The performance of polluted insulator surfaces under direct applied voltages.

M. R. Raghuveer
University of Windsor

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THE PERFORMANCE OF POLLUTED INSULATOR SURFACES
UNDER DIRECT APPLIED VOLTAGES

by

M. R. RAGHUVEER

A Dissertation
Submitted to the Faculty of Graduate Studies through the Department of Electrical Engineering in partial fulfillment of the requirements for the Degree of Doctor of Philosophy at the University of Windsor

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1972
ABSTRACT

While the problem of insulator contamination has been recognized since as early as 1940, it has sprung into prominence only recently. This is not only due to an increase in air pollution but also due to the emergence of E.H.V. and U.H.V. lines. Contamination will be a major factor in establishing insulation levels for such lines. There is, therefore, an urgent need for artificial contamination tests which can evaluate the performance of new and existing insulator designs. In an artificial contamination test an attempt is made to simulate the natural environment. As a result, there are many parameters which influence the results of these tests. In this study an effort has been made to study the relative effect of such parameters. The data presented are based on tests carried out on a model insulator. It is shown that the presence of an inert contaminant leads to more stable flashover values. Furthermore, the flashover voltages are independent of the wetting rate provided a certain amount of the inert component is present on the insulator surface corresponding to at least a "medium" deposit. An excessive amount of the inert component increased the flashover voltage.

Also a theoretical model has been developed which describes dry band growth and evaluates temperatures at points in the dry band. This model is applicable to simple geometries and involves necessary simplifying assumptions. Finally a series of tests were carried out to determine the effect of geometry on the performance of polluted insulators. It is shown that the use of materials other than glazed porcelain can result in a considerable improvement in insulator performance.
ACKNOWLEDGEMENTS

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CHAPTER I

INTRODUCTION

The reliability of a High Voltage Transmission line is dependant on the reliable performance of the supporting insulation. This insulation is subjected to many kinds of over-voltages such as lightning and switching surges. Further, contamination of the insulating surfaces leads to abnormal local voltage gradients on the surface which may lead to a flashover across the insulator. Owing to the employment of improved protective measures as well as increasing system voltages, over-voltages due to lightning strokes are no longer serious. While the same cannot not be said about switching surges, yet, techniques are available to limit this type of over-voltage to about 2-2.5 times the operating line to neutral voltage. In contrast, because of an increase in air pollution the contamination problem has risen into prominence especially at the higher line voltages. This is evident from the classification, presented below, of the factors which determine line insulation design.

- 0 - 4 kv: mechanical clearances
- 4 - 34.5 kv: corona and surges
- 69 - 220 kv: lightning and switching surges
- 345 - 765 kv: switching surges and contamination
- 765 - 1500 kv: contamination

The above is only a general classification. For example, environmental conditions may result in the contamination problem becoming serious even at the lower voltages.

Basically, the insulator contamination problem arises due to the deposition of wind borne natural and man made contaminants on the
insulator surface. A recent survey\(^1\) indicates the possible types of contaminants found on insulator surfaces in various locations in the North American Continent. These various types of pollution can be broadly classified into two categories, i.e. industrial and coastal or marine pollution. Coastal pollution occurs when a transmission line is situated within 5-6 miles from a sea coast. In this case wind borne salt deposits are found on the insulator surface. In contrast, the contaminants arising out of industrial pollution comprise of conducting as well as inert (non conducting) parts.

There are many forces acting on a particle of contamination, the resultant of all of which is responsible for the preferential settlement of the contaminants on the insulator surface. These forces are those due to gravity, the presence of wind and electrical forces on charged and uncharged particles. Whether the applied voltage be alternating or direct, the non electrical forces are identical if identical conditions prevail. However, the electrical force on charged particles produces an oscillatory motion in the case of alternating applied voltages and translatory motion in the case of direct applied voltages. The electrical force on neutral particles produces translatory motion in the case of direct as well as alternating applied voltages. In view of the above it is possible that contamination levels will be higher in the case of insulators supporting a D.C. line than a corresponding A.C. line under identical geographical conditions. However, the magnitudes of the various forces have been compared by Gertsik\(^2\); it can be seen that wind forces usually predominate. If this is so, then the amount of contaminant deposited on an insulator surface should be independent of the type of the voltage in the presence of wind.
When the surface of the insulator is dry, then the magnitude of the surface leakage current is very low in spite of the presence of surface contaminants and therefore normal conditions prevail. However, in the presence of wetting agents such as fog, dew or mist, the surface film becomes conducting and relatively large leakage currents of the order of milliamperes flow over the insulator surface. Owing to factors such as non-uniform current distribution, non-uniform wetting and non-uniform surface distribution of the contaminants, the heating effect due to the passage of leakage current is non-uniform. This leads to the formation of dry bands or zones which then support more voltage than when in the wet condition. This is because of the higher resistance associated with the dry bands. At a certain critical stress, surface breakdown ensues and an arc is struck across the dry zone. This arc is then either extinguished or proceeds to a flashover along the wet contaminated surface depending on the nature and resistance of the wet portion of the contaminated insulator. Essentially, therefore, failure of the insulation occurs because of the combined effect of contaminants on the insulator surface and the presence of a slow wetting agent such as fog. Rainfall, on the other hand is beneficial in that it washes the contaminants off the surface. The extent of the washing effect depends on the frequency of rainfall, insulator geometry and configuration.

Forrest was the first person to observe the formation of dry bands and carry out a systematic study of the insulator contamination problem. Since then many investigators working in various laboratories have worked on various aspects of the problem. The work done so far may be broadly classified as follows:
1) Field tests and observations

2) Laboratory tests on naturally contaminated line insulators

3) Laboratory tests on artificially contaminated line insulators 10-13, 18-22, 43-48

4) Laboratory tests on simple models subject to artificial contamination 9, 14-17, 22-25

5) Theoretical work 14, 15, 24, 25-35, 42

Laboratory tests on naturally contaminated line insulators have to be conducted with great care because of their limited availability. Such tests in conjunction with field tests and observations can bring out useful information regarding the validity of artificial contamination test procedures. Besides, laboratory analyses of naturally contaminated insulators have yielded both qualitative and quantitative information regarding the contaminants present. The artificial contamination tests are useful in evaluating the relative performance of different insulator designs under polluted conditions. In recent years many such test procedures have evolved. It is difficult to make comparisons of the results obtained in these tests not only because of the difference in the test procedures but also because of the different insulators used. Tests conducted on models subjected to artificial contamination have yielded useful basic information such as dry band characteristics, flashover mechanisms etc. It is difficult to obtain such information by conducting tests on line insulators because of their complicated geometry. Therefore models have been used which usually give an oversimplified representation of line insulators.

There have been relatively few papers dealing with the theoretical aspects of polluted insulators. Alston and Zoledziowski were the first
to propose a criterion based on a mathematical model for arc extinction and its growth. Their work was followed by Hampton\textsuperscript{15} and Hesketh\textsuperscript{27} who proposed additional criteria using similar models. It can easily be shown that these criteria are in fact identical. Rizk\textsuperscript{34,35} has arrived at the same criteria by using a completely different approach to the problem. More recently, Wilkins and Al Baghdadi\textsuperscript{50} have proposed a new mechanism for arc elongation along a polluted surface. McElroy\textsuperscript{31} has proposed a theoretical model describing dry zone formation. These theoretical efforts have contributed substantially to a better understanding of the mechanisms involved in the flashover process of a contaminated insulator. However, attempts to predict flashover voltage values of a contaminated line insulator by using the techniques developed have not been successful. This is because any mathematical analysis of the contamination problem involves many simplifying assumptions without which it is impossible to arrive at a solution.

Many solutions\textsuperscript{41} have been proposed to overcome the contamination problem such as washing\textsuperscript{36}, greasing of insulators\textsuperscript{4,37}, and the application of a semiconducting glaze\textsuperscript{38-40}. In the first method, the insulators are washed with water, the line being either energized or not. In the former case the washing procedure is referred to as "hot line washing". Hot line washing is accomplished by spraying the insulators either with a jet of water from portable washing units or by means of nozzles fixed at suitable locations around the insulators\textsuperscript{41}. In the former case, precautions have to be taken to ensure the safety of the operator while in the latter case the disposition of the nozzles is important so that surrounding electrical equipment is not damaged. The greasing of insulators is accomplished by hand application of a thin film of silicone
grease or petroleum jelly on to the insulator surface. In doing so, dirt particles are enveloped by the grease and kept separate. Moreover, water settling on the insulator surface forms separate beads which run off the surface. Thus the formation of a continuous conducting film is avoided and this contributes to an improvement in the performance of the insulator under polluted conditions. As dirt accumulates, the usefulness of the grease coat decreases; the old coat is then removed and a new one applied. Both these remedial measures -- washing as well as greasing do not offer a long term solution. The insulators have to be washed or greased periodically depending upon the severity of the pollution in the particular area.

Semiconductor glazed insulators offer a possible solution to the contamination problem. By adjusting the resistivity of the glaze and therefore the resulting surface conduction current, it is possible to keep the surface of the insulator at a few degrees centigrade above ambient. Thus moisture condensation is avoided and there is an improvement in the performance of the insulator under polluted conditions. An added advantage is that the voltage distribution across a string of insulators becomes linear even in the case of alternating applied voltages. This results because the resistive part of the leakage current is much higher than the capacitive part. The main disadvantage in this technique arises because of the negative temperature coefficient of resistance associated with the glaze. Furthermore, the thickness of the glaze has to be known precisely. There are also other problems such as the difficulty in providing a reliable contact between the semiconductive glaze and the metal fittings of the insulator. In addition it has been reported that there is little
improvement in the insulator performance at high contamination levels in spite of the employment of semiconducting glazes$^{40}$. Also it may be necessary to simplify insulator shapes in order to facilitate the application of such glazes$^{38}$.  

A trivial solution would be to simply increase the string length. But, cases are known where even a hundred percent increase did not overcome the problem$^7$.

Object of Present Study

The initial part of this study consisted of experiments designed to gain a better understanding of the effects of the various parameters involved in an artificial contamination test. The results of such experiments constitute a small but important step in arriving at a standard test procedure capable of evaluating insulator performance under polluted conditions. The parameters studied are listed in the next chapter which also deals with the techniques developed to study the problem. Chapter 3 includes the results of such tests. Certain experimental observations made in Chapter 3 led to a theoretical model describing dry band growth which has been included in Chapter 4. The initial tests described in Chapter 3 were carried out on a simple model as the sole object was to investigate the relative effects of the parameters involved. However, the effect of geometry has to be considered and evaluated in order to be able to re-design insulator shapes. With this in mind certain simple but representative geometries are considered in Chapter 5. Finally Chapter 6 gives the conclusions reached from this study and suggestions made for further work in this area.
CHAPTER II

TEST METHODS FOR ARTIFICIALLY POLLUTED INSULATORS

2.1: Introduction

It was pointed out in the previous chapter that the initial part of this study was concerned with some of the parameters which affect the results of artificial contamination tests. It was felt that the geometry of a suspension insulator is too complex to permit a study of the fundamental aspects. Therefore, it was decided to carry out the tests on a model insulator of cylindrical geometry. Such a model not only has a simple geometry but also resembles line insulators more closely than a flat plate model. This chapter presents the results of several exploratory tests which were carried out in order to establish well defined and reproducible polluting and testing procedures capable of evaluating the relative effect of the various parameters under study. This is essential as otherwise any variation in the testing procedure can mask the effects of the parameters under study.

2.2: Test equipment and circuit

The voltage source consisted of a 3 kVA 220v/120kV X-Ray High Voltage unit modified to function as a biphasic half wave rectifier 220v/60kV yielding D.C. output voltages of positive polarity. A wire wound 275kΩ resistor was inserted in the charging circuit of the capacitor bank "C" as shown in Figure 2.1. The purpose of the capacitor bank "C" is not only to get a smooth D.C. output voltage but also to ensure a minimal output voltage drop due to any discharges which may occur on the surface of the polluted insulator in the course of an experiment. The 275kΩ resistor was divided into four sections having resistances of 100kΩ,
Figure 2.1: - The test circuit

A - D.C. Supply
R₁ - 275 kΩ Resistor
C - Capacitor Bank
R₃ - 600 MΩ Resistor
M - D.C. Microammeter
R₂ - 3 kΩ Resistor
FC - Fog Chamber
B - Measuring Circuit
100kΩ, 50kΩ and 25kΩ. By making suitable connections it was possible to include any section or sections in the charging circuit. The purpose of this resistance was to limit the maximum current through the diodes in the High Voltage unit to the recommended safe value. The capacitance C in the capacitor bank initially consisted of two 50 kV, 0.25 μF, capacitors in parallel, giving a total capacitance of 0.5 μF. A 600MΩ resistor with a D.C. microammeter in series was used for High Voltage measurement. Details regarding this voltage divider set up and the manner in which the voltage measuring set up was calibrated are included in Appendix A2.1. Lastly a 3kΩ wire wound resistance was inserted in the discharging circuit in series with the test sample (model insulator) and the measuring circuit to limit the short circuit current. Details regarding the measuring circuit are included in Chapter III.

Figure 2.2 shows the fog chamber used in the study. It consisted of a 4' x 4' x 6' high wooden framework the sides of which were lined with polyethylene sheet and sealed with caulking. The chamber was also provided with a plexiglass door, centrally located plexiglass windows on the sides to facilitate bus bar entry and exit, a drainage hole at the base and adequate sealing. All wooden parts which would be exposed to the fog were treated with a wood preserver to prevent deterioration due to prolonged exposure to moisture.

2.3: Parameters studied

Basically, there are three ingredients involved in the flashover process of a contaminated insulator. These are the conducting contaminant, the inert contaminant and a wetting agent such as fog. The conducting contaminant is some salt which provides a conducting path on the surface when wet. The inert contaminant does not contribute to
FIGURE 2.2: VIEW OF FOG CHAMBER USED IN THE PRESENT STUDY
the conduction process directly. Such a contaminant is usually present except in the case of coastal pollution. Initially, therefore, it was decided to study the effects of the parameters listed below on the performance of the model insulator.

a) the effect of variation of the amount of the conducting contaminant on the insulator surface.

b) the effect of variation of the amount of the inert contaminant on the insulator surface.

c) the effect of changing the conducting contaminant.

d) the effect of a change in the wetting rate, i.e. change in fog characteristics.

e) the effect of insulator configuration, i.e. horizontal, vertical and inclined.

2.4: The test sample

The test samples were cylindrical in shape 1" diameter and 4" long and were of glazed porcelain. When tests were carried out in the horizontal configuration, the sample was mounted horizontally between the bus bars at a height of 3 feet from the base. It was possible to slide the bus bars in and out of the chamber and thus secure a central location for the test sample. The inclined and vertical configurations were obtained by suspending the sample suitably from one bus bar and then rotating it to secure the desired configuration. Figure 2.3 shows the test insulator in these three basic configurations. Figure 2.4 shows the electrode and the electrode assembly. The electrodes were of brass. The indentation in the electrode face ensured a good contact with the insulator surface.
FIGURE 2.3: TEST INSULATOR IN THE 3 BASIC CONFIGURATIONS

FIGURE 2.4: ELECTRODE ASSEMBLY
2.5: Fog generation

Figure 2.5 shows details of the method employed in generating fog inside the test chamber. Fog was produced by means of two nozzles located at the base. On passing compressed air through these nozzles, distilled water was siphoned out and an atomized spray was produced. As the siphoning head (Figure 2.5) was maintained constant the rate of moisture delivery into the chamber was solely dependant on the air pressure. Thus the wetting rate was reproducible. The maximum allowable air pressure for the nozzles used was 60 psi. The air pressure could therefore be set at any value between 0 and 60 psi and the rate of entry of moisture into the chamber could be controlled within wide limits. Two values of air pressure were chosen - 60 psi and 20 psi. At the former pressure the fog filled the chamber faster, was more dense and it is possible that the size of the drops was also bigger. These two values of air pressure correspond to two wetting rates which shall be referred to as quick and slow respectively.

The method of fog generation is an important parameter. To simulate natural conditions the fog must build up slowly and its density should be uniform especially in the region of the test sample. For model testing, the method used in this study is quite adequate as the model occupies a very small portion of the test chamber volume. Furthermore, owing to the central location of the sample (i.e. at a height of three feet from the base), the larger water droplets do not get a chance to reach the sample as they settle down. Also, direct wetting by the nozzle spray was absent as the spray was directed horizontally.
FIGURE 2.5: FOG GENERATING SYSTEM

A - WATER STORAGE TANK
B - FLOAT TANK
W.L. - WATER LEVEL
P - COPPER PIPING
C - HEAT EXCHANGER
D - SPRAY NOZZLES
E - SHUT OFF VALVE
F - AIR PRESSURE REGULATOR AND GAUGE
G - AIR FILTER
There are several methods of determining the wetting rate. A collection method, described below, was chosen which is the simplest and the most expedient. To check the uniformity of fog deposition, fog water was collected in small cylindrical flasks (approximately 4" long and 0.3825" internal diameter, Type 8549A procured from the Fisher Scientific Company) over a period of thirty minutes after bringing the flasks into thermal equilibrium with the surrounding fog. This was achieved by sealing the open end of the flask and inserting it into the chamber at the desired location and then turning on the fog for an initial period of thirty minutes; the seal was then removed and fog water collected for a further period of thirty minutes. Knowing the weight of the empty flask and that of the flask containing the collected water, the weight of fog water collected over a period of thirty minutes is easily found. This procedure was followed to obtain the fog deposition rate at various locations in the vicinity of the test sample. Figure 2.6 shows the locations at which the above exercise was carried out; the amount of fog water collected at these locations is summarized in Table 2.1. On examination of this table it is seen that the fog deposition is reasonably uniform in that part of the fog chamber which is occupied by the test sample.

The method described above does not give the true rate of fog deposition on a horizontal surface. For this purpose, fog water was collected in small plastic rectangular containers (2.13" x 1.63" x 0.125" high) at the location marked X in Figure 2.6. This exercise was carried out at both the slow and the quick wetting rates. The average fog deposition rate was found to be 0.37 mg/cm²/min and 0.46 mg/cm²/min respectively. It is seen that the deposition rate at the quick wetting rate is 124.3 percent of that at the slow wetting rate.
**FIGURE 2.6**: LOCATIONS (A, B, C, D) AT WHICH FOG DEPOSITION RATE WAS CHECKED

**TABLE 2.1**

CHECK FOR UNIFORMITY OF FOG DEPOSITION

<table>
<thead>
<tr>
<th>AIR LINE PRESSURE</th>
<th>AMOUNT OF FOG WATER COLLECTED (MILLIGRAMS) IN THIRTY MINUTES AT</th>
<th>LOCATION A</th>
<th>LOCATION B</th>
<th>LOCATION C</th>
<th>LOCATION D</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td></td>
<td>62.5</td>
<td>70</td>
<td>62.5</td>
<td>70</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>60.0</td>
<td>67.5</td>
<td>60</td>
<td>72.5</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>60.0</td>
<td>70</td>
<td>65</td>
<td>75</td>
</tr>
<tr>
<td>60</td>
<td></td>
<td>75</td>
<td>82.5</td>
<td>82.5</td>
<td>90</td>
</tr>
<tr>
<td>60</td>
<td></td>
<td>77.5</td>
<td>80.0</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>
It was felt that the use of a warm fog does not offer any advantage when insulators are tested in fog conditions apart from accelerating the wetting process. When tests are carried out in humidity conditions below 100 percent then it is necessary to cool the insulators prior to testing in order to accelerate the wetting process. In all the tests reported in this study, the fog was generated from distilled water at ambient temperature although provision did exist to heat the water (Figure 2.5).

2.6: Polluting technique

In order to select a suitable technique for the artificial contamination of the insulators, the following methods were carefully considered.

1) Dipping the insulator in salt solution and then allowing the sample to dry.

2) Dipping the insulator in a slurry composed of inert and conducting contaminants and then allowing the sample to dry.

3) Blow inert contaminant on to surface, then blow salt or salty water on to the surface. Allow the insulator to dry if salty water is used.

4) Subject insulator to salt fog only during testing.

5) Spray insulator with a predetermined slurry composed of inert and conducting contaminants and then allow the sample to dry.

In the selection of a polluting method, the following guidelines were set. First, the contaminants on the insulator should consist of inert as well as conducting parts. Secondly it should be possible to vary the amount of the conducting as well as inert contaminants (on the insulator surface) independently. Thirdly, the method selected should
be capable of yielding reasonably uniform layers of pollution as it was decided to conduct all the tests with uniform layers of pollution. Lastly the pollution layer should be reproducible to a certain extent.

Methods (1) and (4) were rejected as these do not involve any inert contaminant. Before proceeding further with the selection of a polluting procedure both the inert as well as conducting contaminants were chosen. Initially Sodium Chloride was chosen as the conducting contaminant. Two types of inert contaminant were considered — Keiselguhr and Bentonite. The former is a diatomaceous earth and is available in various mesh sizes; the finest mesh size (100/120) was selected. Bentonite is a powdery substance and is available in many grades with differing water absorptive capacities. The type used in the present study was procured from the Fisher Scientific Company and is a laboratory grade classified as type B-235. Both Bentonite and Keiselguhr have good water absorption properties. In addition, pink Keiselguhr changes color to red when it absorbs moisture.

When method (2) was tried out using either of the above two inert contaminants, it was found difficult to achieve uniformity, reproducibility or retain independant control of the amount of the inert and conducting deposits on the insulator surface. With method (3), similar difficulties were encountered when Keiselguhr was used. Bentonite was found to be more suitable for this method. However, in this method many different operations are involved such as — coating the sample with Bentonite; enveloping the coated insulator in a salt fog followed by a drying cycle and then lastly followed by the test itself. These practical difficulties therefore favoured the adoption of method (5) described below.
First a plastic bottle with a hand spray mechanism was chosen. The spray head has an adjustable nozzle by means of which it is possible to produce a fine spray. It appeared that Bentonite was more suitable for this method than Keiselguhr because of its fine particle size as well as its ability to stay in suspension in water for much longer periods. Accordingly, a mixture of known quantities of Bentonite, Sodium Chloride, a few drops of photo-flo and distilled water was prepared in the bottle. The mixture was then thoroughly agitated until all the Bentonite was in suspension. This slurry could then be sprayed upon the insulator evenly. A spraying technique was then developed to ensure uniformity and reproducibility. First, the number of sprays per sample was fixed. Further, by maintaining a particular spraying angle and distance it was possible to achieve reproducibility. Minimizing the number of sprays per sample prevented the deposition of an excess of slurry on the sample surface which may then redistribute itself on the surface after completion of the spraying process and thus cause pronounced non-uniformities in the polluted layer. It was also found that it is possible to vary the amount of the inert and conducting deposits on the insulator surface independently of each other by simply varying their respective proportions in the slurry.

The next step was to check the uniformity of the polluted layer as well as establish a method for determining the quantities of the inert and conducting deposits. A standard method for evaluating the amount of the salt deposit is to find the equivalent salt deposit density (weight of salt on the surface ÷ surface area of the insulator). In this method, the deposits on the insulator are washed with a certain volume of distilled water. The salt dissolves in this wash water which
is then transferred to an electrical conductivity cell. The volume resistance is then determined by a bridge method. Knowing this resistance and the temperature of measurement it is possible to arrive at the weight of salt which was deposited on the sample surface by referring to predetermined curves of volume resistance versus weight of salt for Sodium Chloride. The weight so determined is the exact weight if the salt on the surface is Sodium Chloride. In the case of any other conducting contaminant, the weight is expressed in terms of an equivalent weight of Sodium Chloride. Details regarding the conductivity cell, etc. and the manner in which the calibration curves were obtained are included in Appendix A2.2.

It is possible to determine the weight of the Bentonite deposited on the sample by a filtration process. After the contaminants have been washed off the surface of the sample, the wash water is then filtered. Care should be taken to ensure that all the soluble contaminants have passed on in the filtrate. This can be accomplished by washing the filter paper several times. However, if the electrical volume conductivity is also to be determined then care should be taken to ensure that the volume of the filtrate does not exceed the allowable volume of the conductivity cell. Knowing the weight of the unused filter paper and that of the same filter paper containing Bentonite, it is easy to calculate the amount of Bentonite deposited on the insulator surface. Care has to be taken to ensure that the filter paper is dry to the same extent during both the weighings. In the present case this was achieved by the adoption of a standard drying procedure. The weight of the unused filter paper was obtained after drying it for 24-hours in a desiccator containing a drying agent. Similarly, after completion of the filtration process, the filter paper was first dried in a laboratory atmosphere and then dried
in the desiccator for a further period of twenty-four hours.

The method of determining the weight of Bentonite as described above is a time consuming one. This is because of the time taken by the filtration process which is due to the fine filter paper employed so as to be able to retain the fine Bentonite particles. As a large number of tests were planned, it became evident that the use of such a technique to determine the amount of Bentonite deposits at the conclusion of each test would lengthen the test time considerably. In order to overcome this difficulty the following was devised. The Bentonite content of the slurry was fixed at three levels, i.e. 6 gms, 30 gms, and 70 gms per 400 cc of distilled water. The salt content could be varied to give varying amounts of salt deposits on the insulator surface. Because of the spraying technique adopted it was hoped that reproducible levels of Bentonite deposits would be attained for each of the three types of slurries. To check this, each of the three types of slurries was used to spray three sets of ten insulators each. The amount of Bentonite deposits on the insulator surface was then determined using the method described earlier in this section. The average Bentonite deposit density (amount of Bentonite / surface area of sample insulator) was found to be .028, .098 and 0.370 mg/cm² corresponding to slurries containing 6, 30 and 70 gms of Bentonite respectively. The maximum tolerance in these measurements was about 20%. It was felt that this is a satisfactory level of reproducibility. It was therefore possible to standardize the slurries as follows:

\[ SLURRY \ A \]
\[
\begin{align*}
400 \text{ cc distilled water} \\
6 \text{ gms Bentonite} \\
\text{varying amounts of salt} \\
few \text{ drops of photoflo solution}
\end{align*}
\]
SLURRY B
{ 400 cc distilled water
   30 gms Bentonite
   varying amounts of salt
   few drops of photoflo solution
}

SLURRY C
{ 400 cc distilled water
   70 gms Bentonite
   varying amounts of salt
   few drops of photoflo solution
}

The levels of Bentonite deposits resulting from use of Slurries A, B and C were then classified as light, medium and heavy respectively.

In order to check the uniformity of the pollution layer the following simple experiment was carried out. First the insulators were divided into four equal sections. This was achieved by wrapping 1/2" electrical tape around the insulators as shown in Figure 2.7. Employing the developed techniques, the insulators were sprayed with Slurry "B" and then allowed to dry. The deposits in each of the four sections were then washed off one by one with a syringe using distilled water. The wash water was then transferred to the conductivity cell and the volume resistance of the solution measured. The weight of the salt present in each section was then determined by referring to the calibration curves. The total weight of the salt present in all the four sections was then calculated. This experiment was carried out on forty insulators. For each insulator the standard deviation and mean value of the salt deposit in milligrams was then calculated.

The coefficient of variation was then calculated for each of the 40 samples. The results are expressed conveniently in the form of a histogram as shown in Figure 2.8. Figure 2.9 shows a plot on normal probability paper of the upper class boundary of the coefficient of
FIGURE 2.7: DIVISION OF TEST INSULATOR INTO 4 EQUAL SECTIONS

Table 2.2: Frequency Table

<table>
<thead>
<tr>
<th>CLASS INTERVAL (COEFF. OF VARIATION IN %)</th>
<th>MID-POINT</th>
<th>FREQUENCY</th>
<th>CUMULATIVE FREQUENCY</th>
<th>FRACTIONAL CUMULATIVE FREQUENCY IN PERCENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 6</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>10%</td>
</tr>
<tr>
<td>6 - 12</td>
<td>9</td>
<td>7</td>
<td>11</td>
<td>27.5%</td>
</tr>
<tr>
<td>12 - 18</td>
<td>15</td>
<td>7</td>
<td>18</td>
<td>45.0%</td>
</tr>
<tr>
<td>18 - 24</td>
<td>21</td>
<td>12</td>
<td>30</td>
<td>75%</td>
</tr>
<tr>
<td>24 - 30</td>
<td>27</td>
<td>8</td>
<td>38</td>
<td>95%</td>
</tr>
<tr>
<td>30 - 36</td>
<td>33</td>
<td>2</td>
<td>40</td>
<td>100%</td>
</tr>
</tbody>
</table>

\[ s = 8.374 \]
\[ \bar{x} = 17.85 \]
\[ n = 40 \]
Figure 2.8: Histogram for the data of Table 2.2
FIGURE 2.9: PLOT OF FRACTIONAL CUMULATIVE FREQUENCY
(FROM DATA OF TABLE 2.2) ON NORMAL PROBABILITY PAPER
variation versus fractional cumulative frequency in percent. The plot is nearly a straight line and therefore the coefficient of variation is normally distributed. This was checked by fitting a normal curve to the observed distribution of the coefficient of variation. The various steps in the calculation are represented in Tables 2.2, 2.3 and 2.4. The observed value of chi square is 1.8351 with 2 degrees of freedom. Testing for significance, the value of $\psi^2.95$ with 2 degrees of freedom is 5.991. As this exceeds the observed value of $\psi^2$ the fit is acceptable. In other words the hypothesis that the coefficients of variation are normally distributed is tenable. It is therefore possible to state that there is a 95 percent probability that the coefficient of variation will fall between 1.45 and 34.25%.

2.7: Preparation of samples

The procedure for polluting the samples was set as follows. First the insulator was sprayed as described in the preceding section. Slurry A, B or C could be used to obtain light, medium or heavy Bentonite deposits on the surface with deposit densities of .028, .098 and .370 mg/cm² (±20%) respectively. The salt content could be varied independently by varying the salt content of the slurry. The range of investigation for the salt deposits varied from .01 to 0.3 mg/cm². From the reported measurements made on naturally polluted insulators it has been found that this range is quite practical.

After spraying, the samples were dried overnight on a rack in a laboratory atmosphere. It was felt that there is no advantage in drying the samples at elevated temperatures, other than accelerating the drying procedure. As the tests were to be carried out in fog conditions, a well dried salt laden insulator will absorb moisture quickly thereby
### TABLE 2.3
FITTING A NORMAL CURVE TO THE DATA OF TABLE 2.2

<table>
<thead>
<tr>
<th>CLASS LIMIT</th>
<th>DEVIATION FROM MEAN IN STANDARD DEVIATION UNITS $x/\sigma$</th>
<th>PROPORTION OF AREA BETWEEN MAX. ORDI NATE &amp; ORDI NATE AT $x/\sigma$ [from normal table of areas]</th>
<th>NUMBER OF CASES BETWEEN MAX. ORDI NATE AND ORDI NATE AT $x/\sigma$</th>
<th>THEORETICAL FREQUENCIES BY CLASSES</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>- 2.13</td>
<td>0.48341</td>
<td>19.34</td>
<td>0-6</td>
</tr>
<tr>
<td>6</td>
<td>- 1.42</td>
<td>0.42220</td>
<td>16.89</td>
<td>0-6</td>
</tr>
<tr>
<td>12</td>
<td>- 0.70</td>
<td>0.25804</td>
<td>10.32</td>
<td>6-12</td>
</tr>
<tr>
<td>18</td>
<td>+ 0.02</td>
<td>0.00798</td>
<td>.32</td>
<td>12-18</td>
</tr>
<tr>
<td>24</td>
<td>+ 0.73</td>
<td>0.26730</td>
<td>10.69</td>
<td>18-24</td>
</tr>
<tr>
<td>30</td>
<td>+ 1.45</td>
<td>0.42647</td>
<td>17.05</td>
<td>24-30</td>
</tr>
<tr>
<td>36</td>
<td>+ 2.17</td>
<td>0.48500</td>
<td>19.40</td>
<td>30-36</td>
</tr>
<tr>
<td>&gt; 36</td>
<td></td>
<td></td>
<td></td>
<td>0.60</td>
</tr>
</tbody>
</table>

Note: The last row indicates the cumulative proportion beyond 36, which is used to calculate the theoretical frequencies by classes.
### TABLE 2.4: CALCULATION OF CHI-SQUARE

<table>
<thead>
<tr>
<th>CLASS LIMITS</th>
<th>OBSERVED FREQUENCY ( f_o )</th>
<th>THEORETICAL FREQUENCY ( f )</th>
<th>((f_o - f))</th>
<th>(\frac{(f_o - f)^2}{f})</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 &amp; LESS</td>
<td>4</td>
<td>3.11</td>
<td>+ .89</td>
<td>.2547</td>
</tr>
<tr>
<td>6 - 12</td>
<td>7</td>
<td>6.57</td>
<td>+ .43</td>
<td>.0281</td>
</tr>
<tr>
<td>12 - 18</td>
<td>7</td>
<td>10.64</td>
<td>- 3.64</td>
<td>1.2450</td>
</tr>
<tr>
<td>18 - 24</td>
<td>12</td>
<td>10.37</td>
<td>+ 1.63</td>
<td>.2562</td>
</tr>
<tr>
<td>MORE THAN</td>
<td>24</td>
<td>9.31</td>
<td>+ .69</td>
<td>.05114</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>40</td>
<td>5 GROUPS</td>
<td>( \psi^2 = 1.8351 )</td>
</tr>
</tbody>
</table>

\( \psi^2 = 1.8351 \) with 5 - 3 = 2 d.f.
rendering a thorough drying process unnecessary. However, with a non-
hygroscopic salt such as Calcium Sulphate, moisture absorption, after
insertion of the sample in the test chamber is slower. In this case
the leakage surface current will take a longer time to increase to its
maximum value thus lengthening the duration of the experiment. This
effect is important when tests are carried out in humidity conditions
below 100 percent. The experiments reported in this paper, however,
were carried out in fog conditions and therefore with moisture deposi-
tion on the surface. Consequently a thorough drying process will have
little effect upon the experiments.

2.8: Method of voltage application

The available methods of voltage application may be summarized as
follows:

1) The voltage applied to the wet polluted insulator is increased
   at a uniform rate immediately after turning the fog on; the
   voltage being raised until flashover occurs.

2) Same as in (1), but the voltage is increased step by step.

3) The test voltage is applied to the polluted and wet insulator
   and then the fog is turned on.

4) Same as method (1) but to a polluted and dried insulator.

5) Same as method (2) but to a polluted and dried insulator.

6) Same as method (3) but to a polluted and dried insulator.

In order to be able to choose a method several preliminary tests
were carried out using all the above methods on identically sprayed
insulators. In method (1) the leakage current increased rapidly to a
high level. Drying out of the pollution layer was very rapid and
elongation of the dry band was readily visible. As the voltage was
increased, arcs were struck across the dry band. It was very difficult to maintain a constant rate of increase of voltage because of extremely poor voltage regulation. This situation did not improve in spite of increasing the capacitance in the capacitor bank to 6.5 µF. On increasing the applied voltage, several flashovers took place in quick succession. It appeared that the presence of fog had no effect at all, i.e. all the events leading to a flashover took place even before the fog had a chance to build up in the chamber. Allowing the fog to build up in the chamber made no difference as long as the insulator under test was still wet before commencement of the test.

In method (3), the technique employed was to apply the high voltage to the insulator, through a switch located on the low voltage side of the insulator under test. Once again it was found that voltage regulation was very poor. Flashover took place in a very short time if the applied voltage was close to the flashover value. The presence of fog seemed to have no effect on the experiments resulting in flashover.

Method (2) produced similar results except that it was now possible to get higher flashover voltage values by using small voltage increments as well as long time intervals between successive voltage steps.

In method (4) the flashover voltage was very high. Moreover, the flashover voltage is dependent on the time of commencement of the experiment. For example if the voltage is increased at a uniform rate immediately after turning the fog on then the flashover voltage obtained is much higher than when the voltage is increased at a uniform rate after the fog has had a chance to build up inside the chamber. This is because some time elapses before the insulator wets. The levels of leakage current obtained by using method (4) were much lower than those obtained by using methods (1), (2), or (3).
Similar remarks apply to the case when method (5) is used. Here too, as in method (2), the magnitude of the voltage step and the time interval between successive steps affected the flashover voltage.

In method (6) as in methods (4) and (5), the voltage regulation was much better than in methods (1), (2) or (3). This is due to the lower leakage currents obtained in the former three methods. After application of method (6) to several insulators, it appeared that the wetting of the insulator was being inhibited owing to the heating effect of the leakage current. The leakage current would never exceed a value of 0.4 to 0.5 ma. It also appeared obvious that flashover voltage values obtained by use of method (5) could be made to fall anywhere in-between those obtained by use of methods (4) and (6), simply by changing the magnitudes of the time and voltage steps.

In general, methods (1), (2) and (3) yield low values of flashover voltage as all the salt on the surface is wet prior to commencement of the experiment. Leakage currents are therefore high and voltage regulation poor. Methods (4), (5), and (6) are characterized by lower leakage currents and tolerable voltage regulation. Method (4) yields higher values of flashover voltage than those arising from use of method (6).

It was felt that the first three methods do not represent closely the field conditions and in addition pose serious practical problems. The choice of the method of application of test voltage was therefore restricted to using either method (4), (5) or (6). Method (4) was rejected as this will yield unrealistically high values of flashover voltage. Finally method (6) was chosen for three reasons. First, method (5) introduces additional variables in the test method itself. Also method (6) is more representative of field conditions. Furthermore,
it is not possible to determine both flashover and withstand voltage values by using method (5). Such a procedure is preferred to one yielding flashover voltage values only as the withstand level of a polluted insulator can be obtained.

The value of the capacitor in the capacitor bank was retained at 6.5 µF. This resulted in good voltage regulation -- the voltage remaining constant within 5 percent for small external discharges of up to about 1" - 1½" in length and within 10 percent for discharges which almost spanned the entire length of the insulator.

2.9: Summary

After careful consideration of many methods, a polluting technique as well as a test procedure has been defined. The methods chosen allow for repeatability and reproducability and furthermore simulate closely the operating field conditions.
CHAPTER III
PARAMETERS WHICH AFFECT THE RESULTS
OF ARTIFICIAL CONTAMINATION TESTS

3.1: Introduction

The effect of the various parameters on the performance of polluted insulators has been investigated by previous workers. Kawai\textsuperscript{8} noted that the inclusion of an inert contaminant decreased the flashover voltage of an insulator. Also the extent of this effect was shown to depend on the type of inert contaminant used. In his study line insulators were used which were polluted by dipping in slurries composed of inert and conducting components. (Kaolin or Fuller's earth plus Sodium Chloride). The insulators were then dried and subjected to steam fog after application of the test voltage. Woodson and McElroy\textsuperscript{24} using a flat plate model insulator obtained data which indicates that the flashover voltages should increase with the density of the inert binder. In their study, the model insulator was contaminated by spraying Bentonite on to it which was then subjected to salt fog after allowing the Bentonite layer to dry; when the desired resistivity was reached, the test voltage was applied to the wet model insulator. More recently Jolly\textsuperscript{9} using an identical model concluded that the density of the inert binder does not affect the flashover voltage. The results of all these three investigators are in contradiction with one another. However, it must be pointed out that the test methods used by them are different.

The effect of solubility of the conducting contaminant on the flashover levels of a polluted insulator has been reported by Kawai\textsuperscript{7}. Insulators polluted with gypsum slurries were found to yield higher flashover voltages than those polluted with Sodium Chloride slurries.
Macchiaroli and Turner\textsuperscript{48} showed that the time variation of surface conductivity of identical insulators polluted with identical slurries can be different because of the different properties of the slurry constituents procured from different sources. This effect was attributed to the presence of impurities.

Lastly, Rizk\textsuperscript{43} has studied the effect of the wetting rate on the performance of line insulators in artificial contamination tests. He found that the flashover voltages were higher with the quicker wetting rate over a wide range of values for the salt deposit density. However, the dependence of the effect of the wetting rate on the density of the inert binder was not studied. In his study the test and polluting procedures are similar to the one used in the present work but the composition of the slurry was different. (Keiselguhr + Aerosil + Sodium Chloride).

This chapter presents the results of tests carried out to investigate the relative effect of the parameters listed in section 2.3. In all experiments the defined polluting techniques and test procedures were strictly followed. Both the withstand and the flashover levels of the insulator were obtained under different pollution conditions. All the results are expressed in terms of the salt deposit density or the equivalent salt deposit density on the insulator surface.

3.2: The measuring circuit

Details of the measuring circuit used for monitoring the leakage currents are shown in Figure 3.1. In order to measure the wide range of leakage currents encountered, a Hewlett-Packard Log Voltmeter/Amplifier Model 7563A was used. This amplifier accepts either positive or negative D.C. signals ranging from 316\mu V to 100V. The output of this
FIGURE 3.1: - THE MEASURING CIRCUIT

G - SPARK GAP
R3 - 1250 Ω
R4 - 250 Ω
N - NEON LAMP
D - ZENER DIODE
C - COUPLING CAPACITOR
A - LOG VOMETER/AMPLIFIER
U.V. - U.V. RECORDER
P.C. - PULSE COUNTER
amplifier is 10mV/dB, the dB level being measured with reference to 316μV. The bandwidth of the amplifier is complex and improves with increasing magnitude of the input signal. The amplifier output was coupled to an S.E. Laboratory U.V. Recorder (serial number 2005/6) fitted with a galvanometer having a flat frequency response up to 600Hz and a natural frequency of 1 KHz. The U.V. Recorder paper speed used in all tests was either 1.25 mm/sec or 2.5mm/sec. Using the above set up, exact pulse reproduction is not possible. However, this did not matter as the Amplifier-Recorder combination was used to measure slowly varying leakage currents and only to indicate the presence of pulses. Examination of the pulse shapes was possible by using an oscilloscope and the number of pulses could be counted with a Hewlett-Packard model 522B Pulse counter. The measuring circuit along with the protection scheme shown, limited the maximum voltage at the input of the logarithmic voltmeter/amplifier to less than 100V -- which is the recommended maximum voltage which can be applied to that instrument. The resistance R was adjusted to such a value that the signal was attenuated by a factor of 3dB. The resistance R₁ was adjusted so that the deflection obtained on the U.V. Recorder was 10dB/cm. (dB reference is 316μV). It was found that the deflections obtained on the U.V.Recorder were linear to within ±1dB for signals ranging in magnitude from 0 to 120dB. (i.e. 316μV to 100V).

3.3: Test Procedure

The polluted insulators were prepared as described in section 2.7. The insulator was then mounted inside the test chamber and D.C. High Voltage applied to it. The fog was then turned on, the leakage current
and the pulse counts being monitored. The duration of the tests did not exceed a predetermined time. This time was fixed at 20–25 minutes since after this period, "washing off" of the deposits from the surface was pronounced. Therefore, prolonging the experiment beyond this time was considered meaningless. If during this time flashover did not take place, then the insulator was marked to have withstood the test. Then, another identically sprayed insulator was mounted and the procedure repeated at a voltage 0.5kV higher. This procedure was continued until flashover took place. Thus the minimum flashover voltage was determined. Also, the maximum voltage at which three successive withstands were obtained was called the withstand voltage. Thus, both the withstand and the flashover voltages were obtained for a particular value of the deposit density of the contaminants. The duration of a test was measured by means of a manually operated stop watch.

Such a testing procedure is preferable to one which involves the determination of a 50% flashover value as the latter not only requires a larger number of tests but also imposes more stringent conditions on the reproducibility of the pollution layers.

3.4: Selection of a Parameter for the Representation of the Results

There are many parameters against which the flashover and withstand voltage values can be plotted, e.g., salt deposit density, salt content in the slurry, and the initial value of the surface resistivity. The salt deposit density figures are obtained after the completion of an experiment as described in section 2.6. If the outcome of an experiment is a flashover and if the duration of the experiment is short, i.e., less than 5–7 minutes, then the salt deposit density figure truly represents the amount of salt present on the insulator surface.
during flashover. However, in the case of a withstand, the salt deposit density value can be low because of the "washing off" of deposits from the surface. As stated earlier, it was found that the "washing off" effect is inappreciable during the first 20-25 minutes. Therefore, the salt deposit density values can be considered to be representative of the amount of salt on the insulator surface in all cases.

The use of the salt content in the slurry as a parameter can give rise to added scatter in the results owing to accidental variations in the spraying procedure. For example, using the same slurry it is possible to spray different amounts of contaminants on to the insulator surface simply by alteration of the spraying angle and distance. As a manual spraying method was used, the possibility of using the salt content in the slurry as a parameter was rejected.

The last parameter considered was the initial surface resistivity. During an experiment the resistivity decreases with time after the fog is turned on. It was pointed out in section 2.8 that the leakage current increases up to a certain level only. This is equivalent to a certain minimum value of resistivity in each case. Thus, if the leakage current and the applied voltage are monitored continuously, it is easy to calculate the value of the equivalent resistivity. In practice, the maximum level of the leakage current is not well defined. Therefore, it may be difficult to obtain the value of the equivalent surface resistivity precisely. An alternative way is to estimate the value of the resistivity in each experiment at a given time, say at 2 minutes after commencement of the experiment. Such a method requires that all the samples tested should be at the same temperature prior to commencement of testing. Furthermore, the initial humidity in the testing chamber
should be maintained constant for all experiments. These precautions are necessary, otherwise additional variable factors are introduced which affect the rate of moisture absorption and consequently the surface resistivity.

It thus became apparent that the most convenient and representative parameter is the salt deposit density. It was therefore decided to use this parameter to represent all test results.

The results of all the tests have been represented graphically with the salt deposit density plotted as the abscissae and the applied withstand or flashover voltage plotted as the ordinate. All the graphs have been drawn to the same scale. Each point on any graph represents the result of a separate test. As explained earlier, after the conclusion of a test, the contaminants on the insulator were washed off the insulator surface using a syringe filled with distilled water. The electrical volume resistance of the collected water was then measured using a conductivity cell. The measured resistance was very useful in estimating the extent of scatter and the usefulness of a test result.

3.5: Tests carried out with the insulator in the horizontal configuration

3.5.1: Salt tests

Initially tests were carried out with the contaminant consisting of salt only (Sodium Chloride). Such deposits were obtained by spraying the insulators with slurries containing salt only. Experiments were carried out using both the slow and the quick wetting rates. The results are shown in Figures 3.2 and 3.3. It is seen that the results are very scattered, especially when a slow wetting rate was employed. With the lighter salt deposits (i.e. salt deposit density < 0.03 mg/cm²) the layer of salt on the surface remained uniform. However, at the
Figure 3.2: Flashover/Withstand Voltage Versus Salt Deposit Density

(Insulator polluted with NaCl only - horizontal configuration - slow wetting rate)

- △ - Flashover
- ○ - Withstand
FIGURE 3.3: FLASHOVER/WITHSTAND VOLTAGE VERSUS SALT DEPOSIT DENSITY
(insulator polluted with NaCl only - horizontal configuration - quick wetting rate)

- △ - Flashover
- ○ - Withstand
higher deposit densities the salt crystallized in patches on the surface; the layer was therefore very nonuniform. With a slow wetting rate the accumulation of fog water on the surface is much slower than with a quick rate of wetting. Therefore in the former case the salt can redistribute itself over the surface. This is a random process and therefore the effective resistance of the pollution layer varies from test to test even if the total amount of salt on the insulator surface remains the same. This accounts for the large scatter observed when a slow wetting rate is employed. With the quicker wetting rate the salt deposits are prone to getting washed off because of the faster rate of accumulation of water at the surface. The results are therefore more reproducible than in the case when a slow rate of wetting is employed and therefore there is smaller scatter.

3.5.2: Tests carried out with Sodium Chloride/Bentonite slurries

Five cases were considered as listed below

1) Insulator coated with medium Bentonite deposits.

   Insulator withstand and flashover levels obtained
   for varying salt deposits under a slow wetting condition.

2) Same as in (1), but using a quick wetting rate.

3) Same as in (1), but using light Bentonite deposits.

4) Same as in (1), but using light Bentonite deposits
   and a quick wetting rate.

5) Same as in (1), but using heavy Bentonite deposits.

The performance graphs for the above five cases are shown in Figures 3.4-3.8. On careful examination it is seen that the performance characteristics represented by the graphs in Figures 3.4, 3.5 and 3.6 which correspond to the first three cases considered, are identical.
FIGURE 3.4: FLASHOVER/WITHSTAND VOLTAGE VERSUS SALT DEPOSIT DENSITY
FOR INSULATORS POLLUTED WITH BENTONITE/NaCl SLURRY. (HORIZONTAL CONFIGURATION - SLOW WETTING RATE)

△ - FLASHOVER, MEDIUM BENTONITE DEPOSITS
△ - FLASHOVER, HEAVY BENTONITE DEPOSITS
○ - WITHSTAND, MEDIUM BENTONITE DEPOSITS
● - WITHSTAND, HEAVY BENTONITE DEPOSITS
FIGURE 3.5: FLASHOVER/WITHSTAND VOLTAGE VERSUS SALT DEPOSIT DENSITY FOR INSULATORS POLLUTED WITH BENTONITE/NaCl SLURRY

(HORIZONTAL CONFIGURATION - MEDIUM BENTONITE DEPOSITS - QUICK WETTING RATE)

△ - FLASHOVER
○ - WITHSTAND
FIGURE 3.6: - FLASHOVER/WITHSTAND VOLTAGE VERSUS SALT DEPOSIT DENSITY FOR INSULATORS POLLUTED WITH BENTONITE/NaCl SLURRY (HORIZONTAL CONFIGURATION - LIGHT BENTONITE DEPOSITS - SLOW WETTING RATE)

△ - FLASHOVER
○ - WITHSTAND
FIGURE 3.7: FLASHOVER/WITHSTAND VOLTAGE VERSUS SALT DEPOSIT DENSITY FOR INSULATORS POLLUTED WITH BENTONITE/NaCl SLURRY (HORIZONTAL CONFIGURATION)

- Triangle (△) - Flashover
- Circle (○) - Withstand
This similarity in performance is more apparent in Figure 3.7 in which the flashover and withstand voltages corresponding to all the first three cases have been included. The results in Figure 3.8 show that the performance graph for case 4 is similar to that for the first three cases except in the case when the salt deposit density is greater than .03 mg/cm². The withstand values in this case are 1kV higher. From the above, it can be concluded that the withstand and flashover levels of the polluted insulator are independant of the wetting rate provided the insulator is coated with medium Bentonite deposits.

In the experiments carried out with Bentonite slurry, the Bentonite helped to spread the salt more evenly over the surface. Also the pollution layers were more strongly bonded to the surface of the insulator than in the case when only salt deposits were used. Therefore, there is considerably less scatter in the results. When the insulators are coated with light Bentonite/salt deposits the bonding of the pollution layer to the insulator surface is weaker than when medium Bentonite/salt deposits are used. Therefore it is possible that the "washing off" effect is more pronounced in the former case when a quick wetting rate is used. This is especially true when there is more salt on the surface. This accounts for the slightly increased withstand levels for the higher salt deposit densities. Thus the amount of Bentonite present on the insulator surface corresponding to a light deposit density appears to be the least amount necessary to keep the scatter down. With less Bentonite on the surface a "salt only" condition will be approached.
The withstand and flashover voltage values corresponding to case 5 are included in Figure 3.4. In these tests, the salt deposit density ranged from 0.15 mg/cm² to 0.35 mg/cm² and a slow wetting rate was employed. From Figures 3.4, 3.5 and 3.6 it is seen that under a slow wetting condition the withstand voltages obtained with heavy Bentonite/Sodium Chloride deposits are higher by 1 kv than those obtained with either light or medium Bentonite/Sodium Chloride deposits. Earlier, in this section, it was shown that the withstand voltages are independent of the wetting rate provided the insulator is coated with medium Bentonite/Sodium Chloride deposits. As the bonding of the pollution layer to the insulator surface was strongest in the case of heavy Bentonite/Sodium Chloride deposits, it is possible that the results, in this case too, will be independent of the wetting rate. It can therefore be concluded that the flashover voltage level of the insulator increases as the amount of Bentonite (inert contaminant) on the surface is increased. Therefore the performance of the insulator is not independent of the amount of inert contaminant on the surface.

With heavy Bentonite/Sodium Chloride deposits, unlike in the case of either the light or medium Bentonite/Sodium Chloride deposits, there was a notable absence of scintillation prior to flashover. Also in the tests which resulted in a withstand, the dry bands were longer.

With such heavy Bentonite deposits, not only does the pollution layer become more uniform but also the thickness of the layer is appreciable. Furthermore, Bentonite hardens on drying. Therefore, in this case, diffusion of water into the layer is slower. Consequently the time taken for the entire layer to wet is much longer than when the pollution layer consists of either light or medium amounts of Bentonite.
With heavy Bentonite layers, the edges of the dry band are not as jagged as with light and medium Bentonite layers. Consequently the electric stresses at the dry-wet band interface are lower which is demonstrated by the absence of discharges. Furthermore, as the pollution layer is more uniform the dry bands grow to longer lengths. With time, the wet part becomes wetter but meanwhile the dry band has also lengthened making flashover difficult. This situation prevails at voltages equal to or below the withstand values. At higher voltages, the electric stress at the interface edges can reach a sufficient value to cause discharges. In the initial stages, the magnitude of these discharges will be limited by the high resistance of the wet land, which is due to the slow rate of diffusion of water into the layer. However, flashover may develop suddenly, provided a continuous path of suitable resistance exists between the interface and the electrode. Owing to the hardness of the layer, not all the layer is wet and therefore not all the salt is conducting; the flashover voltages are therefore higher. With heavy Bentonite layers, pollution conditions are more accurately reproduced and therefore the results are less scattered.

3.5.3: Effect of changing the conducting contaminant

Tests were carried out with Calcium Sulphate used as the conducting contaminant and with medium levels of Bentonite deposits. The slow rate of wetting was employed in these experiments. The withstand and flashover voltages for this condition are indicated in Figure 3.9. The withstand voltage values are higher than those obtained for identical deposit densities of Sodium Chloride. This difference is greater at the higher deposit densities. The high withstand values (Figure 3.9) may be attributed to the lower solubility of Calcium Sulphate (0.241)
FIGURE 3.9: EFFECT OF SOLUBILITY

(HORIZONTAL CONFIGURATION - SLOW WETTING RATE - MEDIUM BENTONITE DEPOSITS)

- Δ - FLASHOVER CaSO₄/BENTONITE SLURRY
- ○ - WITHSTAND CaSO₄/BENTONITE SLURRY
- ▲ - FLASHOVER Na₂CO₃/BENTONITE SLURRY
- ■ - WITHSTAND Na₂CO₃/BENTONITE SLURRY
than that of Sodium Chloride (35.7). As a result the amount of fog water deposited on the insulator surface is not sufficient to dissolve all the Calcium Sulphate present in the pollution layer. Therefore the effective resistance of the pollution layer between the electrodes is higher than that in the case of identical deposits of Sodium Chloride. The withstand and flashover voltage levels are therefore higher. Also, in the case of insulators coated with Calcium Sulphate slurry it took a longer time for the leakage current to attain its maximum value. This effect is also due to the lower solubility of Calcium Sulphate as compared to that of Sodium Chloride.

A third salt, Sodium Carbonate (Baking Soda) was also tested using medium levels of Bentonite deposits. The withstand and flashover voltages for this case are included in Figure 3.9. It is seen that these values fall between the corresponding values obtained for Calcium Sulphate and Sodium Chloride slurries as the solubility of the salt also lies between that of Sodium Chloride and Calcium Sulphate.

3.6: Tests Carried Out on Insulators Sprayed With Bentonite/Sodium Chloride Slurries; Arranged in the Inclined and Vertical Configurations.

The insulators were coated with medium Bentonite deposits and the experiments were carried out using a slow wetting rate. The insulator was suspended from the High Voltage Bus Bar and then rotated to give the desired configuration. There are, therefore, two positions, 180° apart, for both the vertical and the inclined configurations. These will be referred to as position 1 and position 2 respectively. In position 1, the grounded cathode is situated above the anode. Essentially, the manner in which the insulator wets will differ with
configuration and therefore different results may be expected. The various cases studied are listed below.

1. insulator in the inclined configuration and in position 1, the angle of inclination being 45° to the vertical.

2. same as (1), but in position 2.

3. insulator in the vertical configuration and in position 1.

4. same as in (3), but in position 2.

The performance graphs for the above four cases are shown in Figures 3.10 - 3.13. Curves representing the maximum withstand voltages were derived from these graphs and are included in Figure 3.14. It is easily seen that the performance differs for the insulator in the various configurations and positions.

Comparison of Figures 3.14 and 3.4-3.7 shows that there is little difference in the performance of the model insulator in the inclined and the horizontal configurations. However, there is a substantial difference in the performance of the insulator in the vertical and the inclined configurations. Examination of Figure 3.14 also shows that the insulator performs better in position 1 than in position 2 especially at the lower levels of the salt deposit density, (i.e. < 0.1 mg/cm²).

This difference is more noticeable in the case of the vertical rather than in the inclined configuration and increases with increasing voltage in the case of the vertical configuration. In the case of the inclined configuration the difference is insignificant. This may be explained as follows.

The disposition of the insulator in the vertical configuration, and in position 1, is shown in Figure 3.15. In this position the grounded cathode end of the insulator is sheltered from direct moisture
FIGURE 3.10: - FLASHOVER/WITHSTAND VOLTAGE VERSUS SALT DEPOSIT DENSITY

(INCLINED CONFIGURATION - POSITION 1 - SLOW WETTING RATE - MEDIUM BENTONITE DEPOSITS)

△ - FLASHOVER
○ - WITHSTAND
FIGURE 3.11: FLASHER/WITHSTAND VOLTAGE VERSUS SALT DEPOSIT DENSITY

(INCLINED CONFIGURATION - POSITION 2 - SLOW WETTING RATE - MEDIUM BENTONITE DEPOSITS)

△ - FLASHOVER
○ - WITHSTAND
FIGURE 3.12: - FLASHOVER/WITHSTAND VOLTAGE VERSUS SALT DEPOSIT DENSITY

(VERTICAL CONFIGURATION - POSITION 1 - SLOW WETTING RATE - MEDIUM BENTONITE DEPOSITS)

△ - FLASHOVER
○ - WITHSTAND
FIGURE 3.13: - FLASHOVER/WITHSTAND VOLTAGES VERSUS SALT DEPOSIT DENSITY

(VERTICAL CONFIGURATION - POSITION 2 - SLOW WETTING RATE - MEDIUM BENTONITE DEPOSITS)

Δ - FLASHOVER
○ - WITHSTAND
FIGURE 3.14: EFFECT OF INSULATOR CONFIGURATION
(SLOW WETTING RATE - MEDIUM BENTONITE DEPOSITS)

- - - - - - VERTICAL CONFIGURATION, POSITION 1
- - - - - - VERTICAL CONFIGURATION, POSITION 2
- - - - - - INCLINED CONFIGURATION, POSITION 1
- - - - - - INCLINED CONFIGURATION, POSITION 2
FIGURE 3.15: - DISPOSITION OF INSULATOR IN THE VERTICAL CONFIGURATION AND IN POSITION 1
deposition due to fog by the electrode at that end. However this is not true for the positive end of the insulator. When the insulator is in position 2, direct wetting takes place at the grounded cathode end of the insulator. Therefore, in almost all the tests carried out, dry bands formed next to the positive electrode in position 2 and next to the grounded electrode when the insulator was in position 1. Actually dry bands will form in the region of the highest current density. In the present case reasonably uniform pollution layers were employed and the dry bands always formed next to an electrode.

In position 1, therefore, the arc struck across the dry band has a positive polarity for its root on the insulator surface. Conversely, the arc root in position 2 is the cathode. The difference in the performance of the polluted insulator in the vertical configuration and in positions 1 and 2 may therefore be due to a polarity effect. It is unlikely that thermal forces are responsible for the difference in performance as in both cases the arc root has to move vertically downward to complete flashover. An explanation of the polarity effect has been proposed in a recent publication \(^{30}\).

As stated earlier, there is very little difference in the performance of the insulator in the inclined configuration for positions 1 and 2. First, wetting due to direct moisture deposition by fog is more pronounced on an inclined surface than on a vertical surface. As a result, the flashover voltages are lower in the former case for identical values of the salt deposit density. Therefore, in the inclined configuration, polarity effects should be observed at comparatively lower values of the salt deposit density. Secondly, in the case of the inclined configuration the sheltering effect by the top electrode is not
as effective as in the case of the vertical configuration. Therefore, dry bands were observed next to the positive as well as the grounded electrode with almost equal frequency in both positions 1 and 2. The polarity effect therefore tends to get evened out. Therefore there is no significant difference in the performance of the insulator in the inclined configuration and in positions 1 and 2.

There is no reason why polarity effects should not occur with the insulator in the horizontal configuration. In the present study, however, dry bands always occurred next to the anode. Examination of Table 2.1 (page 17) reveals that the wetting is slightly more prominent towards the Right Hand side of the Fog Chamber. This is true even in the initial stages when the fog is building up. However, differences in the fog density could not be noted visually. Because of this preferential fog settlement, the grounded cathode end was always wetted more than the anode end. As a result dry bands always occurred next to the positive electrode. Should wetting be uniform then dry bands can occur with equal probability next to either electrode.

3.7: General Remarks

When the voltage was applied to a polluted and dried insulator, the resulting current depended upon the moisture content on the insulator surface and in general was fairly low (< 1 μA). On admitting the fog, the current increased to a maximum value (0.4-0.5 mA) which remained approximately the same in all tests irrespective of the applied voltage, contamination density or its type. This is indicated in Figure 3.16 which shows a typical leakage current recordogram. It is possible that such a level of leakage current was required to initiate the formation of a dry band; equilibrium conditions are now
FIGURE 3.16: LEAKAGE CURRENT RECORDOGRAM

(LIGHT BENTONITE DEPOSITS - SLOW WETTING RATE)
established between the rate of deposition of moisture due to fog and the rate of loss of moisture due to evaporation caused by the heating effect of the leakage current. This condition is related to the fog characteristics and the geometry of the insulator under test. Thus, there exists an equivalent resistance (volts applied ÷ maximum leakage current) in each test. This is only an apparent value of resistivity and does not reflect the total amount of conducting deposit on the insulator.

Visually, in the presence of fog it was difficult to observe dry band formation. However, weak scintillation, at first bluish white in colour and bridging the dry band in its initial stages of growth could be noted. As the resistance of the wet band decreased, the arc assumed its familiar colour. In the case of insulators polluted with Calcium Sulphate or Sodium Carbonate slurries as well as insulators lightly contaminated with Sodium Chloride slurry, the arc always remained bluish white in colour.

In the horizontal configuration, with the exception of heavily Bentonite coated insulators, the arc after extending to about one inch in length tended to revolve around the insulator. In some cases there were many attempted flashovers with some arcs nearly spanning the electrodes. If the applied voltage corresponded to the withstand voltage, then scintillation usually died out in about 15 minutes. Sporadic arcing followed but none serious enough to cause flashover. Pulse activity was usually pronounced.

In the case of the remaining two configurations, there was a lesser tendency for the arc to revolve around the insulator. Times to flashover, remained approximately the same. A notable difference was that
there were fewer pulses. Also, it was possible for the U.V. Recorder to resolve the pulses.

In all the configurations arcs of lengths varying from 1/2" to 3" were noticed. This seems to indicate the absence of any critical length as proposed by Alston $^{14}$. This is understandable as the criteria developed by Alston is applicable only to the case when the pollution layer is uniform.

As mentioned in section 3.3, the number of pulse counts were monitored in all the tests. Examination of the recorded current pulses showed no evidence of any relationship between the number of pulse counts and insulator performance.

Examination of the leakage current recordings revealed another interesting aspect. There was little change in the magnitude of the leakage current even after the formation of a dry band. For example, the leakage current decreased to a value not less than about half of its maximum value even in the tests which resulted in a withstand and when the dry band had extended to half of the length of the insulator.

After a withstand test, the dry band could be seen readily. Most dry bands were between 1 to 2 inches in length except in the case of insulators coated with heavy Bentonite deposits; in this case, the dry bands were longer. Usually the dry bands preceding flashover were very short and sometimes difficult to observe. When flashover occurred within 3-4 minutes of commencement of the experiment, a continuous moist path could be seen nearly bridging the electrodes. When times to flashover approached 7-8 minutes then the dry bands were longer and up to about an inch in length. The time to flashover depended on the magnitude of the applied voltage. If the applied
voltage was much higher than the flashover voltage value for the parti-
cular test condition then flashover took place within 3 minutes of
commencement of the test. As the applied voltage approached the with-
stand voltage value then the times to flashover increased.

Even after the conclusion of a test resulting in a withstand, the
deposits were sticky and adhered well to the surface of the insulator.
This effect was very pronounced in the case of insulators contaminated
with Calcium Sulphate/Bentonite slurry.

In all the cases studied, the flashover voltage decreased with
increasing the salt deposit density and reached a minimum value.
This minimum value is represented by the flat portion of the performance
graphs and curves shown in Figures 3.4 - 3.14. The initial decrease may
be attributed to the gradual increase in voltage across the dry band as
the conductivity of the wet portion increases with increasing the salt
deposit density. It is likely that beyond the minimum value, most of
the applied voltage is supported by the dry band. Any further increase
in the salt deposit density does not lead to a correspondingly greater
increase in the voltage across the dry band. A more detailed explana-
tion of this aspect appears in the next chapter.

3.8: Summary

In this chapter the results of about 500 tests have been presented
to illustrate the effect of the various parameters considered. It is
shown that the presence of an inert contaminant such as Bentonite is
essential if scatter is to remain low. Further, the measured flashover
and withstand voltages are independent of the wetting rate except in
the case of insulators coated with either only salt deposits or light
Bentonite/NaCl deposits. In the latter case the withstand level of the
insulator is increased at the higher salt deposit density when a quick rate of wetting is employed. The withstand level of the insulator increases as the amount of Bentonite (inert contaminant) on the insulator surface is increased. Also it is shown that the withstand levels depend upon the solubility of the conducting contaminant.

The configuration of the insulator has an appreciable effect on its performance even in the case of the simple model insulator considered.
CHAPTER IV

THEORETICAL MODELLING OF THE GROWTH OF DRY BANDS

4.1: Introduction

It was pointed out in the introductory chapter that very few papers in the literature have dealt with the theoretical aspects of the insulator contamination problem. This is particularly true in the case of the mathematical modelling of the formation of dry bands. McElroy\textsuperscript{31} has proposed a mathematical model which predicts leakage currents as well as the distribution of water density on the insulator surface. His model is based on the following equation for the conservation of mass of water on the insulator surface.

\[
\text{Time rate of increase of surface density of water within infinitesimal control surface} = \text{Deposition rate of water by fog onto the control surface} + \text{Permeation rate of water into the control surface} - \text{Evaporation rate of water out of the control surface}
\]

In his study, McElroy applied the analytical techniques to a circular flat plate model insulator fitted with concentric circular electrodes. He concluded that while prediction of the leakage current was satisfactorily achieved, the estimated water density on the surface of the insulator was not as good as desired.

More recently, Loberg and Salthouse\textsuperscript{25} carried out experiments on a flat plate model insulator of rectangular geometry and obtained experimental data for the various dry band characteristics such as temperature and surface resistivity distribution along the dry band,
variation in dry band width with applied voltage and power dissipation in the dry band for various lengths of the dry band. A mathematical analysis was also carried out by these authors to arrive at the temperature distribution along the length of the polluted model insulator. This analysis indicated that while the initial temperature distribution along the polluted insulator surface is determined by conduction, the temperature distribution at a later time is determined by convection.

In the present work, a heat transfer model is proposed which describes analytically, the growth of dry bands on polluted insulators as well as the temperatures at points in the dry band as the dry band extends along the insulator surface. Sample solutions have been worked out for the case of the model insulator used in the tests described in Chapter III. In order to facilitate the calculations, certain assumptions have been introduced. These assumptions are based on the experimental observations presented in the previous Chapter.

4.2: Experimental observations

Before proceeding with a description of the mathematical model, certain experimental observations made in Chapter III will be discussed. As described in the preceding chapter, when the polluted insulator was subjected to fog conditions, the leakage current increased to a maximum value after which equilibrium conditions were established between the rate of moisture deposition due to fog and the rate of loss of moisture from the surface because of evaporation due to the heating effect of the leakage current. Further it was mentioned that even for the cases where the dry band had elongated to about half the length of the insulator the leakage current dropped to approximately only half its maximum value. This suggested that the dry bands were not completely
dry so as to terminate conduction. In order to verify this the following simple experiments were carried out.

First the model insulator consisting of a glazed porcelain cylinder 4" long and 1" diameter was polluted with Sodium Chloride/Bentonite slurry. The deposit densities of the Sodium Chloride and the Bentonite were 0.15 mg/cm² and 0.1 mg/cm² respectively. The dry insulator was then mounted inside the test chamber in the horizontal configuration. Direct High Voltage was applied to it and then the fog was turned on. The magnitude of the applied voltage (5.5kV) was below the flashover voltage value determined previously for this particular pollution condition. After a short time the leakage current increased to a maximum value of about 0.4 ma. Twenty minutes after commencement of the experiment, the applied voltage was decreased step by step in steps of 0.5kV with the fog still on. The leakage current was monitored continuously; its value remained practically constant until the voltage was brought down to 4kV. At this point, the leakage current dropped to about 0.32 ma and it remained at this value until the voltage was brought down to 500 volts. Further reduction in the applied voltage was accompanied by a rapid decrease in the leakage current. The test was then terminated and another identically polluted insulator was mounted inside the test chamber. The procedure described above was repeated but on this occasion, twenty minutes after commencement of the experiment the fog was shut off and the fog chamber door opened with the voltage still applied to the insulator. In a short time, the fog in the chamber dispersed and the leakage current dropped to a very low value. These experiments showed that conduction is practically absent in the presence of a true dry band. Dry bands which occur in practise
are not completely dry but dry relative to the wet portion of the insulator.

4.3: Outline of Theoretical Model

4.3.1: General equations

After the formation of a dry band, the surface of the insulator can be divided into 3 parts — the dry band, the wet region and the dry/wet interface. It is assumed that the dry band forms next to one electrode and further that the length of the dry band as measured from this electrode is the same at all points on the insulator surface. Heat equations will now be written for each of the three parts into which the insulator was divided. Owing to the symmetry of the cylindrical model insulator the heat equations reduce to one dimension. In the interior of the dry band the one dimensional heat equation including power generation and heat loss due to convection is given by

\[ K \frac{\partial^2 t}{\partial x^2} \omega dx + P \omega dx = \omega dx \alpha \frac{\partial t}{\partial T} + \frac{h}{\pi} \frac{R}{d} \frac{dt}{dx} \]

which reduces to

\[ \frac{\partial t}{\partial T} = \alpha_d \left[ \frac{\partial^2 t}{\partial x^2} + \frac{P_D}{K_D} - \frac{h_D t}{K_D s_D} \right] \quad (1) \]

A similar equation can be written for the wet region as

\[ \frac{\partial t}{\partial T} = \alpha_w \left[ \frac{\partial^2 t}{\partial x^2} + \frac{P_W}{K_W} - \frac{h_W t}{K_W s_W} \right] \quad (2) \]

where

\[ t = \text{temperature} \quad (^\circ \text{C}) \]
\[ T = \text{time} \quad (\text{sec}) \]
\[ \alpha = \text{thermal diffusivity} \quad (\text{cm}^2 \text{sec}^{-1}) \]
\[ P = \text{Power dissipation per unit volume} \quad (\text{cal cm}^{-3} \text{sec}^{-1}) \]
\[ \omega = \text{relates to distance} \quad (\text{cm}) \]
\[ K = \text{Thermal conductivity \ (cal cm}^{-1} \text{C}^{-1} \text{sec}^{-1}) \]

\[ h = \text{Convection coefficient of heat transfer \ (cal cm}^{-2} \text{sec}^{-1} \text{C}^{-1}) \]

\[ \delta = \text{Pollution layer thickness (cm)} \]

\[ \sigma = \text{Specific heat \ (cal gm}^{-1}) \]

\[ \omega = \text{Pollution layer cross sectional area \ (cm}^{2}) \]

\[ \sigma = \text{density of layer \ (gm cm}^{-3}) \]

\[ R = \text{radius of model insulator (cm)} \]

and subscripts \( D \) and \( W \) refer to the dry band and the wet region respectively.

Equations (1) and (2) are coupled at the interface of the dry and wet regions by a coupling equation. The dry/wet interface is in motion as the dry band extends along the insulator surface. Let \( \eta(T) \) be the location of the dry/wet interface at any time. \( \eta(T) \) is measured from \( x = 0 \) at the electrode adjacent to the dry band. One boundary condition is that

\[ t_D = t_W \quad \text{at} \quad x = \eta(T) \quad \text{(3)} \]

Another boundary condition may be written by consideration of the following energy balance equation at the interface

\[
\begin{bmatrix}
\text{net energy supplied to the interface per unit time in the direction of the cooled face}
\end{bmatrix} = \begin{bmatrix}
\text{energy absorbed at the interface per unit time as a result of absorption of latent heat during evaporation}
\end{bmatrix}
\]

\[ (4) \]

The right hand side of equation (4) is given by \( \mu L \omega \frac{dn}{dt} \)

where \( \mu = \text{density of water \ (gm cm}^{-3}) \)

\[ L = \text{Latent heat of vaporization \ (cal gm}^{-1}) \]

and \( \omega \) and \( n \) have been defined earlier.
The left hand side of equation (4) is given by

\[ \omega \left[ \frac{\partial t_w}{\partial x} - \frac{\partial t_D}{\partial x} \right] \]

Equation (4) is therefore expressed mathematically as

\[ \omega \left[ \frac{\partial t_w}{\partial x} - \frac{\partial t_D}{\partial x} \right] = \mu \omega \frac{dn}{dt} \]

(5)

In equation (5) \( \mu = 1 \) as water is the substance that is being evaporated. Also \( t_D = t_w \) from (3). A factor \( C \) may now be introduced which expresses the degree of wetness of the layer. For example if \( C = 0.5 \) then the amount of water present in the pollution layer at the interface occupies only half the available layer cross sectional area. The factor \( C \) takes into account the characteristics of the pollution layer such as thickness, hardness of the layer and solubility of the conducting contaminant. The wetness of the layer is a function of time. Initially, the layer is only slightly wet. As time progresses the degree of wetness increases. \( C \) is therefore a function of time and may be written as

\[ C = C_1(T) \]

(6)

Substituting (3) in (5), putting \( \mu = 1 \) and introducing the factor \( C \) we obtain,

\[ \left[ \frac{K_w}{\partial x} - \frac{K_D}{\partial x} \right] = L \left\{ C_1(T) \right\} \frac{dn}{dt} \]

(7)

In order to obtain the desired solutions a method involving a travelling space network was employed. In this method the dry band is divided into \( r \) equal intervals which increase in size as the dry band elongates. Similarly, the wet region is divided into \((N-r)\) equal intervals which decrease in size as the dry band elongates. This division of the length of the insulator into intervals is shown in
Figure 4.1. At any internal node we may write

$$\frac{dt}{dT} = \frac{\delta t}{\delta x} \frac{dx}{dT} + \frac{\delta t}{\delta T}$$

(8)

In addition, we have the following equation relating the velocities of the internal nodes in the dry band with that of the interface.

$$\frac{dx/dT}{x} = \frac{dn/dT}{\eta}$$

(9)

On combining equations (1), (8) and (9) we obtain

$$\frac{dt_n}{dT} = \frac{x_n}{\eta} \frac{\delta t_n}{\delta x} \frac{dn}{dT} + \alpha_D \left[ \frac{\partial^2 t_n}{\partial x^2} + \frac{P_D}{K_D} - \frac{h_D}{K_D \delta_D} \right]$$

(10)

Equation (10) is valid at interior points in the dry band where \( n = 1, 2, \ldots, (r-1) \).

In order to obtain a similar equation for the wet region, equation (9) will have to be modified to relate the velocities of the internal nodes in the wet region with that of the interface. This is possible by replacing \( x \) and \( \eta \) in equation (9) by \((E-x)\) and \((E-\eta)\) respectively.

On doing so, equation (9) becomes

$$\frac{dx/dT}{(E-x)} = \frac{dn/dT}{(E-\eta)}$$

(11)

where \( E = \) length of the model insulator (cm).

On combining equations (2), (8) and (11) we obtain

$$\frac{dt_n}{dT} = \left( \frac{E-x_n}{E-\eta} \right) \left( \frac{\partial t_n}{\partial x} \right) \frac{dn}{dT} + \alpha_W \left[ \frac{\partial^2 t_n}{\partial x^2} + \frac{P_W}{K_W} - \frac{h_W}{K_W \delta_W} \right]$$

(12)

Equation (12) is valid at interior points in the wet region where \( n = (r+1), \ldots, (N-1) \). At the interface \((n=r)\) equations (10) and (12) are coupled by equation (7). These three equations along with suitable boundary conditions are sufficient to solve for temperatures
FIGURE 4.1: - DIVISION OF THE LENGTH OF THE INSULATOR INTO N INTERVALS

FIGURE 4.2: - DISTRIBUTION OF RESISTIVITY ALONG THE LENGTH OF THE INSULATOR

FIGURE 4.3: - RESISTIVITY LUMPED AT NODES IN THE DRY BAND
at the nodal points and the rate of growth of the dry band provided \( P_D \) and \( P_W \) are known, i.e., the power dissipated in the dry and wet regions per unit volume.

### 4.3.2 Evaluation of the Power Dissipated in the Dry Band

As mentioned earlier, when a polluted and dried insulator is subjected to fog conditions and voltage applied to it, the leakage current increases to a maximum value in all cases. If \( i_{eq} \) represents this value then we may write

\[
R_{eq} = \frac{V}{i_{eq}}
\]

(13)

where \( V \) is the applied voltage. Further a resistivity \( \rho \) can be associated with \( R_{eq} \) so that

\[
R_{eq} = \frac{\rho E}{\omega}
\]

(14)

where \( \omega \) is the cross-sectional area of the pollution layer and is given to a first approximation by

\[
\omega = 2\pi R_0
\]

(14a)

When the leakage current reaches its maximum value \( (i_{eq}) \) an equilibrium condition is established between the rate of moisture deposition due to fog and the rate of moisture evaporation due to the heating effect of the leakage current. This leads to the formation of a dry band. At this early stage, diffusion of moisture into the dry band is insignificant as the moisture content of the polluted layer is very low. In the early stages of its formation, the dry band is confined to a very small area on the insulator surface where the current density is highest and is actually a "dry patch". The temperature of this dry patch suddenly increases over that of the remainder of the insulator surface. As a result, the dry patch extends itself laterally around the circumference.
of the insulator because of lateral drying and a dry band is formed. In the present analysis it is assumed that the dry band forms next to one electrode. This is essentially the case if the pollution layer is reasonably uniform; when the current density is highest next to an electrode. Once a dry band has formed, it then extends itself along the insulator surface due to further heating inside the dry band. As the dry band elongates, its temperature increases. However, the temperature cannot increase indefinitely. If this happens, then the resistance of the dry band increases. The leakage current will then eventually decrease to a value less than that required to maintain equilibrium in this condition. As the equilibrium state is upset, wetting is enhanced and the resistance of the dry band decreases. The leakage current then increases and the cycle repeats itself. Thus, the temperature of the dry band cannot increase without limit. Furthermore the temperature cannot be identical throughout the length of the dry band. This is because there will be no appreciable change in the temperature of the electrode end of the dry band, in spite of heat production inside the dry band. This is due to the high thermal capacity of the metallic electrode. It can, therefore, be assumed that the end of the dry band terminating in an electrode remains at ambient temperature for all time. Furthermore, because of the temperature increase in the dry band the wetting rate changes due to the establishment of convection currents. This results in lesser moisture deposition on the dry band. On the contrary, the remainder of the insulator surface wets as usual. This portion therefore gets progressively wetter resulting in the establishment of a wet region. It can, therefore, be assumed that the temperature of the wet region and therefore that of the interface is
always at ambient temperature. At the interface there is diffusion of moisture (except at the early stages) into the dry band. It, therefore, appears that the maximum temperature in the dry band occurs somewhere in between its extremities. Furthermore there could be differences in the wetting rate over the length of the dry band because of the existence of a temperature gradient. Therefore the moisture content of the dry band varies -- being more at its ends than in the middle. The resistivity $\rho_D$ of the dry band, being a function of the moisture content in the pollution layer, therefore varies over the length of the dry band, being greater in the middle portion of the dry band than at the ends.

As far as the wet region is concerned, its resistivity will decrease with time as wetting progresses. At a later stage the resistivity increases due to the washing off of deposits from the surface. In order to simplify the procedure, the resistivity of the wet region was assumed to be constant and equal to $\rho$ for all time. Furthermore, it was assumed that the power dissipation in the wet region is insignificant. These two assumptions are essentially incompatible. It is necessary to take into account the variation of resistivity of the wet region if the power dissipation in this region is to be neglected. The time variation of resistivity of the wet region will vary with geometry and configuration. Therefore this relationship has to be obtained experimentally. However, this was not done in order to retain simplicity in the theoretical model.

The distribution of resistivity in the dry band was then assumed to be triangular with the values of resistivity at $x = 0$ and $x = \eta$ being $\rho$ for all time. This distribution is shown in Figure 4.2. At the middle of the dry band the resistivity peaks at a value $A\rho$ where $A$ is a numerical factor. In actual practise, the distribution of
resistivity in the dry band will be more complex. Also the curve representing this variation may be asymmetrical because changes in the resistivity in the wet region at \( x = \eta \) may not be identical with that at \( x = 0 \). The total resistance \( R_T \) between the electrodes is then given by
\[
R_T = \frac{\rho (E-\eta)}{\omega} + \frac{\nu \eta (A+1)}{2\omega}
\] (15)

In order to be able to calculate \( R_T \), \( A \) has to be known. Actually \( A \) varies with time. Initially at \( t=0 \), when \( i = i_{eq} \), \( A \) must be =1 as the resistivity of the dry band is \( \rho \). As time progresses, "A" increases. However "A" cannot increase indefinitely for reasons explained earlier. To simplify the calculations, "A" was assumed to remain constant and an average value was assigned to it. When the dry band has covered half the length of the insulator \( \eta = E/2 \). When \( \eta = E/2 \), then \( A \) should be equal to 5 so that the leakage current given by \( V/R_T \) is half of the value at \( t = 0 \). The choice of \( A = 5 \) is consistent with the experimental observation that the leakage current dropped to approximately only half its maximum value although the dry band covered half the length of the insulator. The initial value of \( A \) being \( A=1 \), an average value for \( A \) is given by \( A=3 \).

The resistivity of the dry band is now assumed to be lumped at the nodal points as shown in Figure 4.3. A general expression for the nodal resistance may then be written as
\[
R_n = \left[ \rho + \left( \frac{2(A-1) \eta n}{r} \right) \right] \frac{n}{r \omega}
\] (16)

\( n = 1, 2, \ldots, r/2 \).

The value of \( R_n \) at \( n = (r/2 + 1) - (r-1) \), can then be assigned by consideration of symmetry.
The leakage current is given by

\[ I = \frac{V}{R_T} = \frac{V}{\frac{\rho (E-\eta)}{\omega} + \frac{\rho n (A+1)}{2\omega}} \]  \hspace{1cm} (17)

Also the volume of the nodal lumped element is given to a first approximation by

\[ \frac{n}{r} \omega \text{ cm}^3 \]  \hspace{1cm} (18)

Therefore the heat generated per unit volume at the nodal lumped elements is given by

\[ \frac{v^2}{\left[ \frac{\rho (E-\eta)}{\omega} + \frac{\rho n (A+1)}{2\omega} \right]^2} \left[ \frac{\rho + \frac{2(A-1)\rho n}{r}}{r} \right] \frac{n}{rw} \]  \hspace{1cm} n = 1, 2, \ldots, r/2. \hspace{1cm} (19)

The heat generated per unit volume at the nodes in the dry band can be found from considerations of symmetry.

But \[ \rho = \frac{R_{eq}}{E} \] from \hspace{1cm} (14)

and \[ R_{eq} = \frac{V}{i_{eq}} \] from \hspace{1cm} (18)

therefore \[ \rho = \frac{V_{eq}}{E} \frac{1}{i_{eq}} \]  \hspace{1cm} \hspace{1cm} (20)

For the cylindrical model insulator of 1" diameter and 4" length (= 10 cm), the cross sectional area \( \omega \) of the pollution layer is given to a first approximation by

\[ \omega = 2\pi (R) \delta_D = 2.54 \pi \delta_D \]  \hspace{1cm} (21)

If \( V \) is expressed in volts and \( i_{eq} \) in milliamps, then

\[ \rho = \frac{V \cdot 2.54 \pi \delta_D}{10 \cdot i_{eq}} \cdot 10^3 \]
Therefore $\rho = \frac{798 V \delta_D}{i_{eq}} \quad (22)

Substituting (22) in (19) we obtain for the heat generated per unit volume at the nodal lumped elements as

$$P_D = \left( \frac{V^2}{\left( \frac{E-n}{\omega} + \frac{n(A+1)}{2\omega} \right)^2} \right) \left( \frac{i_{eq}}{798 V \delta_D} \right) \left( \frac{1 + \frac{2(A-1)n}{r}}{\omega^2} \right)$$

for $n = 1, 2, \ldots, r/2$.

which reduces to

$$\frac{4V i_{eq}}{[2E + n(A-1)]^2} \quad \frac{1 + \frac{2(A-1)n}{r}}{798 \delta_D} \quad \text{watts/cm}^3$$

which is the same as

$$P_D = \frac{V \ i_{eq}}{838 \ \delta_D} \ \frac{1 + \frac{2(A-1)n}{r}}{[2E + n(A-1)]^2} \ \text{cal cm}^{-3} \ \text{sec}^{-1}$$

for $n = 1, 2, \ldots, r/2$. \quad (23)

The heat generated per unit volume at the other nodes in the dry band can be found from considerations of symmetry.

Substituting (23) into (10) we obtain

$$\frac{dt_n}{dT} = \frac{x_n \ \delta t_n}{n \ \delta x} \ \frac{dn}{dT} + \alpha_D \left\{ \frac{\beta^2 t_n}{\delta x^2} + \frac{V \ i_{eq}}{838 \ \delta_D K_D} \ \frac{r + 2(A-1)n}{[2E + n(A-1)]^2} \right\}$$

$$- \frac{h_D t_n}{K_D \ \delta_D}$$

for $n = 1, 2, \ldots, r/2$. \quad (24)
Also if \( C_1(T) \) is to be varied in discrete steps, then (7) may be re-written as

\[
\left[ K_D \frac{\partial t}{\partial x} - K_D \frac{\partial t}{\partial x} \right] = \frac{LC}{\Delta T} \frac{dn}{dT}
\]

(25)

The temperature of the wet region has been assumed to be equal to ambient temperature for all time. By choosing the ambient temperature as the reference (25) may be simplified to

\[
- \frac{K_D}{LC} \frac{\partial t}{\partial x} = \frac{dn}{dT}
\]

(26)

To be able to solve the problem digitally, equations (24) and (26) have to be transformed into difference equations. Details regarding the derivation of the difference equations have been included in Appendix A4.1. Using a three point approximation, the following difference equations are obtained

\[
\frac{(t_{n+m+1} - t_{n+m})}{\Delta T} = \sum_{n} \left[ \frac{t_{n+1} - t_{n-1}}{2} \right] \frac{dn}{dT} + \frac{a_D}{\eta^2} \left( \frac{t_{n+1} + t_{n-1} - 2t_n}{\eta^2} \right)
\]

(27)

\[
+ \frac{a_D}{838} \frac{V_i_{eq}}{K_D r^2} \left( \frac{1 + \frac{2(A-1)n}{r}}{2E + \eta(A-1)} \right) - \frac{h_D}{K_D} \frac{t_n}{\delta T}
\]

\[
\frac{dn}{dT} = \left[ \frac{t_{n+1} - t_{n}}{\Delta T} \right] = \sum_{n} \left\{ \frac{4t_{n-1} - t_{n-2}}{2\eta} \right\}
\]

(28)

Equations (27) and (28) along with the initial conditions

\[
\begin{align*}
t(0,T) &= t(n,T) = 0 \\
t(n,0) &= 0 \\
&\quad n = 1, 2, \ldots, (r-1)
\end{align*}
\]

(29)

are sufficient to solve for temperatures at points inside the dry band \([t(n,T)]\) as well as the length of the dry band \((\eta)\) at various times.
As a travelling space network is employed, the time variation of temperature at internal points in the dry band will have to be obtained by interpolation.

4.3.3: Sample solutions

Equations (27) and (28) were solved using a digital computer with the following values for the constants and the parameters involved:

\[ V = 10kV, \quad A = 3, \quad \delta_D = 0.0175 \text{ cm}, \quad K_D = 145 \times 10^{-4} \text{ cal/cm}^2\text{C sec} \]
\[ r = 6, \quad \alpha_D = 324 \times 10^{-4} \text{ cm}^2\text{sec}^{-1} \quad L = 584.9 \text{ cal/gm} \]
\[ i_{eq} = 0.4 \text{ ma} \quad E = 10\text{cm} \quad C = 0.1 \]

The value of \( h \), the convection coefficient of heat transfer was chosen from the available literature for horizontal cylinders to be 1 BTU/hr/\text{sq.ft/}^\circ\text{F} and transformed to the proper units before using it in the calculations. The solution was started at \( \eta = 0.5 \text{ cm} \). A starting solution is necessary as otherwise some of the terms become infinite. The values assigned to the constants \( K_D \) and \( \alpha_D \) were chosen from standard tables for Sodium Chloride. In practice, the contaminant on the insulator surface is a mixture of Sodium Chloride and Bentonite. Furthermore the practical values may depend on the thickness of the layer \( \delta_D \) owing to a variation in the continuity between adjacent salt particles in the dry band. The values chosen for the constants may therefore be unrealistic; also many simplifying assumptions have been made so that a solution is possible. It is for this reason that the theoretical and experimental values are not compared. However, the object of this exercise is to demonstrate the effectiveness of the model in arriving at the desired solutions without leading to any physical absurdities. In spite of the possible error in the assigned
values of the constants it is seen that there is very good general agreement between the theoretical solutions and experimental observations.

In all computations, a fixed time step of 0.04 secs was employed. This satisfies the stability criteria \( \frac{a(\Delta T)}{(\Delta x)^2} < \frac{1}{6} \), \( \Delta x = \frac{\eta}{r} \). If the number of intervals is increased or if the starting value of \( \eta \) is decreased then the time interval, as determined from the stability criteria, will become shorter. The time of computation therefore increases. It may then be necessary to use a variable time step. However, as the dry band elongates, the nodal network in the dry band becomes coarser, i.e. \( \Delta x \) increases. Thus the use of a variable time step without setting an upper limit for it will result in overflow.

The choice of the value of \( r \) is a compromise between speed of computation and accuracy. If the solution is to be carried with large values of \( \eta \) which makes the network too coarse then it may be necessary to increase \( r \) after \( \eta \) has exceeded a certain limit. In the present case the solutions were carried out until \( \eta = 2.5 \) cm with \( r = 6 \). According to Murray and Landis the method used yields the same accuracy as a conventional method with twice the number of nodes. (i.e. \( r = 12 \)).

4.4: Discussion of Results

Figures 4.4 and 4.5 show the temperature distribution along the dry band and the growth of the dry band with time for a simulated experiment of 10 minutes duration. Figure 4.5 shows that the rate of growth of the dry band decreases gradually as the dry band length increases. This is due to a decrease in the power dissipation term in equation (27). The effect of changing the value of the wetting
FIGURE 4.4: TEMPERATURE DISTRIBUTION ACROSS THE DRY BAND

- AT 200 SECS AFTER COMMENCEMENT OF EXPERIMENT
- AT 400 SECS AFTER COMMENCEMENT OF EXPERIMENT
- AT 600 SECS AFTER COMMENCEMENT OF EXPERIMENT
FIGURE 4.5: GROWTH OF DRY BAND WITH TIME

- $C = 0.1$
- $C = 0.2$

TIME IN SECONDS

DRY BAND LENGTH (CM)
factor $C$ (from 0.1) to 0.2 at 400 seconds from commencement of the simulated experiment is shown by the dotted line in Figure 4.5. An increase in the value of $C$ represents a wetter layer. The growth of the dry band is therefore slowed down even more than when $C$ is left unchanged.

Examination of Figure 4.4 shows that, initially, the temperatures across the dry band increase as the dry band length increases. After a certain stage the maximum temperature (at $x = \eta/2$) actually decreases. This is due to the increase in the length of the dry band ($\eta$) which decreases the power dissipation term in equation (27). Furthermore as time progresses the shape of the temperature distribution curve changes. There is a tendency for the temperatures to equalize at all the nodes. This can be seen to some extent in Figure 4.4 (and would have been more obvious had the solution been carried out for a longer time). In other words, as the dry band extends, the temperature distribution is determined more and more by convection. In the initial stages the temperature distribution is determined primarily by conduction. This conclusion is similar to the one reached by Loberg and Salthouse in a recent publication. Figure 4.4 also shows a very steep temperature gradient near the interface of the dry and wet regions. This is a consequence of the assumptions made that the variation of resistivity is linear over the length of the dry band and also that there is no power dissipation in the wet band. If a smoother variation of resistivity is assumed, the resulting temperature curve will also be smoother.

Solutions were also obtained for other cases by changing the values of some of the parameters involved. These solutions were carried
out for periods up to 3 minutes only of simulated experiment duration. Since the general shapes of the curves are similar, these results are summarized in Table 4.1. Examination of Table 4.1 shows that an increase in the layer thickness ($\delta_p$) does not produce the same end result as a corresponding decrease in the applied voltage. This is because any change in $\delta$ also affects the convection term. The value of $i_{eq}$ remains unaltered as this is determined solely by equilibrium considerations between loss and deposition of moisture. Increasing the wetting factor "$C" results in a slower rate of growth of the dry band. Temperatures at interior points in the dry band are also higher. Increasing "$A" not only increased the temperatures but also the rate of growth of the dry band.

For a particular pollution condition the rate of growth of the dry band is dependant on the applied voltage and increases as the applied voltage is increased. This is evident upon examination of Figure 4.5 and Table 4.1. From Figure 4.5 the length of the dry band is 1.3 cm at 200 seconds after commencement of the simulated experiment. In this case the applied voltage was 10 k.v. From Table 4.1 the dry band length is only 0.95 cm at 200 secs. after commencement of the simulated experiment when the applied voltage is 5kv and with identical values for the constants and the remaining parameters. From a theoretical standpoint, the dry band will eventually cover the full length of the insulator in both cases. In practice, this is not possible because of the progressive wetting of the wet region. In the initial stages, the factor "$C" increases due to wetting of the layer. This contributes to a decrease in the rate of growth of the dry band. Later, due to washing off of deposits from the surface the resistivity of the wet
<table>
<thead>
<tr>
<th>APPLIED VOLTAGE V (kV)</th>
<th>LAYER THICKNESS $S_D$ (cm)</th>
<th>MAX. LEAKAGE CURRENT $i_{eq}$ (mA)</th>
<th>WETTING FACTOR C</th>
<th>DURATION OF SIMULATED EXPERIMENT (SECS)</th>
<th>DRY BAND LENGTH AFTER 3 MINS. (CM)</th>
<th>FINAL MAX. TEMPERATURE ABOVE AMBIENT ($^\circ$C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>.0175</td>
<td>0.4</td>
<td>0.1</td>
<td>5</td>
<td>200</td>
<td>1.52</td>
</tr>
<tr>
<td>10</td>
<td>.0175</td>
<td>0.4</td>
<td>0.25</td>
<td>3</td>
<td>200</td>
<td>0.856</td>
</tr>
<tr>
<td>10</td>
<td>.035</td>
<td>0.4</td>
<td>0.1</td>
<td>3</td>
<td>200</td>
<td>1.06</td>
</tr>
<tr>
<td>5</td>
<td>.0175</td>
<td>0.4</td>
<td>0.1</td>
<td>3</td>
<td>200</td>
<td>0.95</td>
</tr>
</tbody>
</table>
region increases in the "washed off" areas and pronounced non-uniformities are introduced in the wet region. These factors can stop the growth of the dry band. Essentially, this is what happens in the case of insulators contaminated with either light or medium Bentonite deposits. As pointed out in the previous chapter, the dry bands were between 1" - 2" in length in these cases. In the case of insulators contaminated with heavy Bentonite deposits the rate of increase of the wetting factor "C" is much smaller due to the hardness of the layer. This results in a faster rate of growth of the dry band which can therefore elongate to greater lengths before "washing off" of deposits can occur. Under identical applied voltages and test conditions, the dry bands will therefore be longer in the case of insulators coated with heavy Bentonite deposits than those coated with either light or medium Bentonite deposits.

In all the calculations the power dissipated in the wet band per unit volume (\( P_w \)) has been ignored as a consequence of the assumptions made earlier. Inclusion of \( P_w \) implies non-zero temperatures in the wet region. As a result the temperature gradient at the wet/dry interface will be reduced and the rate of growth of the dry band will decrease. On the other hand the resistivity of the wet region decreases with time. Therefore the assumption that \( \rho_w \) (resistivity of the wet region) is constant and equal to \( \rho \) for all time implies a lower leakage current and therefore lesser power dissipation in the dry band than when the variation of \( \rho_w \) is taken into account. Therefore, it is seen that these two assumptions lead to exactly opposite effects. The assumption \( P_w = 0 \) results in a greater rate of growth of the dry band \( (dn/dT) \) while the assumption of a constant
resistivity of the wet region results in a lesser rate of growth of the dry band.

As mentioned earlier, the rate of increase of wetness of the pollution layer \( \frac{dC}{dT} \) is much lesser in the case of insulators coated with heavy Bentonite deposits. Also \( \frac{|dP_W|}{dT} \), the rate of decrease of resistivity of the wet band is slower. Therefore the leakage current given by \( \frac{V}{R_T} \) and calculated by using \( R_T \) from equation (15) is theoretically more accurate in this case. Because \( |dP_W|/dT \) is small, \( P_W \) the power dissipated in the wet band can not be neglected. A smaller \( dC/dT \) implies a higher rate of growth for the dry band \( \frac{dn}{dT} \) while inclusion of \( P_W \) implies a decreased rate of growth of the dry band. Experimental evidence indicates that the effect of a smaller \( dC/dT \) is predominant. i.e. - the dry bands were longer in the case of insulators coated with heavy Bentonite deposits.

From equations (27) and (28), it can be seen that for identical applied voltages as the amount of salt on the surface of the insulator is increased differences arising in the rate of growth of the dry band will be solely due to the differences in the rate of change of the wetting factor \( C \). The equilibrium current \( i_{eq} \) remains the same irrespective of the amount of salt on the insulator surface.

In Chapter III it was pointed out that in all the cases studied the flashover and withstand values reach a minimum value as the salt content on the insulator surface is increased. This behaviour can be explained with the aid of the theoretical model proposed in this chapter. As mentioned earlier the surface resistivity of the wet region will initially decrease due to progressive wetting. As the resistance of the wet region decreases (i.e. wetness increases) the
voltage supported by the dry band increases. On the other hand as the dry band elongates, the voltage supported by the dry band decreases. Consider the case when voltage is applied to a polluted and dried insulator in the presence of fog. As the amount of salt on the surface of the insulator is increased, \( \frac{dC}{dT} \) increases i.e.; the layer becomes wet more rapidly. Due to this \( \frac{dn}{dT} \) decreases. Furthermore, a higher \( \frac{dC}{dT} \) implies a higher \( \left| \frac{dp_w}{dT} \right| \) i.e.- rate of decrease of resistivity of the wet region is now faster. As there is more salt on the surface the total resistance of the wet region is lower. These factors contribute to a greater voltage being supported per unit length of the dry band. Therefore the breakdown voltage decreases as the salt deposit density is increased. However, a stage is reached when a further increase in the salt deposit density will not result in a corresponding increase in the factor \( \frac{dC}{dT} \). In other words the value of \( \frac{dC}{dT} \) as well as \( \left| \frac{dp_w}{dT} \right| \) stabilize; so does the total resistance of the wet band. Therefore the rate of growth of the dry band as well as the voltage supported per unit length of the dry band reach a minimum value. Thus the flashover values stabilize at a minimum value as the salt deposit density is increased.

Consider the case when the wetting rate is very slow. In such an event, \( \frac{dC}{dT} \) is small. As a result \( \frac{dn}{dT} \) is increased and the dry band can now grow longer, i.e. at the end of a prescribed time the dry band will be longer than that in the case when a faster rate of wetting is employed. With a very slow wetting rate, therefore, the voltage supported per unit length of the dry band is decreased. Also because of a slower \( \frac{dC}{dT} \), \( \left| \frac{dp_w}{dT} \right| \) is slower. These factors will increase the flashover levels — (an effect similar to that observed when heavy Bentonite layers were employed). This statement does not contradict
the findings of Chapter III. It only shows that the wetting rate will have to be much slower than the "slow wetting rate" of Chapter III if increased flashover voltages are to result.

As mentioned earlier, the case considered in the development of the theoretical model is that when the dry band forms next to an electrode. This was usually the case in almost all the experiments described in Chapter III. Also the validity of the model is restricted to the case when the test procedures are similar to the one used in this study. The theory presented in this chapter will have to be modified slightly to suit the case when the dry band forms in the middle. In such a case the dry band elongates in both directions and the origin can be chosen at the centre of the dry band. In the case when the dry bands forms next to one electrode the temperature of that end will rise above ambient if there is poor thermal contact between the electrode and the dry band. A theoretical solution of this case is possible using the present method if the coefficient of thermal contact conductivity is known.

The main limitation of the proposed theoretical model is that the flashover voltages are not predicted. Thus one can obtain solutions for dry band lengths and temperatures even if the applied voltage is unrealistically high.

4.5: Summary

A theoretical model has been described for evaluating the rate of growth of the dry band as well as predicting temperatures at internal points in the dry band. The problem becomes complex if exact solutions are desired even for the case of the simple cylindrical model insulator considered. Sample solutions have been obtained by making approximations
consistent with experimental observations. The solutions obtained are quite realistic in spite of these approximations. Furthermore, the theoretical model has been used to explain certain experimental observations made earlier in Chapter III.
CHAPTER V

THE EFFECT OF GEOMETRY ON THE PERFORMANCE
OF INSULATORS UNDER POLLUTED CONDITIONS

5.1: Introduction

This chapter describes the experiments carried out to investigate the effect of geometry on the performance of insulators (single units) under polluted conditions. Essentially the surface of an insulator is made up of segments vertical, parallel and inclined to its longitudinal axis. In this study, two additional models have been considered. These models together with the one used in the tests described earlier in Chapter III are made up by varying the sizes of surface parallel and vertical to the longitudinal axis of the insulator. In all the three models the leakage length and the electrode diameter are identical. The new models were made of "plexiglass" (Polymethylmethacrylate) because of its ready availability and ease of manufacture. In all the tests the spraying technique and the testing procedure, described earlier in Chapter II, were strictly followed.

5.2: Geometries considered

Figure 5.1 shows all the three geometries considered in the vertical inclined and the horizontal configurations. The insulators are classified as Type I, II and III; Type III being the cylindrical porcelain insulator used in the tests described in Chapter III. The entire surface of insulator Type III is parallel to its longitudinal axis. Insulator Type I represents the other extreme case with practically all of its surface oriented in a direction perpendicular to the longitudinal axis whereas insulator Type II possess some of the geometrical
FIGURE 5.1: THE THREE MODELS IN THE VERTICAL, HORIZONTAL AND INCLINED CONFIGURATIONS
characteristics of both Types I and III. In this case 48.25 percent of the total surface area is parallel to the longitudinal axis and the remaining part is oriented in a direction perpendicular to the longitudinal axis. In all the three types of geometries considered, the leakage length and the electrode diameter are identical being 4" and 1" respectively. However, the surface areas are different being 243.2 sq.cm, 220.0 sq.cm and 81.38 sq.cm. in the case of Types I, II, and III respectively.

In all the tests reported in this chapter, the insulators were coated with 'medium' Bentonite deposits (i.e. 0.098 mg/cm², ± 20%) and Sodium Chloride was used as the conducting contaminant. A "slow" rate of wetting was employed. Also, in all the tests carried out with either insulator Type I or II in the inclined or vertical configuration, the cathode was situated at a higher level than the anode (i.e. position 1). The spraying technique and the testing procedure remained the same as described earlier. The measuring circuit used in this series of tests is shown in Figure 5.2. As the logarithmic amplifier is excluded, the deflections on the U.V. Recorder are now proportional to the current up to about 0.3 ma. As the current increases beyond this value the diode becomes more and more conducting and the relation is therefore nonlinear.

5.3: Comparison of the performance of the different geometries

There are two methods of comparing the performance of the different geometries considered in this study. These are

(1) comparison of results on the basis of test configuration
(2) comparison of results for various orientations of surfaces.

In the first method, the performance of insulator Types I and II
Figure 5.2: The Measuring Circuit.
in any configuration should be compared with that of Type III in the same configuration. However, in the horizontal configuration an appreciable portion of the surface of both Types I and II is vertically oriented. Therefore comparison can be made with the performance of Type III in the vertical configuration. On the same basis the performance ofTypes I and II in the vertical configuration can be compared with that of Type III in the horizontal configuration. This corresponds to the second method of comparison. Such a method of comparison is possible only when simple geometries such as Types I or II are considered. In the present study comparison is made in both ways. The performance ofTypes I and II in the inclined configuration is compared with that of Type III in the same configuration.

5.4: Experimental Results

5.4.1: Experiments carried out with Types I and II in the horizontal configuration

In these tests, the insulators were washed with distilled water, dried and then sprayed with Sodium Chloride/medium Bentonite slurry; the polluted and dried insulator was then tested under fog conditions. Both insulator Types I and II were tested in this manner in the horizontal configuration. The resulting performance graph is shown in Figure 5.3 which for comparison, also includes the withstand curve of Type III in the horizontal as well as in the vertical configuration and in "position 1", (i.e. cathode situated above the anode). It may be recalled that insulator Type III performs better in this position than in "position 2". Examination of Figure 5.3 shows that insulator Type I performs slightly better than Type II. Furthermore both these
FIGURE 5.3: - FLASHER/WTIHSTAND VOLTAGES VERSUS SALT DEPOSIT DENSITY (HORIZONTAL CONFIGURATION - MODELS POLLUTED WITH NaCl/BENTONITE SLURRY - MEDIUM BENTONITE DEPOSITS - SLOW WETTING RATE)

Δ - FLASHER TYPE I  Δ - FLASHER-TYPE II  --- - WITHSTAND CURVE TYPE III - VERT. CONFIGURATION (FROM FIGURE 3.12)
O - WITHSTAND TYPE I  ⭢ - WITHSTAND TYPE II
--- - WITHSTAND CURVE TYPE III - HORIZ. CONFIGURATION (FROM FIGURE 3.4)
types show vastly improved performance characteristics compared to Type III. However, this superior performance cannot be attributed to a change in the geometry. Close examination of the insulators revealed that the fog water tends to bead up on the surface of the "plexiglass" insulators. As a result, the wet band is not continuous and consequently the flashover voltages are higher. The superior performance of Types I and II is therefore associated with the surface material properties rather than with the geometry. Therefore, further testing of insulator Types I and II as described in this section was discontinued as the main objective was to check if any improvement would result from a change in the geometry of the insulator.

5.4.2: Tests carried out on Types I and II after surface treatment

The results of the previous section indicate that direct comparisons cannot be made between the performance of "plexiglass" and porcelain insulators because of a difference in the wetting characteristics of the two material's surfaces. Therefore, it was decided to treat the surface of the "plexiglass" insulators with photoflo solution before spraying with pollution. This treatment formed a film of photoflo on the surface of the insulator. The film reduces the surface tension of the water droplets. Consequently the pollution layer becomes more uniform and the fog wets the surface more evenly. Beading of water drops is prevented and a continuous wet band is obtained as in the case of porcelain insulators. Thus, with photoflo treatment the surface wetting characteristics of the "plexiglass" insulators should resemble those of the corresponding porcelain insulators. The method of treating the surface of the insulators with photoflo solution was as follows.
First the insulators were cleaned and dried; a few drops of photoflo solution was then spread evenly on the surface after which it was wiped dry with a lint free cloth. The insulators (Types I and II) were then sprayed with pollution, dried and tested under fog conditions. Insulator Type I, treated in this manner, was tested in the vertical, horizontal and inclined configurations. Type II was tested in the vertical and horizontal configurations only. The results of these tests are included in Figures 5.4 to 5.6. Figure 5.4 shows the withstand and flashover levels of Types I and II in the horizontal configuration. The withstand curve of Type III in the horizontal as well as in the vertical configuration (position 1) has been included in the same figure for comparison. Comparison of Figures 5.3 and 5.4 shows that the flashover levels of Types I and II have decreased as a result of the surface treatment. The performance of Type I is still better than that of Type II. It can also be seen that the decrease in the withstand levels of Type II is greater than that in the case of Type I. Also, the withstand levels of Type I are higher than those of Type III in the vertical configuration whereas those of Type II are slightly lower at low values of the salt deposit density, (< .04 mg/cm²). Lastly, both Types I and II perform much better than Type III in the horizontal configuration.

The performance of Types I and II in the vertical configuration is shown in Figure 5.5 which includes, for comparison, the withstand curve of Type III in the horizontal as well as in the vertical configuration (position 1). It is seen that insulator Types I and II perform almost identically and slightly worse than Type III in the vertical configuration. However, both Types I and II perform slightly better than Type III in the horizontal configuration. Comparison of Figures 5.4 and 5.5
FIGURE 5.4: - FLASHOVER/WITHSTAND VOLTAGES VERSUS SALT DEPOSIT DENSITY (HORIZONTAL CONFIGURATION - SURFACE OF TYPES I & II TREATED WITH PHOTO FLO - MODELS POLLUTED WITH NaCl/BENTONITE SLURRY - MEDIUM BENTONITE DEPOSITS - SLOW WETTING RATE)

- Δ - FLASHOVER TYPE I
- Δ - FLASHOVER TYPE II
- --- WITHSTAND CURVE TYPE III - VERT CONFIGURATION (FROM FIG. 3.12)
- O - WITHSTAND TYPE I
- O - WITHSTAND TYPE II
- ----- WITHSTAND CURVE TYPE III - HORIZ CONFIGURATION (FROM FIG. 3.4)
FIGURE 5.5: FLASHOVER/WITHSTAND VOLTAGES VERSUS SALT DEPOSIT DENSITY (VERTICAL CONFIGURATION - SURFACE OF TYPES I AND II TREATED WITH PHOTO FLO - MODELS POLLUTED WITH NaCl/BENTONITE SLURRY - MEDIUM BENTONITE DEPOSITS - SLOW WETTING RATE)

- △ - FLASHOVER TYPE I  - ▲ - FLASHOVER TYPE II  - --- - WITHSTAND CURVE TYPE III - VERT CONFIGURATION (FROM FIG. 3.12)

- ○ - WITHSTAND TYPE I  - ◆ - WITHSTAND TYPE II  - --- - WITHSTAND CURVE TYPE III - HORIZ CONFIGURATION (FROM FIG. 3.4)
FIGURE 5.6: FLASHER/WITHSTAND VOLTAGE VERSUS SALT DEPOSIT DENSITY (TYPE I - INCLINED CONFIG. - SURFACE OF TYPE I TREATED WITH PHOTOFLO - POS.1 - MODELS POLLUTED WITH NaCl/BENTONITE SLURRY - MED. BENTONITE DEPOSITS - SLOW WETTING RATE)

- △ - FLASHOVER
- ○ - WITHSTAND
- --- - TYPE III WITHSTAND CURVE INCLINED CONFIGURATION POSITION 1

(from Figure 3.10)
shows that both Types I and II perform better in the horizontal than in the vertical configuration. It is also seen that the difference in the withstand levels of Type II, in the two configurations, is smaller than that in the case of Type I. Figure 5.6 compares the performance characteristics of insulator Type I with that of Type III for the inclined configuration (position 1). It is readily seen that the performances are almost identical.

The above results indicate that surface treatment with photoflo solution leads to a lowering of withstand levels. The reason for this has been pointed out earlier in this section. The following experiment was then carried out in order to check if the withstand levels would be affected by a more intensive treatment of the surface with photoflo solution. In this case, the clean and dry surface of the "plexiglass" insulator was wiped with a small clean piece of lint free cloth saturated with photoflo solution; the spraying process was then carried out without wiping the surface dry. This method of surface treatment will be referred to as a "liberal surface treatment". Only insulator Type I was tested in the horizontal configuration after "liberal surface treatment". The performance graph for this case is shown in Figure 5.7. Once again the performance of Type III in the horizontal configuration has been included for comparison. Comparison of Figures 5.7 and 5.4 shows that the Flashover and withstand levels of Type I have decreased further due to a "liberal" treatment of the surface with photoflo solution. It can also be seen from Figure 5.7 that the performance of Type I is not significantly different from that of Type III in the horizontal configuration.

As the objective of the experiments described in this chapter was
FIGURE 5.7: FLASHOVER/WITHSTAND VOLTAGE VERSUS SALT DEPOSIT DENSITY (TYPE I - HORIZONTAL CONFIGURATION - "LIBERAL SURFACE TREATMENT" - MODELS POLLUTED WITH NaCl/BENTONITE SLURRY - MEDIUM BENTONITE DEPOSITS - SLOW WETTING RATE)

△ - FLASHOVER
○ - WITHSTAND

- WITHSTAND CURVE TYPE III HORIZ. CONFIGURATION (FROM FIGURE 3.4)
to evaluate the effect of geometry, it is necessary to determine whether
or not the performance of a porcelain insulator is identical to that of
the corresponding plexiglass insulator after surface treatment of this
insulator with photoflo solution. In order to check this a "plexiglass"
insulator, (cylindrical shape 4" long, 1" dia.) was polluted and tested
in the horizontal configuration both with and without "liberal surface
treatment". In these tests, the salt deposit density ranged from
.015 mg/cm² to 0.0225 mg/cm². Fig.5.8 shows the flashover and withstand
levels. For comparison, the withstand curve of the corresponding porcelain
insulator in the horizontal configuration has been included in the same
figure. It is seen that the withstand levels of the "plexiglass" insulator
are higher than those corresponding to a porcelain insulator. After
"liberal surface treatment" of the "plexiglass" insulator, the withstand
level decreases but it still remains higher than that of the porcelain
insulator. Fig.5.8 also shows the flashover (F) and withstand (W)
levels of a cylindrical shaped insulator with a partially porous surface
for a heavy pollution condition. Additional details regarding these
points are included in Chapter VI.

5.5: Discussion

5.5.1: Discussion of results in section 5.4

From the results of the preceding section, it is apparent that the
flashover levels of the "plexiglass" insulators decrease on treating
the surface with photoflo solution. This results essentially from the
lowering of surface tension of the water drops by the photoflo solution.
From Figs.5.3, 5.4 and 5.7, it is seen that the flashover levels depend
upon the extent of the surface treatment. This shows that the lack
of a well defined surface treatment procedure will result in more
scatter in the test results; therefore reproducability will be
difficult. Although every effort was made to maintain a constant
FIGURE 5.8: COMPARISON OF PERFORMANCE OF IDENTICAL "PLEXIGLASS" AND PORCELAIN INSULATORS UNDER IDENTICAL CONDITIONS.

△ - FLASHOVER, PLEXIGLASS INSULATOR (NO SURFACE TREATMENT)
△ - WITHSTAND, PLEXIGLASS INSULATOR (NO SURFACE TREATMENT)
△ - FLASHOVER, PLEXIGLASS INSULATOR (LIBERAL SURFACE TREATMENT)
O - WITHSTAND, PLEXIGLASS INSULATOR (LIBERAL SURFACE TREATMENT)
—— - WITHSTAND, CURVETYPE III HORIZ. CONFIGURATION (NO SURFACE TREATMENT) (FROM FIGURE 3.4)
W - WITHSTAND, POROUS INSULATOR (CYL. SHAPE 4" LONG X 1" DIAMETER)
F - FLASHOVER, POROUS INSULATOR
surface treatment condition during a test series yet some scatter is present. This is especially noticeable in Figure 5.7.

Examination of Figures 5.4 and 5.5 shows that insulator Type I performs better than Type II in the vertical and horizontal configurations. It is for this reason that tests were not carried out on Type II with "liberal surface treatment". Furthermore it is seen that insulator Type I performs best in the horizontal configuration followed by the inclined and the vertical configurations. This is because moisture deposition due to fog is heaviest on horizontal surfaces and least on vertical surfaces.

When insulator Type I is in the horizontal configuration practically all of its surface is vertically oriented and therefore wetting is not pronounced. In the vertical configuration the entire surface is now horizontally oriented of which one half is subjected to direct moisture deposition due to fog. Any wetting of the remaining half is due to absorption and is lesser than that of the top face (Figure 5.9). It is seen that in this configuration wetting is more pronounced than in the horizontal configuration. As a result, there is a notable difference in the performance of this insulator in the two configurations.

With insulator Type II in the horizontal configuration approximately 52% of its total surface is oriented vertically. Of the remaining 48% only a small part is subject to direct moisture deposition due to fog. However, because of the curvature the wetting of this surface is not insignificant. In the vertical configuration approximately 26% of the entire surface is subject to direct moisture deposition due to fog. Also approximately 48% of the entire surface is now
FIGURE 5.9: INSULATOR TYPE I IN VERTICAL CONFIGURATION

direct moisture deposition on this face.

FIGURE 5.10: INSULATOR TYPE II IN HORIZONTAL AND VERTICAL CONFIGURATIONS

48% CURVED SURFACE

Top face is 26% of total surface

48% VERT. SURFACE.

FIGURE 5.11: SHOWING FORMATION OF DRY BANDS ON TYPES I AND II IN THE HORIZONTAL CONFIGURATION
vertically oriented (Figure 5.10). The wetting characteristics are now only slightly enhanced. As a result, the performance of Type II is only slightly worse in the vertical configuration than in the horizontal configuration — as can be seen from Figures 5.4 and 5.5.

Figure 5.5 showed that there is no significant difference in the withstand levels of Types I and II in the vertical configuration in spite of a larger horizontally oriented surface subject to direct moisture deposition due to fog in the case of Type I. Once again the reason for this behaviour is inherent in the geometrical characteristics of the two insulators. With Type II the horizontally oriented top face represents approximately 26%; also approximately 48% of the total surface is oriented vertically. On the other hand with Type I 50% of the total surface is subject to direct moisture deposition due to fog. The remaining 50% can only wet by absorption. The wetting characteristics of the two insulators are not significantly different and therefore there is not much difference in the performance of the two insulators in the vertical configuration.

With insulator Type I in the horizontal configuration, dry bands formed on both faces (Figure 5.11) and were always identical in shape. This is due to the small thickness (1/16") of this insulator. As a result as soon as a dry band is formed on one face the heat developed in this dry band is conducted through the material and forces a dry band to form at identical locations on the other face. In the inclined and vertical configurations the dry bands formed on only one face. This is because of the pronounced wetting associated with the face exposed to direct moisture deposition due to fog. These remarks also apply to insulator Type II with the only exception that in this case, in the
horizontal configuration, the dry bands which formed on the vertical faces were not identical.

With both insulator Types I and II, the dry bands did not always form next to an electrode. This is possibly due to the step changes in geometry in these models. As a result the pollution layer is not as uniform as in the case of Insulator Type III.

With either insulator Type I or II in the vertical and inclined configurations, only a single arc extended itself to flashover. The effect of the thermal forces was more prominent with Type II; the arc removing itself from the surface soon after flashover. With either insulator type in the horizontal configuration, arcs were struck simultaneously across the dry bands on both the vertical faces. The arcs would revolve, and in the case of Type I, lined up during flashover. In the case of Type II, flashover occurred when one of the arcs on the vertical face extended itself along the axially oriented surface. This is another factor which contributes to an improved performance of the insulators in the horizontal configuration. There are now two arcs which have to line up for flashover to occur.

In all the tests carried out with Types I and II it was difficult to remove the contaminants from the surface, after the completion of a test, for the purpose of measuring the salt deposit density. This was especially true when the surface was treated with photoflo solution. An artist's paint brush was therefore used to facilitate complete removal of the contaminants from the surface.

5.5.2: Effect of a change in the geometry

It was seen in section 5.4.2 that even after application of a "liberal surface treatment" with photoflo solution the withstand level
of a "plexiglass" insulator is higher than that of a porcelain insulator of similar shape. Thus the withstand level of insulator Types I and II will be higher than that of porcelain insulators of a similar shape. To evaluate the effect of geometry, only Type I will be considered as this insulator has higher flashover levels than Type II in all configurations. From Figure 5.7 it is seen that after a "liberal surface treatment" the performance of Type I ("plexiglass") in the horizontal configuration is not substantially different from that of Type III (porcelain) in the same configuration. This result together with those presented in section 5.4 lead to the conclusion that there will be no substantial improvement in the performance of porcelain insulators similar in shape to that of Type I over that of Type III no matter what the configuration. Further, as the results of the various tests described in this chapter indicate that there will be no improvement in the performance of a porcelain insulator with a geometry similar to that of Type II, it can be concluded that there is no significant improvement in the performance of porcelain insulators due to changes in the geometry such as those considered in this study.

Additional changes in the geometry (while still maintaining a leakage length of 4" and an electrode diameter of 1") may involve

1. the inclusion of inclined surfaces

2. the inclusion of a number of steps in the insulator surface.

The introduction of inclined surfaces will transform insulator Types I and II to a more or less conventional shape; it is unlikely that any significant improvement will result. It is possible, though, but
there will be a change in the order of merit of performance in the various configurations.

The introduction of a small inclination in the surface of Type I may result in a slight improvement in its performance in the vertical configuration. This is because the fog water deposited on the top face can now drain off the surface. Because of the small inclination of the faces, there will be a slight decrease in the flashover and withstand levels of this insulator in the horizontal configuration.

The introduction of a number of steps in the insulator surface has already been suggested by previous investigators. In such insulators a multiplicity of arcs can be expected. This result follows from the differential wetting rates of the horizontal and vertical surfaces. A small increase in the flashover values can be expected because of the probability involved in all the arcs lining up. This is a phenomenon similar to that observed with insulator Types I and II in the horizontal configuration.

5.5.3: Effect of material surface

From the results of the tests described in this chapter it appears that the surface material of the insulator has a pronounced effect on its performance. For example, the poor surface wetting characteristics of "plexiglass" insulators led to the formation of a discontinuous wet band thus contributing to increased flashover levels. Examination of Figure 5.3 shows that the resulting increase is substantial. The use of this material or any other material with similar or worse surface wetting characteristics will result in a much improved insulator performance under polluted conditions.

It was also noted that in the case of the "plexiglass" insulators,
the leakage current prior to commencement of scintillation was much lower than that recorded in the case of the porcelain insulators used in the experiments described in Chapter III. At first, it was thought that this effect is due to a change in the geometry. However, even during the tests carried out in the horizontal configuration with "plexiglass" insulators similar in shape to that of Type III (i.e. porcelain insulator 4" long and 1" diameter) the leakage current seldom reached a level of 0.15 to 0.2 ma (Figure 5.12) as compared with 0.4 to 0.5 ma in the case of porcelain insulators. Surface treatment of the "plexiglass" insulator with photoflo solution did not change this equilibrium value of the leakage current.

The low values of the leakage current are due to the relatively poor thermal conductivity of "plexiglass" as compared to porcelain. As pointed out in Chapter III, when a voltage is applied to a polluted and dried insulator under fog conditions, the leakage current increases to such a value that equilibrium conditions are established between the rate of deposition of moisture due to fog and the rate of evaporation of moisture due to the heating effect generated by the leakage current. Because of a poor thermal conductivity, more of the local heat generated is retained in the case of a "plexiglass" insulator as compared to a porcelain insulator. Therefore, in the former case, the leakage current does not have to increase to as high a value as in the case of porcelain insulators in order to establish the equilibrium conditions.

5.6: Summary

The results of the tests described in this chapter indicate that little improvement, if any, is possible due to changes in the geometry of the insulator such as those considered in this study. The surface
Figure 5.12: Leakage current recordogram for "plexiglass" insulator
material of the insulator has a pronounced effect on its performance because of properties such as thermal conductivity and wetting characteristics. The use of materials with poor surface wetting characteristics will result in a considerable increase in the flashover levels; the use of materials with low thermal conductivity will result in low values of the leakage current. Further it was seen that it is possible to improve the surface wetting characteristics of a material by treating its surface with photoflo solution.
CHAPTER VI

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

One of the objectives of this study was to evaluate the relative effects of the various parameters involved in an artificial contamination test. With this objective in mind, a polluting technique and test procedure was selected. The pollution layers consisted of inert and conducting components and a spraying method was used to deposit the contaminants on the surface of the model insulator as evenly as practically possible. The deposits adhered well to the surface thus resembling field conditions closely. In addition the test procedure followed in this study closely resembles the physical environment.

The results of Chapter III point out that the inclusion of an inert component in the pollution layer makes the test results more reproducible and independent of the wetting rate provided a minimum amount of the inert component is present on the insulator surface corresponding to a "medium" deposit. For less than "medium" amounts of the inert deposit, the flashover voltage increased for the "quicker" wetting rate. In Chapter II it was pointed out that the fog deposition rate is 24.3% greater at the "quick" wetting rate that at the "slow" wetting rate. It is conceivable that this figure is greater in practice because of the increased turbulence in the fog chamber at the "quick" wetting rate. It was also shown in Chapter III that an excessive amount of the inert component in the pollution layer led to increased flashover voltage levels. This observation is in contradiction with that of Kawai. However, in Kawai's study, the contaminating slurry included only 40 to 80 gms of the inert component per litre of distilled water as compared to 70 gms. per 0.4
litres of distilled water used in the present study. Thus, the inert deposits in Kawai's case correspond to less than a "medium" deposit as per the classification of Chapter II. It is therefore probable that the decreased flashover levels reported by Kawai may be due to a more uniform deposit obtained after the inclusion of the inert contaminant. The results of Jolly are in contradiction because of the different testing technique employed. As the test procedures followed in this study bear close resemblance to the field conditions, it is probable that effects similar to that reported in Chapter III will be observed in practice.

The effect of changing the type of the inert contaminant was not studied. It is reasonable to expect different results because of properties associated with the inert component such as water absorptive capacity, ability to harden on drying and particle size. Thus it is important to specify completely the type of inert contaminant used in an artificial contamination test. Also, as shown in Chapter III, the solubility of the salt has an appreciable effect on the flashover voltages. In view of the above it is important to ascertain the type of contaminants prevailing in a particular area before proceeding with an artificial contamination test which can realistically evaluate the performance of the insulator.

In Chapter IV a theoretical model has been presented which evaluates the growth of dry bands and predicts temperatures at points in the dry band for the case of the model insulator used in the tests described in Chapter III. Such a solution was possible mainly because of the recognition of the existence of an equilibrium current \( i_{eq} \) and the fact that dry bands are not completely dry so as to terminate conduction. The application of this theoretical technique is restricted to the case of simple geometries coated with uniform deposits and tested
under conditions similar to those in this study. To arrive at a
successful solution several assumptions were made; such assumptions
are necessary as it is difficult to arrive at an exact solution even
for the case of the simple geometries mainly because of the inestimable
parameters which are involved in the solutions. The solutions gener-
ted by the theoretical model did not lead to any physical absurdities.
Moreover, it was possible to explain certain physical phenomenon using
the theoretical model as a basis.

Chapter V presents a limited study of the effect of geometry on
single units. The essential feature in this study was that the leakage
lengths and the electrode diameter were maintained constant for all the
models studied. The results indicate that there is little improvement
in the insulator performance due to changes in geometry such as those
considered. However, it may be advantageous to use materials other
than porcelain which have poor surface wetting characteristics and
lower thermal conductivity. The latter property is responsible for
the lower leakage currents.
Suggestions for further work:

Perhaps three aspects need further study. First the effect of the
wetting rate needs to be known more precisely. Using similar test
procedures, it would be useful to find the upper limit of the wetting
rate beyond which the flashover values increase even for insulators
coated with "medium" Bentonite deposits. It is possible that either
more nozzles or a different arrangement of nozzles or both these measures
will have to be adopted in order to increase the wetting rate. With
the method of fog generation used in the present study the fog density
was very low for air line pressures less than 20 psi. For example,
at 10 psi the wetting rate was approximately 33% of that at 20 psi.
It is probable, therefore, that for air line pressures less than 20 psi the flashover values will increase. The reason for this has been pointed out in sec. 4.4.

Secondly the effect of geometry needs to be considered in greater detail. This could involve different shapes and larger models. Larger models are necessary so that there is more freedom to manipulate the orientations of the surfaces without arriving at impractical insulator shapes. The performance of multiple units can then be determined for any one or more geometries which show improved performance characteristics under polluted conditions.

The possibility of using porous insulators also needs further investigation. Only a few such samples (of cylindrical shape 1" diameter and 4" long) were available; the performance of these insulators is included in Figure 5.8. It is seen that the porous insulators have a vastly improved performance over that of the corresponding glazed insulators. However, neither the porosity of the samples nor the depth of the porous layer was known. In the case of the porous insulators too, an equilibrium current ($I_{eq}$) was noticed - indicating that the magnitude of the leakage current is controlled by thermal phenomenon. The leakage current is more uniformly distributed than in the case of the glazed insulators; the electrode/insulator contact is better and the contact area is larger. These are some of the factors that contribute to increased flashover levels.

It may be necessary to change the polluting procedure when testing porous insulators. The disadvantage of the spraying technique is that the salt is already in solution and can therefore readily enter the pores and distribute itself uniformly throughout the porous layer. In
actual practise both the conducting and the inert deposits are deposited on the surface. The conducting contaminants go into solution only in the presence of a wetting agent such as fog. Also, in any further study other factors will have to be taken into account such as the extent of porosity and depth of the porous layer. It is possible that with an increase in the depth of the porous layer the leakage currents will be abnormally high during a 'wet test'.

Another advantage arising out of the use of porous insulators is that there is no power loss involved during dry conditions as in the case with semiconducting glazed insulators. On the other hand the resistive grading effect is lost.
APPENDIX A 2.1

VOLTAGE MEASUREMENT

The Direct High Voltage was measured by means of a D.C. microammeter connected in series with a high resistance connected to the High Voltage Bus Bar as shown in Figure A2.1.1. This resistance (600 MΩ ±15%) was measured using a General Radio Megohm Bridge (Type 544B Serial Number 1821) to an accuracy of 3%; its value was found to be 639 MΩ. The direct current was measured by a Simpson D.C. microammeter (accuracy ±2% of full scale) which comprised of a 0-15μA movement and a 0-100 scale. The microammeter was shielded by housing it in a metallic enclosure. By means of a switch it was possible to select three different shunt resistances thus giving three ranges designed to read 10, 50 and 100 kV full scale. The shunt resistances were set to the appropriate values by measurement on a L&N Guarded Wheatstone Bridge (Type 4735 Serial Number 1544586 accuracy better than 1%).

It was not possible to calibrate this set up by using sphere gaps because of the small gap settings necessary at the voltages of interest i.e. 5-15 kV. For this reason, calibration was carried out according to the circuit of Figure A2.1.2. In this circuit, the voltage across the 1kΩ precision resistance was measured using a Fluke Digital Voltmeter (Type 145, Serial Number 8300A, accuracy 0.01% of input). The value of the 1kΩ precision resistance was measured by the L&N Guarded Wheatstone Bridge to be 1001.23Ω.

For a particular applied voltage, the reading on the microammeter as well as the voltage drop across the 1 kΩ precision resistance was noted. Knowing this latter voltage, the applied voltage is determined by a trivial calculation. By comparing this value with that read on the
FIGURE A 2.1.1: DETAILS OF HIGH VOLTAGE DIVIDER

B.B. = BUS BAR (HIGH VOLTAGE)
R₁ = 600 M.Ω RESISTOR
CC = COAXIAL CABLE
B = METALLIC ENCLOSURE
C = CAPACITOR
M = D.C. MICROAMMETER
S = RANGE SELECTOR
R₉, R₉', R₉'' = FIXED RESISTORS
R₉, R₉', R₉'' = VARIABLE RESISTORS
R₂ = .6506 M.Ω
R₃ = 15.164 M.Ω
R₄ = 15.561 M.Ω
R₅ = .06956 M.Ω
FIGURE A 2.1.2: - CALIBRATION OF HIGH VOLTAGE MEASURING SET UP

M  - D.C. MICROAMMETER
R_1 - 600 MΩ RESISTOR
F.C. - FOG CHAMBER
R_2 - 10.88 MΩ
C.C. - COAXIAL CABLE
R_3 - 1 KΩ PRECISION RESISTANCE
V  - DIGITAL VOLTMETER
D.C. microammeter it is possible to determine the accuracy of the voltage divider set up. It was found that the accuracy was better than +3% throughout the range of voltage of interest.
The salt deposit density was obtained as follows. First, the contaminants on the insulator surface were washed into a clean beaker using a syringe filled with distilled water. The wash water was then transferred to a conductivity cell which is shown in Figure A2.2.1. An essential feature of this cell is that the top plate and electrode assembly are easily removable to permit thorough washing of the cell after every measurement. Also the electrode geometry in the cell was fixed. In all measurements the volume of the wash water in the cell was 300 cc. The electrical volume resistance was then measured by a bridge method using an alternating supply of frequency 1 KHz to avoid polarization effects. The maximum resistance measured by the cell (for the lowest salt deposit density) was of the order of 30 kΩ, and therefore capacitive effects were not predominant. The measured resistance was then referred to previously determined calibration curves of resistance versus weight of Sodium Chloride which were obtained as follows.

First, the resistance of a N/100 solution of Potassium Chloride was measured using the cell. The weight of Potassium Chloride necessary to make up a N/100 solution was measured using a Mettler electric precision balance type H-6. The conductance of a N/100 solution at the temperature of measurement was then found from available literature.\(^{69}\)

Thus,
\[
R = \rho \frac{L}{A}
\]
\[
\frac{L}{A} = \text{cell factor}
\]
FIGURE A 2.2.1: - VIEW OF CONDUCTIVITY CELL USED TO MEASURE THE SALT DEPOSIT DENSITY
\[ R = \frac{R}{\rho} = KR \]

where \( K \) is the conductance in mho cm\(^{-1}\). Therefore, \( L/A \), the cell factor is determined. If the geometry of the cell is unaltered, then \( L/A \) is a constant for the cell.

The equivalent conductance of Sodium Chloride at various concentrations and at 25\(^{\circ}\)C was then obtained from available literature\(^{67,68}\). These concentrations are expressed in terms of equivalents/litre, which were converted into milligrams/300 cc., 300 cc being the allowable volume of the conductivity cell. The equivalent conductances were converted to specific conductances and then corrected to take into account the conductance of the distilled water which was obtained by using a Radiometer A/S CDM2e conductivity meter and type CDC104 cell (accuracy 1\% of full scale). The corrected conductances were then transformed into resistance in ohms using the cell factor determined previously. Thus a table was constructed giving the resistance in ohms (as would be measured by the conductivity cell) versus weight of Sodium Chloride in milligrams. A calibration curve was then drawn valid for a temperature of measurement of 25\(^{\circ}\)C. Calibration curves for 23, 24, 26 and 27\(^{\circ}\)C were obtained by using a temperature correction according to the formula

\[ R_t = \frac{R_{25}}{1 + \alpha(t-25)} \]

where \( \alpha = 0.02 \)

The calibration curve for 25\(^{\circ}\)C is shown in Figure A 2.2.2.
FIGURE A 2.2.2: - CALIBRATION CURVE FOR NaCl AT 25°C
APPENDIX A 4.1

DERIVATION OF THE DIFFERENCE EQUATIONS

If a function \( f(x) \) and its derivatives are finite, single valued and continuous then the function \( f(x) \) may be expanded in the form of a Taylor series about the point \( x \) as

\[
f(x + h) = f(x) + h \frac{df}{dx} + \frac{h^2}{2!} \frac{d^2f}{dx^2} + \frac{h^3}{3!} \frac{d^3f}{dx^3} + \cdots \tag{1}
\]

\[
f(x - h) = f(x) - h \frac{df}{dx} + \frac{h^2}{2!} \frac{d^2f}{dx^2} - \frac{h^3}{3!} \frac{d^3f}{dx^3} + \cdots \tag{2}
\]

Subtracting equation (2) from (1) we obtain

\[
\frac{df}{dx} \bigg|_{x} = \frac{f(x + h) - f(x - h)}{2h} + O(h^2) \tag{3}
\]

which is the central difference approximation of the first derivative.

From equation (1) we obtain the forward difference approximation

\[
\frac{df}{dx} \bigg|_{x} = \frac{f(x + h) - f(x)}{h} + O(h) \tag{4}
\]

and the backward difference approximation is obtained from equation (2) as

\[
\frac{df}{dx} \bigg|_{x} = \frac{f(x) - f(x - h)}{h} + O(h) \tag{5}
\]

By adding equations (1) and (2) we obtain

\[
\frac{d^2f(x)}{dx^2} \bigg|_{x} = \frac{f(x - h) + f(x + h) - 2f(x)}{h^2} + O(h^2) \tag{6}
\]

which is a finite difference approximation for the second derivative.

The second term in each of the equations (4), (5) and (6) represents the order of the error involved in the approximation.
If \( t_0, t_1 \) and \( t_2 \) are the temperatures at nodal points 0, 1, 2 situated along the \( x \) axis with equal spacing \( \Delta x \), then a Taylor series expansion of the derivative is immediately obtained as

\[
\left( \frac{dt}{dx} \right)_2 = \left( \frac{dt}{dx} \right)_1 + \Delta x \left( \frac{d^2t}{dx^2} \right)_1 + \frac{(\Delta x)^2}{2!} \left( \frac{d^3t}{dx^3} \right)_1 + \ldots \tag{7}
\]

and

\[
\left( \frac{dt}{dx} \right)_0 = \left( \frac{dt}{dx} \right)_1 - \Delta x \left( \frac{d^2t}{dx^2} \right)_1 + \frac{(\Delta x)^2}{2!} \left( \frac{d^3t}{dx^3} \right)_1 - \ldots \tag{8}
\]

\( \frac{dt}{dx} \) and \( \frac{d^2t}{dx^2} \) are obtained from (3) and (6) and therefore (7) and (8) may be rewritten as

\[
\left( \frac{dt}{dx} \right)_2 = \frac{t_2 - t_0}{2\Delta x} + \frac{t_2 + t_0 - 2t_1}{\Delta x} + O(\Delta x)^2 \tag{9}
\]

and

\[
\left( \frac{dt}{dx} \right)_0 = \frac{t_2 - t_0}{2\Delta x} - \frac{t_2 + t_0 - 2t_1}{\Delta x} + O(\Delta x)^2 \tag{10}
\]

Equations (9) and (10) reduce to

\[
\left( \frac{dt}{dx} \right)_2 = \frac{1}{2\Delta x} \left[ t_0 - 4t_1 + 3t_2 \right] + O(\Delta x)^2 \tag{11}
\]

\[
\left( \frac{dt}{dx} \right)_0 = \frac{1}{2\Delta x} \left[ -3t_0 + 4t_1 - t_2 \right] + O(\Delta x)^2 \tag{12}
\]

Equation (24) of Chapter IV can now be transformed into a difference equation

\[
\frac{3t_n}{\Delta x} = \frac{t_{n+1} - t_{n-1}}{2\Delta x} \quad \text{--- (13) from (3)}
\]

\[
\frac{3^2t_n}{\Delta x^2} = \frac{t_{n+1} + t_{n-1} - 2t_n}{(\Delta x)^2} \quad \text{--- (14) from (6)}
\]

also

\[
\frac{3t_n}{\Delta x}_{x=t_r} = \frac{1}{2\Delta x} \left\{ t_{r+1} - 4t_{r-1} + 3t_r \right\} \quad \text{--- (15) from (11)}
\]
but \( t_n = 0 \) because of the assumptions made in the theoretical model of Chapter IV, therefore

\[
\frac{\partial t_n}{\partial x} = \frac{1}{2\Delta x} \left\{ t_{n-2} - 4t_{n-1} \right\}
\]  

(16)

also

\[
\frac{dt_n}{dT} = \frac{t_{n,m+1} - t_{n,m}}{\Delta T}
\]  

(17)

where the subscript \( m \) relates to time and \( \Delta T \) is the time step employed.

Similarly \( \frac{dn}{dT} = \frac{n_{m+1} - n_m}{\Delta T} \)  

(18)

Equations (24) and (26) of Chapter IV are then transformed to equations (27) and (28) by using the above relations.
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