Volt/cm
Horizontal Scale: 0.1 sec/cm
PREBREAKDOWN CHARACTERISTICS
SCHOTTKY CURVE

SUPPLY: NEGATIVE DC
ELECTRODES: ALUMINIUM
MEDIUM: AIR

\[ \ln(I) \]

\[ V^{1/2} \]

fig(4.27). The Schottky curve.
Chapter V

CONCLUSIONS

The electrical breakdown and prebreakdown characteristics of highly compressed gases have been investigated and comparisons have been made with the insulation characteristics of lower pressure gases. The classical analysis of Townsend, which bases its theory on the formation of electron avalanches caused by ionization as a result of frequent electron collisions, fails to hold, at high pressures, since there is a marked deviation from linearity in the Paschen curve - this deviation occurring at different 'pd' values for different gases.

The phenomena occurring in the gap, in compressed gases, have been found to be too intricate for a full quantitative description and hence experimental determination of the breakdown and the prebreakdown behaviour, has been the main source of information for this study.

It would be of interest to mention some of the smaller details which have gone a long way toward enhancing accuracy in these measurements.

1. As mentioned earlier, this study has handled electrical field values up to 50 MV/m. It could be
expected, at these high fields, that any sharp point, protrusion or even dust, can be a source of significant corona losses. For DC measurements the incoming high voltage line was a 3" dia copper pipe, whose smooth surface ensured that there were no sites where field intensification could take place.

2. When dealing with very sensitive measurements, like prebreakdown currents at high pressures, it is of utmost importance to eradicate the influence of external noise signals. This has been achieved, by carefully shielding all the measuring circuitry, the equipment and the HV lab. Hence, it could be safely assumed that the large amount of noise indicated by the oscilloscope, while measuring the prebreakdown currents, was generated by the phenomena in the gap.

3. Gas leakage is almost a certainty in high pressure systems. Attempts were made to reduce this as much as possible. It was noticed that there was an average pressure drop of 0.2 bar in 48 hours, which was decided as an acceptable value, since work at one pressure never lasted for more than 4 hours.

4. When doing comparative studies, care must be taken to ensure similar experimental conditions.
5.1 CONCLUSIONS OF THIS STUDY

The following are the conclusions of this study of breakdown and prebreakdown characteristics of electrode systems, placed in highly compressed gaseous insulants.

1. Studies were made, on the effect of conditioning of the electrodes. It was observed that fresh electrodes required significant conditioning — sometimes after a few sparks, the insulation strength increased to twice its initial value. It was also seen that electrodes conditioned at one pressure, required further conditioning when the pressure was increased. However, the amount of conditioning required was much less, when compared to that required by a fresh electrode.

2. Breakdown studies were conducted for nitrogen, air, helium and argon. In all these gases, the breakdown voltage increased linearly and steeply, with increasing values of electrode separation. But the steepness of this increase in insulation strength was more pronounced at lower pressures, (e.g.) for nitrogen, the steepness in the increase of the breakdown voltage, started declining beyond a pressure of 7 bar.
3. Air showed a higher value of insulation strength, when compared to nitrogen, for a fixed value of electrode separation. Argon and helium, being rare gases have far lower breakdown voltages, since they are non-attaching gases — however argon did exhibit a slightly higher insulation strength than helium.

4. At lower pressures the breakdown voltage did not depend on the electrode material. However, at pressures above 12 bar in air, aluminium electrodes when used, showed a higher breakdown voltage than stainless steel.

5. Under AC stress, air, nitrogen, helium and argon indicated similar trends, as observed under negative polarity DC stress.

6. Deviations from the linearity of the Paschen curve at higher pressures, is observed in all the gases experimented on. The value of 'pd' at which this deviation occurs varies with the gaseous insulant used.

7. The insulation strength of air is slightly higher when subjected to AC voltages, when compared to its value under negative polarity DC stress.

8. Prebreakdown current measurements indicated some agreement with the Schottky-Richardson equation. Note however, that only the DC component of the prebreakdown current was studied, since the pulses
generated in the gap, were too erratic for an accurate measurement.

5.2 POSSIBLE EXTENSIONS TO THIS WORK

1. It would be useful to work at pressures above 16 bar, and determine whether these observed trends continue at these high pressures.

2. Extensive work has been done using SF₆ as the gaseous insulant, up to pressures close to 6 bar, by several investigators. This work could be extended to higher pressures, even though this would mean working with electric fields much higher than 50 MV/m.

3. The effects on insulation strength, due to superimposition of AC and DC, or DC and Impulse voltages could be explored.
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