The effects of low temperatures on the DC breakdown characteristics of plane-plane and rod-plane gaps insulated with compressed sulphur hexafluoride.

Frank Joseph. Ewasyshyn

University of Windsor

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THE EFFECTS OF LOW TEMPERATURES
ON THE DC BREAKDOWN CHARACTERISTICS
OF PLANE-PLANE AND ROD-PLANE
GAPS INSULATED WITH COMPRESSED
SULPHUR HEXAFLUORIDE

by

Frank Joseph Ewasyszyn

A Thesis
submitted to the Faculty of Graduate Studies
through the Department of
Electrical Engineering in Partial
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the Degree of Master of Applied Science at
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Windsor, Ontario, Canada

1976
ABSTRACT

The dielectric strength of SF$_6$ insulated uniform and non uniform fields has been examined at subzero temperatures. This experimental investigation has been conducted in a temperature range of +20°C to -30°C at pressures from 1 to 5 atm. The dielectric strength of both a constant pressure and a constant density environment has been examined within these ranges of temperature and pressure. An experimental system capable of generating the necessary environment and testing the dielectric strength of the SF$_6$ in this environment has been described. The data obtained from this experimental study and the conclusions based on this data are presented. It has been shown that subzero temperatures in a constant pressure environment can affect the insulation strength of SF$_6$ in different ways depending on the uniformity of the electric field and the pressure of the system.
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CHAPTER 1
INTRODUCTION

Gases have been used to insulate high voltage equipment for many years. The first gaseous insulating media used were air and nitrogen at atmospheric pressure. With the need for higher operating voltages, equipment insulated with air or nitrogen at atmospheric pressure became very bulky. To make the insulation more compact and efficient the air and nitrogen were compressed.

When the insulation limits of air at high pressures were reached new insulating gases with superior characteristics were sought. A group of gases classified as electronegative, by chemists and physicists, were found to have highly desirable electrical properties. These gases have the ability to capture free electrons and form stable negative ions. (1) The depletion of free electrons by the formation of these less mobile negative ions results in high dielectric strengths for electronegative gases as compared to air or nitrogen.

In order for a gas to be utilized as a practical insulation medium, it must meet certain requirements. An insulating gas must be non toxic, chemically inert, and remain in a gaseous state at operating pressures and low temperatures. Many electronegative gases although possessing high dielectric strengths do not meet all of these requirements.

The gas which best meets these requirements is sulphur hexafluoride (SF$_6$). With a dielectric strength reported to range from 1.8 to 3 times that of air and the necessary physical and chemical properties, SF$_6$ has been implemented as a practical gaseous insulator.

SF$_6$ is currently being used as insulation in transformers, circuit breakers, high voltage test sets and more recently in underground transmission.
2.

cables. The need for more compact and aesthetically pleasing distribution substations has led to the design and installation of metal clad gas insulated stations. Entire substations, of this type, have been installed in the interior of modern urban building complexes. The use of compressed gas insulation in this particular area has meant reductions in installation costs and substantial reductions in station size.

The SF₆ used as insulation in electrical equipment is maintained in a state of constant pressure or constant density. In SF₆ insulated circuit breakers, two major designs are now in use; single pressure and double pressure circuit breakers. A single pressure circuit breaker is contained in an environment of SF₆ at a pressure of 3 - 5 atm, which is maintained by artificially heating the gas to 20°C above ambient. In a double pressure circuit breaker, a high pressure reservoir of 16 atm is used to extinguish the interruption arc. The remainder of the system is maintained at a pressure of 3 - 5 atm. The high pressure reservoir and the rest of the system are both maintained at a temperature of at least 20°C. The heaters installed in both systems are used to prevent the liquefaction of the SF₆ gas.

With the increasing demand for electrical energy, generating and distributing systems are being built in the northern regions of the country. Ambient temperatures range from +25°C to -40°C, are becoming potential operating temperatures for some gas insulated equipment.

Little information has been reported on the effects of subzero temperatures on the dielectric strength of SF₆. A detailed review of available literature has yielded very little information on the electrical behavior of SF₆ at temperatures below 0°C.
3.

These facts have prompted the undertaking of the present study in which the effects of temperature, ranging from $+20^\circ \text{C}$ to $-30^\circ \text{C}$, on the dielectric strength of $\text{SF}_6$ have been examined. This study has included the effects of temperature on both uniform and non-uniform field gaps insulated with compressed $\text{SF}_6$ under conditions of constant pressure or constant density. After some preliminary work the investigation was conducted using the following plan.

1.1 Organization of Investigation

An initial literature review was conducted to determine if, in fact, any information did exist on the effects of sub-zero temperatures on the dielectric strength of $\text{SF}_6$. When this literature review yielded little information on the topic a detailed literature review was undertaken. This detailed review covered both the electrical breakdown characteristics of electronegative gases and their physical characteristics. The review included a computer search of the National Research Council Library, Ottawa, for any available information of $\text{SF}_6$. When little material relevant to the topic was found the experimental study was undertaken.

Before undertaking this study it was necessary to design an experimental system capable of controlling and measuring the parameters to be investigated. A test chamber together with the necessary measuring equipment was designed and constructed. The system was suitable for testing the breakdown strength of $\text{SF}_6$ over temperatures ranging from $+20^\circ \text{C}$ to $-30^\circ \text{C}$, and pressures ranging from 1 to 5 atm. Pressure, temperature and breakdown voltage were measured and recorded for both uniform and non-uniform field gaps.

The factors affecting breakdown such as electrode material and gap length were examined before an experimental procedure was adopted. Once these factors had been examined and an experimental procedure adopted the
actual experimental work was undertaken. A total of 3300 breakdown
tests were conducted over a pressure range of 1 to 5 atm., in 1
atmosphere steps, and a temperature range from +20°C to -30°C in 10°C
steps.

The experimental systems used in this investigation and the results
obtained are presented in this thesis. For clarity of exposition the
material has been presented in 7 chapters.

The measuring and the testing systems are described in Chapters 2
and 3 respectively. Chapter 4 deals with the relevant theoretical
considerations. The experimental procedure, the measured data and the
discussions are presented in Chapters 5 to 7. Chapter 8 contains a
comparison of results, conclusions, experimental limitations and
suggestions for future work.
CHAPTER 2
MECHANICAL SYSTEM

2.1 Introduction

In any experimental system in which a controlled environment is necessary a closed chamber must be used. At temperatures above or below ambient and at pressures higher than atmospheric the design of the chamber becomes complicated. For the present work a thermally insulated pressure test chamber was designed.

The generation and measurement of subzero temperatures required an efficient and controllable cooling system. The temperatures in the present study could be recorded to within ± 2%. The quality and purity of the SF₆ used throughout the tests was also monitored.

2.2 The Physical Characteristics of SF₆

Sulphur hexafluoride (SF₆) is a stable non toxic gas. The physical characteristics of SF₆ have been examined in great detail by several research groups,(3) (4) particularly since its introduction as an electrical insulator. The most important characteristics under the present experimental conditions are the critical temperature, the critical pressure, the density, the thermal conductivity, the viscosity and the heat capacity.

The critical temperature and pressure are single measured values. The temperature above which the gas cannot be liquified by an increase in pressure alone is defined as the critical temperature. The pressure under which the substance may exist as a gas in equilibrium with the liquid at the critical temperature is defined as the critical pressure point. (5) The values recorded for these parameters are 45.55°C for critical temperature and 37.1 atmospheres for critical pressure. (6)
In the present study the critical point at which $\text{SF}_6$ passed from a gas to a liquid was reached at a pressure of 4.3 atm. and a temperature of $-30^\circ$C. In the remainder of the study $\text{SF}_6$ remained in the gaseous state. The density of $\text{SF}_6$ has been found to be approximately 5 times that of air. This property has been examined in temperatures ranging from $+45^\circ$C to $-250^\circ$C. (6) at 1 atm.

The thermal conductivity of a gas is an important parameter in its cooling capacity. Since the electrical equipment normally insulated with $\text{SF}_6$ generates considerable amounts of heat, the ability of the gas to cool this equipment is necessary to ensure its operation. The published values of thermal conductivity for $\text{SF}_6$ in the gas phase have been found to range from approximately $30 \times 10^{-6}$ (cal/sec x cm x $^\circ$C) at $0^\circ$C to $140 \times 10^{-6}$ (cal/sec x cm x $^\circ$C) at $800^\circ$C. The maximum difference in published values has been found to be 7% (6).

The other factors affecting the cooling capabilities of a gas are its viscosity and heat capacity. The heat capacity of $\text{SF}_6$ has been found to be of the same order as that of air, .175 cal/g/$^\circ$C over a temperature range of $0^\circ$C to $300^\circ$C in a constant volume system. (7) The viscosity of $\text{SF}_6$ is the main factor in its cooling capacity. With a viscosity value lower than that of air $\text{SF}_6$, in the presence of a thermal gradient, circulates much faster. This results in better heat dissipation and lower operating temperatures.

The pressure-temperature characteristics of a gas used in practical installations are also important. This applies particularly to equipment in which the temperature cannot be regulated.

Camilli and Chapman (1947) (8) reported that $\text{SF}_6$ behaves as an ideal gas at temperatures ranging from $+45^\circ$C to $-30^\circ$C in a constant volume system, at an initial pressure of 3 atm.
The pressure-temperature characteristics were measured in the present study. The results are plotted in Fig. 1 and indicate that SF$_6$ does behave as an ideal gas, and that SF$_6$ will obey the ideal gas law,

$$PV = nRT \quad (1)$$

Where $P$ is the gas pressure, $V$ the gas volume, $n$ is the number of moles, $R$ is the universal gas constant and $T$ is the absolute temperature. If a gas is obeying the ideal gas law a pressure $P_2$ measured at temperature $T_2$, in a constant volume system, would equal pressure $P_1$ at temperature $T_1$ calculated from equation (2)

$$P_1 = P_2 \times \frac{T_1}{T_2} \quad (2)$$

Thus if the ideal gas law is applied to the 5 atm. pressure measured at 20°C in Figure 1, the calculated pressure at -29°C should equal the measured value in Figure 1. Application of equation (2) in this case resulted in a difference of .09 atm. With an experimental error of ±2% in the pressure measurement the agreement was considered good and the gas was assumed to behave ideally over the temperature and pressure ranges of interest in this study.

2.3 Test Chamber

The test chamber used in the present study was designed to meet the following requirements:

a) The uniform field electrodes must be mounted and set parallel inside the chamber. Similarly the rod electrode when used should be mounted inside the chamber. The gap length for either type of electrode should be adjustable and measurable for all pressures and temperatures of interest.
Fig 1  PRESSURE vs TEMPERATURE CHARACTERISTICS FOR SF$_6$
b) The chamber must be capable of accepting the high voltage coaxial supply cable.

c) It should be possible to cool or heat the system so that the temperature of the gas in the chamber could be varied.

d) The chamber must be able to accommodate temperature sensors and pressure gauges.

The chamber was constructed from a section of carbon steel cylindrical pressure pipe 21 in. long, 1\(\frac{1}{4}\) in. in diameter and 3/8 in. thick. The top and the base of the cylinder were closed with 1 in. thick mild steel plates. These plates were chosen to minimize changes in gap length due to the deformation of the chamber caused by varying temperatures and pressures. The end plates were sealed with "O" rings and bolted to the cylinder flanges with 9/16 in. high torque bolts.

The chamber was hydraulically tested to a pressure of 40 atm. for a period of 5 to 6 hours. When no reduction in pressure was observed the system was assured safe to a working pressure of 20 atm., even though the present work required a maximum pressure of 6 atm. Figure 2 gives a simplified drawing of the pressure test chamber.

The high voltage feed through was constructed of solid epoxy. This feed-through was designed by Delta Ray Corporation to accommodate the high voltage coaxial cable. The high voltage was applied to the electrodes through a current limiting resistor. The upper electrode, the cathode, was supported by a 13 in. diameter plexiglass plate 3/4 in. thick. The plate was supported on 3 plexiglass rods fastened to the base of the chamber. The lower electrode, the anode, was removable allowing for the installation of either the plane or rod electrode and it was supported by
Fig 2. PRESSURE CHAMBER

1. High Voltage Feed through
2. Current Limiting Resistor
3. Plexiglass Supports
4. Rogowski Electrodes
5. Fibre glass Insulation
6. Coolant Circulating Jacket
an adjustable shaft. The lower Rogowski profile electrode could be
adjusted for height and set parallel to the upper electrode.

The electrode adjustment system was designed to minimize measurement
errors caused by the variation of temperature and pressure over wide ranges.
Fig. 3 shows the main components of this adjustment system. The gap
length was measured using a Mercer micrometer depth gauge. The gauge had
a resolution of ± 0.01 mm. and an accuracy of ± 0.01 mm. The main adjusting
shaft was made from a 1/2 in. diameter stainless steel rod. Initially a
mild steel adjusting rod was used. At low temperatures the mild steel
contracted and a gas leak developed. The mild steel was also easily
corroded causing an even greater leak. Silicon rubber "0" ring seals
were employed around the shaft to ensure a flexible seal at -30°C.

This chamber served as the main component in the testing system.
All tests conducted in this study were carried out in this chamber.

2.4 Cooling System

To obtain the desired temperature range, +20°C to -30°C, it was
essential to have an efficient cooling system. The system chosen was a
Neslab LT-9 cooling-circulating unit. This system had a low temperature
limit of -70°C with the bath temperature controllable to within ± 1°C
over a range from +10°C to -70°C. The LT-9 cooler required 10 - 12 hours
to lower the temperature of the tank from +20°C to -30°C.

Figure 4 shows a block diagram of the cooling system. The walls of
the chamber were covered with a galvanized coolant retaining jacket 1 1/2
in. thick and 11 in. in height. The cooling system was connected to the
vessel by 1/2 in. diameter hoses. The vessel walls were insulated with 4
in. thick fibre glass wrapped with aluminum foil. The top and base of the
vessel were insulated with 4 1/2 in. thick styrofoam collars. The top plate
was also covered with 1 in. thick compressed fibre glass plate.
Fig 3. ELECTRODE ADJUSTMENT MECHANISM

1 Electrode Leveling Screws
2 Electrode Support Plate
3 Insulator
4 Gap Length Gauge
5 Adjustment Control
Fig 4. COOLING SYSTEM

1 Test Chamber
2 Styrofoam Collars
3 Fibreglass Insulation
4 Temperature Control Unit
5 Circulating Cooler
6 Circulating Hoses
7 Cooling Jacket
The cooling medium chosen was methanol which has a freezing point of approximately -90°C. The methanol was circulated at a rate of 130 gallons per hour.

2.5 Temperature and Pressure Measuring Systems

The pressure measuring system consisted of two "Thermo - Gauge" test gauges mounted on the top of the test chamber. One gauge was calibrated for the range of pressures from 0 to 60 psig, pounds per square inch gauge, (1 - 5 atm.). The second was calibrated to read from 0 to 300 psig (1 - 21 atm.). Both gauges were compared with the standard gauges and found to be within 1% of the standard reference. A "Hoke" low temperature "Dyna Pak" valve was connected in series with the 0.5 atm. gauge. This valve was installed so that the gauge could be cut off if pressures above 5 atm. were to be measured.

The purity of SF₆ entering the tank was controlled by means of a mechanical filter and a gas dryer. The filter was connected in the gas supply line. It was capable of removing particles larger than .03 microns. The drying agent was calcium sulphate (CaSO₄) and was capable of supplying a dew point of -74°C. An additional drying agent in the form of silica gel was placed in a beaker inside the chamber.

Despite the fact that the chamber had been tested to a pressure of 40 atm. with no noticeable leaks two safety valves were installed. The main safety valve consisted of a 20 atm. relief valve mounted on top of the chamber. The second was a 5.1 atm. relief valve connected in series with the 5 atm. gauge to protect the gauge from possible overloading.

Prior to filling the chamber the air was removed by a vacuum pump which was operated for 6 to 10 hours until the pressure level in the tank reached .1mm. Hg. The tank was then flushed with SF₆ and filled to the
desired pressure. The SF used throughout the experimental studies was supplied by Liquid Carbonic of Canada Limited. It had a guaranteed purity of 99.98%.

Figure 5 gives a simplified block diagram of the pressure control and measurement system described previously.

Figure 6 is a block diagram of the temperature measuring system employed throughout the course of the present study. The temperature was measured with a copper – constantin thermocouple. This type of thermocouple was chosen for its high sensitivity in the temperature range used in this work. According to the manufacturer's specifications the thermocouple has a working range of -100°C to +400°C. A 0°C ice bath was used as the reference junction for all measurements. The manufacturer's supplied chart of millivolt output to degrees centigrade was used for conversion. This chart was adopted only after it was checked with the actual thermocouple at 0°C and 100°C. The measured millivolt values were found to be within 1% of the manufacturer's chart.

The millivolt output was recorded on a Honeywell Electronik 194 strip chart recorder. The input resistance of this chart recorder is theoretically infinite at the balance point. The chart recorder was capable of resolving temperature of .5°C over the entire 20°C to -30°C range. The desired accuracy of the measuring system was ± 1°C. This accuracy was readily achieved.

The main measuring thermocouple was located inside the uniform field electrode. It was covered by a spring copper plate inside the anode. In the rod-plane system this thermocouple was connected to an aluminum plate which was used to support the rod electrode. A second thermocouple was positioned in the gas below the anode. It was made available as an auxiliary sensor or control thermocouple.
Fig 5. VACUUM PRESSURE SYSTEM

1  0-300 psig Guage
2  0-60  psig Guage
3  60 psig Safety Valve
4  300 psig Safety Valve
5  Isolation Valve
6  Gas Inlet Valve
7  Vacuum Pump
8  SF$_6$ Cylinder
9  Nitrogen Cylinder
10 Gas Regulator
Fig 6. TEMPERATURE MEASURING SYSTEM

1. Rogowski Electrodes
2. Electrode Thermocouple
3. Control Thermocouple
4. Temperature Control Unit
5. Ice Bath
6. Chart Recorder
CHAPTER 3

HIGH VOLTAGE TEST SYSTEM

3.1 High Voltage Supply and Measuring System

The tests were all conducted under direct applied voltage supplied by a Cockcroft Walton type multiplier designed by Delta Ray Corporation. It consisted of 7 sealed modular stages with a maximum output of 150kV and a maximum current of 4mA. The output voltage had a specified ripple of 15V pk-pk over the full output range.

The high voltage was supplied to the test chamber by a Belden 8871 H.V. coaxial cable. The coaxial cable was connected to the steel test chamber by a Delta Ray feed-through. The feed-through was designed to accommodate the coaxial cable in such a way that the entire system was electrically shielded. A 1.25 MΩ current limiting resistor was connected in series with the test gap and the high voltage supply. This resistor served two purposes; one to protect the generator from the high breakdown current pulses, and secondly, to protect the electrodes from excessive pitting. The lower, or anode, electrode was grounded at all times through a feed-through, located in the base of the chamber, to a 4 x 8 ft. x 1/16 in. copper sheet. The feed-through consisted of an automotive spark plug with the firing gap removed. It was installed to provide an above ground connection through the chamber base. The copper ground sheet was used to reduce inductance in the ground circuit. Figure 7 gives a block diagram of the high voltage supply system.

The high voltage output was measured indirectly with a 3 ½ digit digital voltmeter. A low voltage signal was taken from the control loop used in the generator feedback circuit. This signal was made available by the manufacturer, therefore no additional voltage dividers were needed. A one volt low level signal corresponded to an output voltage of 10^5 volts.
Fig 7. SCHEMATIC DIAGRAM OF HIGH VOLTAGE SYSTEM

1 DC Generator 150 KV
2 Coaxial Cable
3 High Pressure Steel Chamber
4 Rogowski Electrodes
5 Current Limiting Resistor
The low level signal was calibrated against a Singer electrostatic voltmeter, capable of directly reading voltages up to 50kV within an accuracy of ± 0.5%. The output voltage was found to differ from the low level signal by -10%. A 10% correction was, therefore, applied to all recorded voltages.

3.2 Electrode Systems

The studies conducted in this work were divided into two parts according to the uniformity of the electric field in the test gap. Both uniform and non-uniform field gaps were examined. The uniform field was generated by two brass 90° Rogowski profile electrodes. The effective uniform field surface area was 50.27 mm² with a gap length of 2 mm.

The non-uniform field was generated by a hemispherically capped brass rod anode, and the 90° Rogowski profile electrode as the cathode. The rod electrode was 3.175 mm. in diameter and 38 mm. long. Figure 8 gives an actual size profile of the 90° Rogowski electrode.

The lower, anode, electrode was mounted to an adjustable shaft which allowed for the setting of the gap length. In the non-uniform field case the anode was mounted on an aluminum plate which served as a connecting point for the measuring thermocouple. The rod electrode could be insulated above ground by a plexiglass spacer which allowed corona current measurements to be made. Figure 9 shows the position of a rod electrode and the thermocouples.

Prior to the start of each set of breakdown tests the electrodes were cleaned and polished in the following manner.

a) The electrodes were cleaned with methanol.

b) Each electrode was hand polished for 10-15 minutes with, Silvo a commercial metal polish, and cheese cloth.
Fig 8. ELECTRODE WITH THERMOCOUPLE (actual size)

1  9/16" Bolts
2  Thermocouple
3  Base Plate
Fig 9. ROD PLANE ELECTRODE SYSTEM

1 Rogowski Electrode
2 Rod Electrode
3 Aluminum Plate
4 Insulated Spacer
5 Adjustment Shaft
6 Thermocouples
7 Vessel Bottom
8 Silicon Rubber ORings
c) Each electrode was washed with methanol, if severe pitting still remained, 1 micron diamond paste was applied to the area pitted and the electrode was repolished.

d) If no severe pitting remained after step (b) 1 micron red rouge lapping compound was applied to each electrode. They were then each hand polished for 20 - 30 minutes.

e) The electrodes were first washed with acetone then methanol and reinstalled in the test chamber.

Due to the small surface area of the rod electrode a less rigorous polishing procedure was followed. One application of silvo and red rouge lapping compound was found sufficient to polish this electrode. The polishing procedure was repeated at the completion of each temperature cycle. Approximately 300 breakdowns were conducted in each cycle.
CHAPTER 4
BREAKDOWN PROCESSES IN SF$_6$

4.1 Introduction

SF$_6$ has been classified as an electronegative gas due to its ability to capture free electrons. The capture of these electrons leads to the formation of stable negative ions. The reduced mobility of these negative ions and the depletion of free electrons in a region of electrical stress results in a higher dielectric strength for SF$_6$ as compared to non-electronegative gases.

The breakdown of gases, both electronegative and non-electronegative, has been explained by two theories, the Townsend theory and the streamer theory. Townsend's theory has been found to be inadequate in explaining fast breakdown processes in non-uniform fields while the streamer theory has been found to be quite adequate under these conditions. The theories have both qualitative and detailed quantitative descriptions. Before either theory can be applied to SF$_6$, however, a knowledge of the microscopic behavior of the gas in regions of electrical stress is important.

4.2 Ionization and Attachment Processes in SF$_6$

Ions are formed in non-electronegative gases by collision. Free electrons accelerated by the applied field collide with neutral molecules releasing more electrons and forming positive ions. The number of free electrons increases until breakdown occurs. In an electronegative gas such as SF$_6$, the free electrons are captured, therefore, their number is decreased and breakdown does not occur.

The capture of electrons in SF$_6$ and the subsequent formation of SF$_6^-$ and SF$_5^-$ have been studied by many research groups. (8) (1) (10) The capture process taking place in SF$_6$ is a resonance capture. Low energy
electrons, .05eV, are attached to neutral SF$_6$ molecules resulting in the formation of metastable ions. The majority of ions in SF$_6$ are SF$_6^-$ and SF$_5^-$ both are formed from an attachment reaction:

$$\text{SF}_6 + e \rightarrow (\text{SF}_6^-)^1$$  \hspace{1cm} (1)

In the case of SF$_6^-$ ions the metastable ion (SF$_6^-)^1$ in reaction (1) is the first step in their formation. This metastable ion is in the first excitation state denoted by the superscript 1. Its lifetime has been measured at 10 microseconds.(9)

The ionization process may now proceed in one of two directions. If the metastable ion is in further collision with a neutral gas molecule a stable SF$_6^-$ ion is formed.

$$(\text{SF}_6^-)^1 + \text{SF}_6 \rightarrow \text{SF}_6^- + \text{SF}_6$$  \hspace{1cm} (2)

If this collision does not take place the metastable ion undergoes an "auto detachment" reaction.

$$(\text{SF}_6^-)^1 \rightarrow \text{SF}_6 + e$$  \hspace{1cm} (3)

The electron is released and the molecule returns to the ground state.

The formation of SF$_5^-$ follows a similar process based on the metastable ion (SF$_6^-)^2$. The lifetime of (SF$_6^-)^2$ is exceedingly short and has been found to be of the order of .1 microseconds (1). A similar resonance capture reaction takes place in the formation of (SF$_6^-)^2$.

$$\text{SF}_6^- + e \rightarrow (\text{SF}_6^-)^2$$  \hspace{1cm} (4)

This metastable ion is in a higher excitation state than (SF$_6^-)^1$. The reaction then proceeds to the formation of SF$_5^-$ and F.

$$(\text{SF}_6^-)^2 + \text{SF}_6 \rightarrow \text{SF}_5^- + F + \text{SF}_6$$  \hspace{1cm} (5)

Edelson, Griffiths and McAfee (1967)(9) reported the existence of SF$_4^-$ and SF$_3^-$ ions. These ions were formed from the metastable ions (SF$_6^-)^4$ and (SF$_6^-)^5$ the electrons captured in each reaction required
energies of 5 and 10 eV respectively.

Other reactions take place in \( \text{SF}_6 \) which do not affect the net ion population in the area under electrical stress. These reactions have been classified as dissociative processes. If neutral \( \text{SF}_6 \) molecules collide with electrons having an energy greater than 17.3 eV \( \text{SF}_5^+ \) and \( F^- \) ions are formed.

\[
\text{SF}_6 + e \rightarrow \text{SF}_5^+ + F^- + e \quad (6)
\]

If neutral \( \text{SF}_6 \) molecules collide with electrons having an energy slightly greater than \( 4 \) eV a change in the net ion population occurs.(10)

\[
\begin{align*}
\text{SF}_6 + e & \rightarrow \text{SF}_5^- + F^- \quad (7) \\
\text{SF}_6 + e & \rightarrow \text{SF}_4^- + F + F^- \quad (8)
\end{align*}
\]

The ionization and attachment reactions have been given quantitative meaning in the form of ionization and attachment coefficients. Both coefficients have been measured experimentally and these values have been used in the analysis of breakdown processes in \( \text{SF}_6 \).

The ionization coefficient, \( \alpha \), has been defined as the mean number of ionizing collisions by one electron per unit length drift in the direction of the applied field.(11) The attachment coefficient, \( \eta \), has been related to the probability that an electron will undergo an attachment reaction as it moves through the gas in the direction of the applied field. (12)

Values for both \( \alpha \) and \( \eta \) have been measured by Bhalla and Craggs (13) (1961) and Boyd and Crichton (1971) (14). By measuring the current in a uniform field gap at fixed values of \( E/p \), and variable gap length \( d \), where \( E \) is the applied field and \( p \) is the pressure in the system, values for \( \alpha \) and \( \eta \) were calculated. The calculations of \( \alpha \) and \( \eta \) have been based on current measured at pressures ranging from .07 to 2.63 atm. Both values
have been found to have a relatively small pressure dependence in the range of 750 – 2000 torr. At pressures below 750 torr no pressure dependence has been reported. These measured values have been used in the streamer and Townsend breakdown theories in an effort to analytically calculate breakdown voltages in a given field configuration.

4.3 Breakdown Mechanisms in SF₆

4.3.1 Uniform Field Breakdown Mechanisms

The electrical breakdown of a gas insulated uniform field has been explained by two theories. The first breakdown theory was developed by Townsend, (15) for non-attaching gases. Townsend’s theory is centred around the formation of an electron avalanche. Initiatory electrons are released from the cathode by photoelectric emission. These electrons are accelerated by the applied field toward the anode. When they collide with neutral gas molecules ionization takes place and more electrons are emitted. This process continues with the number of electrons increasing exponentially. Townsend’s theory relates the current in the gap, i, to the initial photoelectric current, i₀, by the expression

\[ i = i₀ \exp (a d) \]  \hspace{1cm} (3)

where \( a \) is the first ionization coefficient and \( d \) is the gap length.

When Townsend applied the expression to uniform fields insulated with compressed gases the calculated values did not correspond to measured data. The theory was then expanded to take into account secondary ionization processes. Electron emission by positive ion bombardment of the cathode and other ionization processes were accounted for by the introduction of the secondary ionization coefficient \( \gamma \). The expression for the current flowing in the gap became:
\[ i = \frac{i_0 \cdot \exp(\alpha d)}{1 - \gamma(\exp(\alpha d) - 1)} \]  

At breakdown the current in the gap theoretically goes to infinity. Townsend's theory, therefore, is expressed as a criterion for breakdown when the denominator of equation (4) goes to zero, or

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

Geballe and Reeves (1953) (16) derived an expression for current flowing in a uniform field gap insulated with an electronegative gas. The following expression is based on Townsend's theory and takes into account the attachment process by including the attachment coefficient

\[ i = \frac{[\alpha / (\alpha - \eta)] \exp\{ (\alpha - \eta) d \} - \eta / (\alpha - \eta)}{1 - \{ \gamma \alpha / (\alpha - \eta) \} \{ \exp\{ (\alpha - \eta) \cdot \eta \} - 1 \}} \]  

Comparisons made by Geballe and Reeves between calculated current, using equation (6), and measured values in \( \text{SF}_6 \) indicated a maximum difference of +1.4%.

Townsend's theory was found to be unsatisfactory in explaining breakdown processes under steep front impulse voltages. Breakdowns occurring in times less than one microsecond could not be satisfactorily explained by a theory which required the generation of many avalanches taking several microseconds to bridge a gap, a fact which led to the concept of the streamer type of breakdown.

The streamer theory was proposed by Meek and independently by Raether. This theory takes into account three processes; the formation of an electron avalanche, the transition from an avalanche to a streamer and the propagation of a streamer across a gap.

The streamer theory is a single avalanche mechanism. A positive
surface charge from a single electron avalanche formed in a similar manner as described by Townsend distorts the electric field in the gap. This results in an enhancement of the field at the avalanche head. Positive ions formed as a result of the electron avalanche move towards the cathode. A cone shaped space charge with a negative head results from the avalanche. When the avalanche reaches the anode the electrons are swept into the anode leaving a cone shaped low ion density space charge across the gap. Due to the low ion density in the cone breakdown does not occur. However during the build up of the avalanche excitation of gas atoms has been taking place. Due to the short life time of these excited atoms photons are released as the atoms return to the ground state. These photons are responsible for photoionization resulting in the initiation of secondary avalanches. These avalanches produce positive ions. A conducting channel formed from the original cone and auxiliary ions bridges the gap. Through this channel the final streamer channel propagates and breakdown occurs.\(^{17}\)

In an electronegative gas the positive space charge is effectively neutralized by the negative ions. The streamer mechanism is halted until the negative ions undergo detachment reactions. Once the applied field is sufficiently high to cause this reaction the streamer mechanism continues in the manner already described.

The dielectric strength of an SF\(_6\) insulated uniform field system has been reported to range from 1.8 to 3 times that of air.\(^{18}\) A value of 89 kV/cm atm is accepted as the dielectric strength which most closely satisfies both measured and calculated values. This value does not apply to the entire pressure range in which SF\(_3\) remains gaseous. As the pressure of the system increases, with a fixed gap length, the slope of the breakdown voltage-pressure curve decreases.
The dielectric strength of SF₆ has been studied at pressures up to the liquid state at 20°C. Works, Dakin and Rodgers (1964) (19) conducted this investigation and found that under impulse applied voltages no discontinuities existed in the curve of breakdown voltage versus pressure when the SF₆ passed into the saturated vapour state.

4.3.2 Non Uniform Field Breakdown Mechanisms

The Townsend theory of uniform field breakdown in a non attaching gas was modified to suit a non uniform field by accounting for the fact that the value of α was dependent on the electric field. The value of α was found to vary as the integral of the distance travelled across the gap. Therefore equation (3) was modified and the current flowing in the gap was expressed as:

\[ i = i_o \exp \int_{0}^{d} \alpha \, dx \]  \( \gamma \)

where \( d \) is the gap length. When secondary ionization processes were accounted for the expression became:

\[ i = \frac{i_o \exp \int_{0}^{d} \alpha \, dx}{1 - \gamma \left( \exp \left( \int_{0}^{x} \alpha \, dx \right) - 1 \right)} \]  \( \gamma \)

(8)

Pederson (1970) (20) derived the following expression for the current in a non uniform field insulated with SF₆:

\[ \frac{i}{i_o} = 1 + \frac{\int_{0}^{d} \exp \{ \int_{0}^{x} (\alpha - \eta) \, dx \} \alpha \, dx}{1 - \gamma \int_{0}^{x} \exp \{ (\alpha - \eta) \, dx \} \alpha \, dx} \]  \( \gamma \)

(9)

The breakdown criterion formed from equation (9) is:

\[ \gamma \int_{0}^{d} \exp \{ \int_{0}^{x} (\alpha - \eta) \, dx \} \alpha \, dx = 1 \]  \( \gamma \)

(10)
The Townsend breakdown theory fails in attaching gases in non-uniform fields due to the rapid variation of $\alpha$ and $\eta$ with field gradient. It is possible to have regions in a non-uniform field where $\eta \gg \alpha$. These regions occur near the cathode which means that the generation of free electrons is virtually impossible since the number of electrons attached is greater than the number of electrons generated through ionization. It follows therefore that the electrons needed to initiate the avalanches cannot be produced, and the breakdown cannot proceed.

The use of the streamer mechanism to explain breakdown in non-uniform fields has met with both success and criticism. The theory has been analytically described and implemented with good results. The qualitative description of the streamer mechanism in a non-uniform field is similar to that described for the uniform field case. In a non-uniform field the streamers can be anode or cathode directed depending on the polarity of the rod electrode.

Pedersen has conducted extensive work on the analytical interpretation of the streamer theory. He has derived the following breakdown criterion for non-attaching gases.

$$\alpha_x \exp\left\{ \int_0^{\alpha_x} \alpha \, dx \right\} = g(x, \rho) \quad (11)$$

where $\alpha_x$ is the value of $\alpha$ at the head of the avalanche, $\rho$ is the gas density and $x$ is the critical avalanche length.

For an attaching gas Pedersen modified equation (11) to account for the attachment process resulting in the expression:

$$\left( \alpha_x - \eta_x \right) \exp\left\{ \int_0^{\alpha_x} (\alpha - \eta) \, dx \right\} = G(x, \rho) \quad (12)$$

where $\eta_x$ is the value of $\eta$ at the avalanche head. Due to the rapid
variation of \( (\alpha - \eta) \) with field strength the implementation of equation (12) resulted in noticeable polarity affects not observed in SF\(_6\). Equation (12) was further modified to account for this variation of \( (\alpha - \eta) \) with field strength, resulting in the expression:

\[
\alpha \exp \left\{ 2 \int_{0}^{x} (\alpha - \eta) \, dx \right\} = F(x, \rho) \quad (13)
\]

Taking the natural logarithm of equation (13)

\[
\frac{1}{2} \ln (\alpha) + \int_{0}^{x} (\alpha - \eta) \, dx = f(x, \rho) \quad (14)
\]

Pedersen introduced still further simplifications by assuming that \( f(x, \rho) \) varied little with \( x \) or \( \rho \) and that the logarithmic term had little effect on the value of \( f(x, \rho) \). This resulted in the final breakdown criterion:

\[
\int_{0}^{x} (\alpha - \eta) \, dx = K \quad (15)
\]

The value of \( K \) has been chosen from the available room temperature uniform field breakdown data and has a value of approximately 18.

Equation (15) can be interpreted to mean that streamers are formed when a critical number of ions is reached.

In highly non uniform fields SF\(_6\) exhibits two distinctly different breakdown voltage pressure characteristics depending on the polarity of the rod electrode. When the region of high stress is located near the anode the characteristic curve has a form similar to that in Figure (10). The curve of breakdown voltage versus pressure has a maximum at \( P_m \) and a minimum at \( P_c \). \( P_c \) is the critical pressure at which corona onset and breakdown coincide.

The breakdown characteristic between the origin and \( P_c \) has been called a region of corona stabilized breakdown. Pollock and Cooper (1939) (21) have attributed the maximum breakdown voltage point at \( P_m \) to the formation of negative ions. These ions form a negative space charge around the rod anode. This space charge reduces the degree of field non uniformity and neutralizes the positive ion channel in the gap. As
Fig 10. Positive point breakdown voltage-pressure characteristics for an electronegative gas.
the pressure in the system increases the number of positive ions in the
gas increases until the pressure P is reached. At this point the positive
ion population is sufficiently high to ensure that the first streamer
formed bridges the gap and breakdown occurs.

In the instance of a rod cathode the negative ion space charge moves
to the planar anode. The degree of non uniformity of the field is not
affected and no corona stabilized breakdown region is observed. The
dielectric strength of the system simply increases in a non linear
fashion with pressure.
CHAPTER 5

EXPERIMENTAL PROCEDURE

5.1 Introduction

The electrical breakdown of an insulating gas is affected by several factors which come under two classifications, those which are controllable by the experimenter and those which are characteristic of the experimental system. Before an experimental procedure can be outlined these factors must be considered in order that valid results are recorded and that the conclusions based on these results are realistic.

5.2 Factors Affecting Breakdown

Experimenter controllable factors are very closely associated with the organization of the experimental procedure. They include the following factors:

a) An increase in dielectric strength of the system by repeated breakdowns due to gas and electrode conditioning and a deterioration of dielectric strength due to electrode damage.

b) The rate of rise of the direct applied voltage has an effect on the observed dielectric strength, in that, if the voltage is raised too quickly the observed breakdown value may be higher than the actual value.

c) The number of breakdown tests taken under any particular set of experimental conditions must be sufficient to give a reasonable statistical picture of the dielectric strength.

The factors which are classified as characteristic of the experimental system must be examined closely before any conclusions are drawn based on the breakdown values recorded in that system. These factors are listed below.

a) The electrode material and its surface have a definite effect on the
breakdown process taking place in the gas.
b) The gap length has an effect on the dielectric strength and possibly on the breakdown mechanism.
c) The surface area of the electrodes have been reported to have an effect on the recorded breakdown values.
d) Foreign particles in the gap in the form of dust or oxide layers on the electrode surface can affect the breakdown mechanism and the recorded value.
e) The temperature of the gas and the surroundings can affect the breakdown strength of the system.

The improvement of the dielectric strength of a system by repeated breakdowns is called conditioning. The phenomena responsible for conditioning have not as yet been satisfactorily explained. Conditioning has been observed in such gases as nitrogen and hydrogen and in slightly attaching gases such as air and carbon dioxide. In SF₆, conditioning, however, has not always been reported. Figure 11 shows a typical set of breakdown values recorded in the present study in SF₆ at 20°C and at a pressure of 2 atm. Based on these values and the observations of other research groups (22) 20 breakdown tests were conducted at each pressure-temperature combination. If conditioning trends should be present 20 breakdown values were assumed sufficient to indicate these trends, and to give a good statistical picture of the dielectric strength of the system.

Through out the course of the work there was no observable deterioration in dielectric strength due to electrode pitting. Even after one temperature cycle during which approximately 300 breakdowns occurred the electrodes suffered little visible damage. This was partially due to the current limiting resistor connected in series with the gap and the high voltage supply.
Fig 11. UNIFORM FIELD 2mm GAP SCATTERING PLOT
The rate of rise of the applied voltage was controlled manually by a 10 turn potentiometer and measured with a stopwatch. A review of the available literature has indicated that each research group has adopted its own procedure for increasing the voltage. The only fact considered by all the groups was that the rate of rise must be sufficiently slow to ensure that the time required for the breakdown to occur was less than that rate of rise. The starting point of the controlled rate of rise has varied from 0 to 90% of the breakdown value. The rate of rise has varied from 1 kV/1.5 min. to 1 kV/10 sec.

Prior to selecting a starting point and a rate of rise several tests were conducted with a uniform field electrode gap insulated with 1 atm. of SF₆ at 20°C. Figure 12 illustrates the results of these tests. The 80% starting point was found from an initial breakdown test which consisted of raising the voltage from 0 at a rate of 1 kV/10 sec. Once this value was found each test proceeded in the following manner. The voltage was raised to the 80% value in 60 sec., left undistributed at this value for 30 sec. then raised at a rate of 1 kV/10 sec. or 1 kV/15 sec. When no significant difference in breakdown voltages were observed, a rate of 1 kV/15 sec. from 80% of the first breakdown was implemented for the remainder of the tests.

The material of the electrodes has a definite effect on the dielectric strength of the system in which it is located. Trump, Cloud, Mann and Hanson (1950) (23) examined the effects of electrode materials on the dielectric strength of several insulating gases. The study involved the examination of the D.C. breakdown characteristics of air, nitrogen and carbon dioxide with uniform field aluminum and stainless steel electrodes. They observed that aluminum electrodes gave substantially
lower breakdown voltages, than stainless steel, regardless of the insulating gas. At pressures up to 8 atm. the aluminum and stainless steel electrodes exhibited the same dielectric strength. Once the pressure was increased beyond this level the stainless steel showed increasingly higher breakdown values than aluminum. At 28 atm. the dielectric strength of the system with stainless steel electrodes was 50% higher than with aluminum electrodes at the same pressure.

Nitta (1974) (24) studied the effects of increased electrode area on the dielectric strength of SF$_6$. He failed, however, to take into account the work conducted by Trump and changed the material of the electrodes when he increased the electrode area. Nitta's conclusions, therefore, are somewhat doubtful or at least inaccurate. Nitta concluded that the increase in electrode area was responsible for a decrease in dielectric strength. In the largest area aluminum electrode set the dielectric strength of the system ceased to increase with pressure when an applied field of 260 kV/cm. was reached. A similar observation was made in the present study with aluminum plane electrodes. When the aluminum electrodes were replaced with brass electrodes having the same surface area the dielectric strength of the system increased in a normal manner with pressure. Figure 13 shows the two breakdown voltage-pressure curves recorded at 20°C for brass and aluminum. Each electrode set had a 90° Rogowski profile and was cut from the same pattern. In each case a 2 mm. gap was maintained over the entire pressure range.

The saturation effect observed in the present work may be the result of the emission of electrons from the cathode surface. Jones and Morgan (1953) (25) have shown that metal oxide layers formed on the surface of electrodes are responsible for the emission of electrons from the underlying metal.
Fig 13. BREAKDOWN VOLTAGE vs PRESSURE
ALUMINUM AND BRASS ELECTRODES
UNIFORM FIELD 2mm GAP
Mott (1947) has reported that oxide layers on the surface of aluminum increase parabolically with time. The most part of the oxide layer forms in the first few minutes of the exposure of the aluminum to the atmosphere. The maximum thickness of the oxide layer on aluminum has been measured at $2 \times 10^{-7}$ cm. This value was obtained after several hours of exposure. In the present investigation the electrodes were exposed to the atmosphere throughout the polishing and installation stages. Based on the observations of Mott the oxide layer on the aluminum electrodes used in this study would be approximately $1 \times 10^{-7}$ cm. thick.

Jones and Morgan concluded that the emission of electrons from the cathode is caused by a positive ion space charge. The positive ions formed as a result of the formation of electron avalanches in the gap are swept towards the cathode. There now exists a surface charge on the oxide layer. This surface charge sets up an electric field between the tarnish film and the cathode. In some cases this field is sufficiently high to produce cold cathode emission from the underlying metal. The electrons emitted in this way can have sufficient energy to initiate breakdown.

Jones has also concluded, that in an electronegative gas, the electrons liberated in dissociative collisions do not contribute to the breakdown process as significantly as those electrons emitted through field emission. This conclusion, however, has been disputed by several research groups. These authors have concluded that the process of electron detachment at high pressures is the predominant source of free electrons responsible for the initiation of breakdown.

If oxide films of similar thicknesses are formed on the brass electrodes the observed saturation of breakdown voltage in aluminum is
probably a function of the oxide and the work function of the material. The work function of the brass and aluminum used in the electrodes is difficult to determine. Both materials are alloys and react in various ways to surface finishing which has an effect on the effective work function of the material. (17)

The extensive use of heaters in SF$_6$ insulated equipment has meant that most temperature investigations have been conducted at temperatures above +20°C. The use of SF$_6$ as an arc quenching medium in circuit breakers has prompted studies into the effects of power arcs on the gas. The temperature on a power arc column has been measured between 9,000 to 29,000°C. The gas therefore has been examined in temperatures beyond the point where thermal ionization is significant.

The electron-attachment process in SF$_6$ has been found to be temperature dependent. At a temperature of +180°C the dielectric strength of an SF$_6$ insulated system was found to be 13% lower than the value recorded at +20°C. (22) These two values were measured at the same pressure gap length product.

The effects of temperatures, below +20°C, on the dielectric strength have received little attention. Camilli and Chepman (8) (1947) have discussed the effects of reduced temperatures on a constant density SF$_6$ insulated system. They concluded that the dielectric strength of a gas insulated system will remain unchanged as the temperature of the system is reduced. This is valid provided that the total quantity of gas in the system remains unchanged.

If the temperature is further lowered the gas will pass into the liquid phase. Below this temperature the pressure of the gas will follow the saturated vapour pressure curve. In the case of a gas whose dielectric
strength is a function of pressure a reduction in pressure results in a decrease in dielectric strength.

The dielectric strength of SF$_6$ has been found to be density dependent. If the density of the system remains constant the dielectric strength will also remain unchanged regardless of the pressure of the system. In the course of the present work the gap length was fixed at 2 mm due to the limited supply voltage available. Short gaps such as 2 mm enhance the effects of surface protrusions. This enhancement results in an increase in the number of free electrons in the gap caused by field emission from the cathode. Increasing pressures under these circumstances results in reduced increases in dielectric strength. This has been observed particularly at the higher pressures.

5.3 Breakdown Test Procedure

The actual experimental investigation was divided into several parts. This division was based on the nature of the electric field in the gap and on the nature of the SF$_6$ atmosphere in the system. Uniform and non-uniform fields were examined under conditions of constant pressure and constant density SF$_6$.

The first tests were conducted with uniform field gaps under conditions of constant density. These tests were conducted in the following manner. The test chamber was evacuated then filled with SF$_6$ up to 2 atm at 20$^\circ$C and then sealed. The gap length was set to 2 mm and 20 breakdowns were recorded following the procedure outlined in section 5.2. The temperature was then lowered 10$^\circ$C and the pressure was allowed to decrease. The gap length was reset and again 20 breakdowns were recorded. This procedure was repeated until the temperature reached -30$^\circ$C. The procedure was then reversed and the temperature was raised in 10$^\circ$ steps to 20$^\circ$C. Twenty
breakdowns were recorded at each temperature. The chamber was evacuated, opened and the electrodes were cleaned using the technique outlined in section 3.2. This procedure was repeated for 1 atm. pressure increments to a maximum of 5 atm.

The constant pressure tests were conducted in a similar manner. The test chamber was evacuated and filled with 1 atm. of SF₆. The gap length was set at 2 mm and 20 breakdowns were recorded. The temperature of the system was reduced by 10⁰ while the pressure was kept constant. The remainder of the test followed the constant density procedure with the main difference being that the pressure was kept constant over the entire temperature cycle. An additional test was conducted at the 6 atm. pressure level. This test was included to clarify an unusual trend observed at 5 atm.

In the non-uniform field study, the constant pressure test was conducted in the same manner as the uniform field study under constant pressure. The non-uniform constant density test was conducted at 2 atm. only over the defined temperature range. Figure 14 gives a flow diagram of the experimental procedure described above.
Fig 14. EXPERIMENTAL FLOW DIAGRAM
CHAPTER 6
UNIFORM FIELD RESULTS

6.1 Constant Density Results

The inability of the pressure gauges to register below 1 atm. resulted in a 2 atm. starting point for the constant density tests. The tests were therefore, conducted in a pressure range of 2 to 5 atm. When no significant changes in dielectric strength with decreasing temperature were observed the 1 atm. test was permanently omitted. Figure 15 represents the results of these tests. Each data point corresponds to the mean of 20 breakdowns taken at the indicated pressure and temperature. Ninety degree Rogowski profile brass electrodes and a gap length of 2 mm. were used in obtaining the values shown in Figure 15.

6.2 Constant Pressure Results

The data recorded in the constant pressure tests followed the experimental procedure outlined in section 5.3. Figures 16 to 21 represent this data recorded at each pressure over the predefined temperature cycle. Each point represents the mean value of 20 breakdowns. The standard deviations are also included. These values were collected using the brass 90° Rogowski profile electrodes set at a constant gap length of 2 mm. Figure 22 summarizes the data presented in Figures 16 to 21. Only the mean values are shown.

6.3 Discussion of Results

The effects of pressure on the dielectric strength of an SF6 insulated uniform field test gap have been studied and the results have been documented. The breakdown values recorded at 20°C in the constant density or constant pressure tests, when plotted against pressure result in a curve shown in Figure 23. The breakdown voltage increases nearly linearly...
Fig 15. BREAKDOWN VOLTAGE vs TEMPERATURE
UNIFORM FIELD 2mm GAP
CONSTANT DENSITY
Fig 16.  BREAKDOWN VOLTAGE vs TEMPERATURE
1 ATM 2mm GAP
UNIFORM FIELD
CONSTANT PRESSURE
Fig 17. BREAKDOWN VOLTAGE vs TEMPERATURE
2 ATM 2mm GAP
UNIFORM FIELD
CONSTANT PRESSURE
Fig 18. BREAKDOWN VOLTAGE vs TEMPERATURE
3 ATM 2mm GAP
UNIFORM FIELD
CONSTANT PRESSURE
Fig 19. BREAKDOWN VOLTAGE vs TEMPERATURE
4 ATM 2 mm GAP
UNIFORM FIELD
CONSTANT PRESSURE

--- TEMPERATURE DECREASING
--- TEMPERATURE INCREASING
Fig 20 Breakdown Voltage vs Temperature
5 ATM 2 mm GAP
Uniform Field
Constant Pressure
Fig 21. Breakdown Voltage vs Temperature
6 ATM 2mm Gap
Uniform Field
Constant Pressure
Fig 22. BREAKDOWN VOLTAGE vs TEMPERATURE
UNIFORM FIELD 2 mm GAP
CONSTANT PRESSURE
Fig 23.  BREAKDOWN VOLTAGE vs PRESSURE
UNIFORM FIELD 2mm GAP 20°C
(MEAN VALUES)
with pressure up to 4 atm. From 5 to 6 atm, the increase in dielectric strength is only 25% of the increase observed between 3 and 4 atm. This deviation from the linear increase in dielectric strength with pressure has been attributed to increased field emission from the cathode at high pressures.

Examination of the constant density tests presented in Figure 15 shows that decreasing temperatures have no significant effect on the dielectric strength of the system. When the temperature is cycled the breakdown values recorded for increasing as decreasing the temperature lie along the same curve. The increase in dielectric strength between 3 and 4 atm. is greater than the increase observed between 2 and 3 atm. The 4 atm. curve appears to be showing signs of an increase in dielectric strength with decreasing temperature. Closer examination of the 4 atm. curve shows an increase of 2 kV over the 50°C reduction in temperature. This is the only increase, in the entire set of tests, which is above 500V. The increase in pressure between 4 and 5 atm. is approximately equal to that observed between 2 and 3 atm. These observations are similar to those made by Camilli and Chapman (7) regarding the effects of constant density on dielectric strength. The constant pressure test results shown in Figure 16 were obtained at a pressure of 1 atm. The curves in this figure show a difference in the breakdown voltage when the temperature of the system is increasing and decreasing. This difference is most pronounced at temperatures below -10°C. The breakdown values recorded for decreasing temperatures are higher than those observed at the same temperature when the cycle was reversed. This decrease in dielectric strength with increasing temperature reaches a maximum at -22°C. The observed difference at this temperature may have been due to a misadjustment of the gap.
When the pressure of the system was increased to 2 atm, the decreasing temperature breakdown voltage curve was lower than the increasing temperature curve. Figure 17 represents the data recorded at 2 atm, in the temperature cycle. The maximum difference in the two curves occurs again at -20°C. The standard deviation calculated for the breakdown tests at this temperature is larger than that calculated at any other temperature. The possibility of moisture causing this occurrence in both the 1 and 2 atm. tests is remote. Any moisture in the system deposited on the electrodes would have turned to ice at approximately 0°C. At this point a significant increase in the dielectric strength would have been expected. Ushio, Shimura, and Tomenaga (1971) (26) studied the effects of moisture on the dielectric strength of SF₆ at lower temperatures. They observed a very pronounced increase in dielectric strength at 0°C. They attributed this increase to the fact that the moisture froze. The water droplets in the system therefore ceased to reduce the breakdown voltage. There is no observed increase of this type in the data recorded in this study.

Figure 18 represents data collected at 3 atm. The slope of the breakdown voltage temperature curve at 3 atm. is greater than the slope at 2 atm. The increasing temperature curve again lies above the decreasing temperature curve and no maximum difference exists between the two curves. The standard deviation in this case is larger than that observed for 1 or 2 atm. The increasing temperature data, however, showed an increase in standard deviation as compared to the decreasing temperature curve.

In Figure 19 a pronounced increase in the standard deviation of the value at 4 atm. pressure is observed. The increasing and decreasing temperature curves appear to cross each other. The great degree of scattering, as indicated by the large standard deviation values, makes it
very difficult to fit an accurate curve to represent the data. A straight line approximation has therefore been made for this data.

Figure 20 shows a very unexpected trend. The breakdown voltage shows no signs of increase with decreasing temperature at a constant pressure of 5 atm. At -30°C, however, the 5 atm. pressure reading may be erroneous in that SF₆ passes into a saturated vapour state at 4.3 atm. at -30°C. Initially this constant breakdown value was attributed to a change of phase of the gas. Close examination of the saturated vapour characteristics showed that at 0°C SF₆ passed into the saturated vapour phase at 11.6 atm. In order to try to determine the cause of this observed saturation of breakdown voltage tests were conducted at a pressure of 6 atm. At 20°C the dielectric strength of the system at 6 atm. increased above the value observed at 5 atm. at 20°C. As the temperature decreased the gas passed into the saturated vapour state and the dielectric strength of the system decreased and approached the constant value observed at 5 atm. Figure 21 shows the decreasing breakdown voltage observed at 6 atm. with decreasing temperature. The increase of pressure to 6 atm. and the corresponding increase in dielectric strength showed that the saturation was not due to the emission of electrons from the cathode. The effect is therefore a function of the temperature and pressure of the system.

If the data presented in Figure 22 is represented in such a way that breakdown voltage versus pressure is plotted at different temperatures the resulting curves show an unusual trend. From the observations shown in Figure 15, it is seen that the dielectric strength of SF₆ is a function of density. If the constant pressure data at 20°C, 0°C and -30°C are plotted against pressure the curves are expected to be shifted vertically from each
other by a constant value. Figure 24 represents the mean of the measured data at 0\(^{\circ}\)C and 20\(^{\circ}\)C and the expected curve.

The 0\(^{\circ}\)C and 20\(^{\circ}\)C curves differ by a constantly increasing value up to 4 atm. From 4 to 5 atm. the 0\(^{\circ}\)C curve begins to indicate deterioration of dielectric strength with increasing pressure. At approximately 5 atm. the 0\(^{\circ}\)C and 20\(^{\circ}\)C curves intersect, from this point onwards the 0\(^{\circ}\)C curve shows slightly lower breakdown voltages than the 20\(^{\circ}\)C curve with increasing pressure.

A similar observation can be made if the -30\(^{\circ}\)C and +20\(^{\circ}\)C breakdown data are plotted together against pressure. Figure 25 shows the two curves based on the mean values recorded in Figure 22. The two curves again intersect at 5 atm. At -30\(^{\circ}\)C 4.3 atm. corresponds to the saturated vapour pressure of SF\(_6\). The last values recorded in this set are not completely reliable since the gas has reached the saturated vapour state.

If the ideal gas law, equation is applied to the data in Figure 18, the resulting plot of breakdown voltage versus pressure shows some temperature dependance. Figure 26 represents a comparison between the breakdown voltages measured at 20\(^{\circ}\)C as a function of pressure and the values measured at the indicated temperatures. If the ideal gas law is applied to a constant 2 atm. pressure at the indicated temperatures the 2 atm. value can be extrapolated to 20\(^{\circ}\)C from each temperature. If the breakdown voltage observed is a function of gas density the extrapolated values should lie along the same curve as the values measured at 20\(^{\circ}\)C. Figure 26 shows that the extrapolated values are higher than the actual measured data at 20\(^{\circ}\)C. The data presented in Figure 26 represents the mean values of each breakdown set. The standard deviations calculated at this pressure were so small that they were omitted.
Fig 24  BREAKDOWN VOLTAGE vs PRESSURE
UNIFORM FIELD 2mm GAP
(MEAN VALUE)
Fig 25.  BREAKDOWN VOLTAGE vs PRESSURE
UNIFORM FIELD 2mm GAP
(MEAN VALUES)
Fig. 26  
BREAKDOWN VOLTAGE vs PRESSURE  
UNIFORM FIELD  2mm GAP  
EXTRAPOLATED DATA  
CONSTANT PRESSURE
By following the same reasoning the data recorded at 4 atm. can be presented in a similar manner to the 2 atm. data. Figure 27 represents the measured and extrapolated data found in Figure 19. The difference in breakdown voltage between the measured and extrapolated data is much less than that observed in the previous figure. The two curves differ only by the values of the standard deviation of the extrapolated data.

Comparing Figures 26 and 27 it appears that the temperature effect observed at 2 atm. decreases with increasing pressure. This decrease is accompanied by an increase in scattering. The effect observed at 2 atm. is possibly masked by the relatively high breakdown strength observed at the higher pressures. From the observations made already it appears as if reduced temperatures affect a uniform field $\text{SF}_6$ insulated gap in different ways depending on the pressure of the system.
Fig 27. BREAKDOWN VOLTAGE vs PRESSURE
UNIFORM FIELD 2mm GAP
EXTRAPOLATED DATA
CONSTANT PRESSURE
7.1 Constant Density Results

The constant density non uniform field tests were carried over only one temperature cycle at a pressure of 2 atm. The tests were conducted using a brass rod-plane electrode set. A gap length of 2 mm. was maintained over the entire test. Figure 28 represents the breakdown voltage - temperature characteristics for this test. Each point in Figure 28 represents the mean of 20 breakdown values.

7.2 Constant Pressure Results

The non-uniform constant pressure tests were conducted in the manner outlined in section 5.3. The tests were conducted with the brass rod-plane electrode set and a constant 2 mm. gap length. Figures 29 to 33 represent the data collected in this test at each indicated pressure over the predefined temperature cycle. The data plotted in these figures represents the mean and standard deviation of each set of 20 breakdowns.

Figure 34 summarizes the data presented in Figure 29 to 33. Each data point in this figure represents only the mean of the 20 breakdown tests conducted at the indicated pressure and temperature.

7.3 Discussion of Results

The constant density non uniform field data presented in Figure 28 shows an apparent increase in dielectric strength with increasing temperature. The difference between the dielectric strength measured at 20°C and that measured at -30°C is approximately 2 kV. This increase is comparable with that observed in the 4 atm. uniform field constant density tests. This represents only a 6% increase in dielectric strength for a 50°C reduction in temperature. This increase was felt to be
**Fig 28**

BREAKDOWN VOLTAGE vs TEMPERATURE

2 ATM 3.175 mm ROD 2 mm GAP

CONSTANT DENSITY
Fig 29

BREAKDOWN VOLTAGE vs TEMPERATURE

1 ATM 3.175mm ROD 2mm GAP

CONSTANT PRESSURE
Fig 30. BREAKDOWN VOLTAGE vs TEMPERATURE
2 ATM 3.175mm ROD 2mm GAP
CONSTANT PRESSURE
Fig 31. BREAKDOWN VOLTAGE vs TEMPERATURE
3 ATM 3.175mm ROD 2mm GAP
CONSTANT PRESSURE

--- TEMPERATURE DECREASING
--- TEMPERATURE INCREASING
Fig 32. BREAKDOWN VOLTAGE vs TEMPERATURE
4 ATM 3.175 mm ROD 2mm GAP CONSTANT PRESSURE
Fig 33. BREAKDOWN VOLTAGE vs TEMPERATURE
5 ATM 3.175 mm ROD 2 mm GAP
CONSTANT PRESSURE

--- TEMPERATURE DECREASING
--- TEMPERATURE INCREASING
Fig 34. BREAKDOWN VOLTAGE vs TEMPERATURE
2mm GAP 3.175 mm ROD
CONSTANT PRESSURE
insufficient to warrant the continuation of the test. Based on this increase and the results obtained in the uniform field tests the constant density tests were discontinued.

The constant pressure results in Figure 29 were conducted on the rod plane gap insulated with 1 atm. of SF₆. The breakdown voltage curve recorded with decreasing temperatures lies above the curve plotted for increasing temperatures. Breakdown voltage in both cases increases parabolically with temperature. The calculated values of standard deviation are larger for the decreasing temperature curve.

When the pressure of the system was increased to 2 atm. the dielectric strength of the system did not continue to increase in the same manner as observed in the 1 atm. test. Figure 30 represents the data recorded at 2 atm. The breakdown voltage curve recorded for decreasing temperatures now lies above the increasing temperature curve. The decreasing temperature curve appears to be increasing towards a constant value. A straight line approximation has been applied to the increasing temperature data. The breakdown voltage readings recorded at approximately -12°C in both curves are much lower than the values recorded at -20°C or 0°C. This sudden decrease in dielectric strength in both directions may have been caused by a process similar to corona stabilized breakdown. Measurements of corona current in this region could verify this possibility.

At a pressure of 3 atm. the breakdown voltage ceased to increase with temperature. A saturation of breakdown voltage occurred similar to that observed in Figure 20 for the uniform field constant pressure test. Figure 31 represents the 3 atm. test. The standard deviation of the breakdown tests, for both increasing and decreasing temperature, increases from +18°C data to a maximum at -12°C. From -12°C to -30°C the standard deviation.
returns to approximately the same value calculated at +18°C. This increase in scattering at -12°C may have been caused by moisture or frost on the electrodes. The increase is gradual which could imply that moisture was depositing on the electrodes and was freezing. At -10°C the moisture would be frozen and repeated breakdowns may have removed the frost. At -20°C the frost from the area affected by the breakdown would have been removed causing a reduction in scattering. The moisture theory however fails to explain the saturation of breakdown voltage.

Increasing the pressure to 4 atm. results in an increase in dielectric strength with pressure. The breakdown voltage temperature characteristics for 4 atm. are presented in Figure 32. The breakdown voltage of the system increases with temperature to a maximum value at -20°C then decreases slightly at -30°C. The standard deviations at this pressure are quite large. The maximum values are observed at +18°C and then decrease to a minimum at -30°C.

When the pressure of the system was further increased to 5 atm. the value measured at +18°C was the same as the value measured at 0°C at a pressure of 5 atm. From this value the dielectric strength of the system increased nearly linearly at a rate of approximately 3kV/10°C. A comparison of Figures 31, 32 and 33 rules out the possibility that field emission is responsible for the saturation curve observed at 3 atm. With the 4 and 5 atm. curves showing definite increases in dielectric strength with pressure at 18°C breakdown caused by a phenomenon which is field dependent is unlikely to occur especially when the applied field at 4 and 5 atm. is much higher than that applied at 3 atm.

If the 18°C values recorded in Figure 34 are plotted against pressure the resulting curve does not show the classical positive point plane
breakdown characteristics observed in highly non-uniform fields in $\text{SF}_6$. Figure 35 represents the mean value of each $18^\circ\text{C}$ breakdown test plotted against pressure. The breakdown voltage curve approaches a constant value of approximately 60 kV. There appears to be no region of corona stabilized breakdown in this pressure range. The breakdown voltages recorded are lower than the uniform field data presented in Figure 23. The values show definite trends of saturation while the uniform field data does not indicate this trend.

If the data recorded at lower temperatures is presented in a similar manner to that in Figure 35 the resulting curves show what appears to be a temperature effect. Figure 36 shows the breakdown voltage pressure characteristics recorded for $10^\circ\text{C}$ temperature. The resulting curve is shifted vertically positive from the $+18^\circ\text{C}$ curve by a small constant amount up to 3 atm. From 3 to 5 atm. the difference between the two curves increases rapidly. At 5 atm. the $10^\circ\text{C}$ breakdown value is 5 kV above the $+18^\circ\text{C}$ values at the same pressure.

When the $-20^\circ\text{C}$ data is plotted in a similar manner the resulting curve, Figure 37, shows signs of what appears to be corona stabilized breakdown. The breakdown voltage of the system at $-20^\circ\text{C}$ increases from 1 to 2 atm. then begins to decrease and intersects the $+18^\circ\text{C}$ curve at 3 atm. The breakdown voltage again increases from 3 to 5 atm. The difference between the $+18^\circ\text{C}$ and $-20^\circ\text{C}$ breakdown voltage at 2 atm. is 8.3 kV. At 5 atm. the difference is 8.7 kV. If the maximum at 2 atm. is indeed caused by corona stabilized breakdown corona current measurements are necessary to clarify this point.

Application of the ideal gas law shown by equation (2) to the 2 and 5 atm. data in Figures 30 and 33 results in what appears to be
Fig 35. BREAKDOWN VOLTAGE vs PRESSURE
3.175mm ROD 2mm GAP 18°C
CONSTANT PRESSURE
Fig 36: Breakdown Voltage vs Pressure
3.175 mm Rod 2 mm Gap 10°C
Open System
Fig 37. BREAKDOWN VOLTAGE vs PRESSURE
3.175 mm ROD 2mm GAP
CONSTANT PRESSURE
temperature dependent breakdown values. By applying the law in a similar manner to that outlined in the uniform field results, Figures 38 and 39 were constructed. Figure 38 represents the extrapolated breakdown values and the measured values. The curve drawn through the extrapolated data represents the mean and standard deviation of each set of breakdown values taken at the indicated temperatures. The difference between the mean value extrapolated from -26°C and the measured value at +18°C is 4.6 kV. From Figure 31, the difference in dielectric strength between the +18°C value and the -26°C value at 2 atm. is 9.2 kV. This increase is the result of constant pressure and reduced temperature. The measured curve in Figure 39 shows the increase in dielectric strength caused by increasing the pressure of the system from 2 to 2.37 atm. This increase in pressure is responsible for a 5.8 kV increase in dielectric strength. The increase in the extrapolated data of 4.6 kV must therefore be a function of temperature. The 4.6 kV increase corresponds to an 11.6% increase in dielectric strength.

If the 5 atm. data is examined in a similar manner the increase measured in Figure 34 is 11.2 kV. From Figure 39, the increase in dielectric strength caused by an increase in pressure at +18°C is 1.1 kV. This value has been obtained by extrapolating the measured +18°C value from 5 atm. to 5.7 atm. This value may therefore contain an error. The extrapolation was made based on the assumption that the breakdown voltage curve would not undergo any sudden changes. Since no changes of this type had been measured at any other pressure at +18°C. From Figure 39, the increase in dielectric strength attributable to temperature is 10 kV. This corresponds to a percentage increase of 16%.
Fig 38  BREAKDOWN VOLTAGE vs PRESSURE
3.175 mm ROD 2 mm GAP
EXTRAPOLATED DATA
CONSTANT PRESSURE

extrapolated from °C
measured at 18°C
Fig 39. BREAKDOWN VOLTAGE vs PRESSURE
3.175mm.ROD 2mm GAP
EXTRAPOLATED DATA
CONSTANT PRESSURE
Based on the observations made in this section one tentative conclusion can be made. The breakdown voltage of a non uniform field SF$_6$ insulated gap is affected in a similar manner regardless of the pressure of the system.
CHAPTER 8

CONCLUSIONS

8.1 Comparison of Results

The uniform and non uniform field constant density test results were affected by temperature in much the same way. The uniform field results corresponded very closely to the observations of Camilli and Chapman (8). There was no significant increase in dielectric strength observed for the uniform field results as the temperature of the system was lowered. The single non uniform field test showed a slight increase in dielectric strength at lower temperatures.

The constant pressure uniform and non uniform field breakdown characteristics were quite different at reduced temperatures. The uniform field characteristics showed an increasing improvement in dielectric strength up to a pressure of 4 atm. When the pressure of the system was increased to 5 and eventually 6 atm., lowering the temperature resulted in a reduction in dielectric strength when compared to the 20°C data. The dielectric strength of the non uniform field gap showed no signs of deterioration at reduced temperatures at any pressure. The dielectric strength measured at 20°C was the lowest value observed over the entire pressure range.

The rod plane configuration adopted in this study corresponds at best to a quasi non uniform field. This is evident in the breakdown voltage pressure characteristics recorded at +10°C and plotted in Figure 36. The reduction of temperature however, resulted in a breakdown voltage pressure curve which exhibited characteristics associated with a non uniform field. As has already been mentioned current measurements were not made. It is therefore difficult to conclude whether the observed
trends at reduced temperatures were actually characteristics of corona stabilized breakdown.

The theoretical considerations outlined in Chapter 4 have been applied to various gases at room temperature. Pederson's criterion for breakdown in SF$_6$ has been applied by Hazel (1974) (12) to various rod plane gaps insulated with compressed SF$_6$ at 20°C. His analytical and measured results agreed quite closely. The majority of the calculated and measured values differed by approximately ± 3%. The application of this technique to the non uniform field tests conducted at -20°C would result in an error of approximately 16% between the data extrapolated from -20°C and the data measured at +18°C.

8.2 Conclusions

The present study has yielded some interesting observations. From the breakdown studies conducted, the following conclusions are suggested.

1) The dielectric strength of SF$_6$ in a uniform field is unaffected by the rate of rise of direct applied voltage. This has been observed in section 5.1 for rates as high as 1 kV/10sec. The main qualification to this conclusion is that the rate of rise must be less than the time required for the gap to breakdown once breakdown has been initiated.

2) The reduction of temperature in an SF$_6$ insulated uniform field gap affects the dielectric strength of the system in two ways. For pressures of the system below 4 atm. reduction in temperatures at constant pressure, increases the dielectric strength of the system. When the pressure of the system exceeds 4 atm. reduction in temperature at constant pressure causes a reduction in dielectric strength. From the available data this reduction in dielectric strength appears to be a function of the gas density and the temperature.
3) In the case of the non uniform field gap constant pressure test, the reduction of temperature results in an increase in dielectric strength. This observed increase appears to be a function of both density and temperature. Reduced temperatures are also responsible for an apparent formation of a region of corona stabilized breakdown.

4) The dielectric strength of an SF₆ insulated system is affected by the material of the test electrode. The use of aluminum electrodes results in a saturation of dielectric strength at an applied field of 260 kV/cm.

5) The theoretical derivations reviewed in section 4.3 do not appear to be applicable to a system insulated with SF₆ at subzero temperatures. The breakdown criterion derived by Pedersen (20) indicates that the conditions required for breakdown are a function of gas density and avalanche length. The studies conducted here seem to indicated that this is not entirely true. The gas temperature also appears to play a role in the breakdown mechanism.

6) Based on the observations made in this study heaters are not needed in SF₆ insulated equipment operating at pressures up to 5 atm. The dielectric strength of both the constant pressure and constant density systems at -30°C is at least equal to the dielectric strength of the system measured at +20°C. The use of heaters to ensure the mechanical operation of SF₆ insulated equipment has not been examined. This conclusion, therefore, must to restricted to equipment in which there are non movable parts.

8.3 Experimental Limitations

Any experimental system has certain limitations and this system is no exception. Based on the tests conducted in this study certain improvements could be made to the existing experimental system. The 2 mm. gap length,
fixed by the limited supply voltage, is one of the major limitations of the system. The coaxial epoxy bushing used in the present study should be replaced by a conventional porcelain bushing. This would allow for the application of higher voltages and hence breakdown at longer gap lengths could be studied.

The pressure gauges on the top of the chamber should be supplemented with an electronic pressure sensor in the tank. This would ensure more accurate pressure readings at lower temperatures. A movable density monitor should also be installed in the tank to check for layering in the gas at reduced temperatures. One major addition to the present system, which would help clarify some points, would be viewing ports located in the sides of the chamber.

A single feed through in the base of the chamber is insufficient, at least, additional feed throughs should be installed in the base.

These limitations have in no way affected the results or observations made in the present study. The suggested changes would make the experimental system more versatile for further studies.

8.4 Suggestions for Future Work

One of the most important studies which should be undertaken is the measurement of corona current in the non uniform field gap at different temperatures and pressures. This study should also include other rod electrodes including a 30° conical point. The addition of the pointed electrode would ensure a region of corona stabilized breakdown at room temperature. This corona current study should include oscillographic studies as well as electrometer studies.

The addition of viewing ports to the tank would allow for visual and photographic studies of corona and actual breakdowns at 20°C and at
subzero temperatures. The effects of low temperatures on the dielectric strength of nitrogen and $\text{SF}_6$ ($\text{N}_2 - \text{SF}_6$) mixtures could also be examined. The studies already conducted and the suggested studies could be conducted with both AC and impulse applied voltages.
REFERENCES


89.


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