Development of materials for EHV and UHV insulation operated in polluted environment.

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DEVELOPMENT OF MATERIALS FOR EHV and UHV INSULATION
OPERATED IN POLLUTED ENVIRONMENT

by

SOHAN SINGH SANGHA

A Thesis
Submitted to the Faculty of Graduate Studies
Through the Department of Electrical Engineering
in partial fulfillment of the requirements for
the Degree of Master of Applied Sciences at the
University of Windsor

Windsor, Ontario
Canada
1975
ABSTRACT

The insulation contamination developed into a primary problem with the emergence of EHV and UHV power transmission systems. Extensive research has been done to replace porcelain as an antipollution insulator or to improve its properties to satisfactorily avoid contamination flashovers and outages, since contamination is a major factor in establishing insulation levels for various applications in the present complexity of power networks. Unfortunately present research has addressed itself to partial development of an antipollution insulator. There is a need for inservice testing of the antipollution insulators.

Silicon carbide (a semi-conducting material) and adiprene LD-955 (saturated urethane rubber) were selected, as constituents of the material to be used for development of antipollution insulators, because of their physical and electrical properties.

A better moulding technique was designed to achieve a sensible economic line production of the required material (silicon carbide filled adiprene). A silicon carbide filled adiprene model was tested for electrical and mechanical properties. The results proved to be very encouraging. Other insulating materials such as epoxies (filled and unfilled with SiC), phenolic, Teflon and ceramics were evaluated for comparison.

Silicon carbide filled adiprene has been found to be most effective of the materials tested. It was found to have:

1. Positive temperature coefficient of resistance which is a vital property for thermal stability.
2. Leakage current almost reaching saturation level at working voltage.
3. Working voltage and breakdown voltage for 40:60 (silicon carbide to adiprene) samples to be 5.5 kV/in. (2.16 kV/cm.) and 11-12 kV/in. (4.33-4.77 kV/cm.) respectively.

Thermal tests further confirmed the current-voltage characteristics. Two standard methods (B.S. 3781-(1964) and ASTM 2303D-68) of testing established the non-tracking property. It was found that the performance in contaminated conditions and under mechanical stresses is excellent.

Finally the need to develop the second stage of this most promising, antipollution insulating material was established. It is hoped that this need can be satisfied through further research and development.

In Chapter I the pertinent literature and the present research work are reviewed.

In Chapter II brief description and properties of the material, silicon carbide and adiprene, and the improved moulding technique are described.

In Chapter III the experimental work done in the laboratory with a brief description of procedure, results obtained and discussion of the respective results are presented.

Chapter IV consists of a general discussion of the study and also the conclusion leading to a few suggestions for future work i.e. the next phase of antipollution insulator development.

The properties of silicon carbide and adiprene have been summarized in Chapter II, tables 2:1 - 2:12, for the convenience of the reader of the thesis.
ACKNOWLEDGEMENTS

The author would like to express his sincere gratitude and appreciation to Professor Dr. E. Kuffel for his invaluable counsel, guidance and assistance, without which, it would not have been possible to complete the research work.

Thanks are also due to Mr. L. Reiter and Mr. J. Novosad for good co-operation and technical assistance rendered and to Miss Mary Ewasyszyn for her excellent typing.

The author also wishes to express his thanks to his wife, Charanjit, for her endurance and good continual moral support.

Thanks are also due to the National Research Council of Canada for financial support.
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CHAPTER I

INTRODUCTION

Electrical power transmission systems have grown tremendously in complexity due to the locating of large capacity generating stations far from load centres. Extra high voltage transmission lines have already been put into operation and the tendency to use UHV power systems is also in an advanced stage. The reliability of such a complex network of power transmission lines and substations is dependent on the adequate performance of supporting insulation. The insulation of EHV and UHV systems is subject to three basic abnormal conditions that can cause surface flashovers and outages. The three basic abnormal conditions are [1]

1. Overvoltage caused by lightning surges.
2. Overvoltage caused by switching operations.
3. Abnormal voltage gradient across the insulation surface created by contamination of solid insulator surfaces.

The first two problems have been controlled to a great extent but the third, the contamination flashover problem is still an unsolved phenomenon.

Jolly [2] has summarized the theoretical works done in understanding the flashover mechanism. He purposed that "contamination flashover is essentially an electrical breakdown process caused by the field concentration at the discharge tip". The major factors affecting the design of insulators at various levels of voltage are [3]

1) 0 - 4 KV mechanical clearance
2) 4 - 34.5 KV corona and surges
3) 69 - 220 KV lightning and switching surges
4) 345-765KV switching surges and contamination
5) 765 - 1500 KV contamination
The contamination problem has attracted the attention of a number of electrical utilities, scientists and engineers throughout the world. The presence of moisture on insulators contaminated with industrial or saline deposits causes flashover leading to outages in the power supply system. Briefly, the flashover phenomenon of a polluted insulator involves the following steps:

1. When the layers of pollutants become wet, their resistance level decreases, leading to a leakage current flowing over the insulator surface.

2. Because of non-uniform layers of pollution under the applied voltage, non-uniform drying occurs leading to an unstable condition and formation of high resistance 'dry bands' around the insulator.

3. The 'dry band' areas spark over the polluted insulation surface creating surges of current.

4. In the case when the pollution persists further discharges develop into a complete flashover.

Partial solution to the problem is sought by the following means [4]

a) Insulators are washed periodically.

b) Insulators are greased (possibly once in two-three years).

c) Over-insulation is provided. (i.e. to increase the insulator strings or post insulators.)

d) Conventional insulators are replaced with antifog insulators (special design in shape).
Washing and greasing is not a permanent solution and also involves high costs, although it is a helpful method of control in the absence of other alternative solutions.

Kawai [5] found that the effective length of insulation is not proportional to the length of the string (or leakage distance). Thus even 100% increase in insulation length for 115 kv and 138 kv insulators and 140% increase for 230 kv have not eliminated contamination flashover.

The antifog insulators have also failed to solve the contamination flashover problem. Various researchers have suggested some alternate solution, though not permanent, to improve the existing system. Some of the recent works are mentioned below:

Kimoto, Kito and Takatori [6] attempted to determine the standard leakage length per kv required for an insulator to be used under different degrees of pollution as given in table 1:1 and 1:2. They have classified pollution areas in terms of salt deposit densities as shown in table 1:1.

The washing procedure still remains the preventive maintenance measure. Kawai[7] has suggested the use of large disc fog type insulators. He related the performance of large disc insulator theoretically for its diameter and has shown it to be much better than conventional standard insulators. Thus he recommends the use of larger size of insulators depending upon the degree of pollution; but other workers found that size has its own limitations.

Dey, Drinkwater and Proud [8] have suggested the use of RBGF [Resin bonded glass fibre] cored epoxy, as an alternative material to ceramics. Though resin bonded glass fibre has been shown to have better mechanical properties, these insulators still lack the anti-pollution properties.

McIlhagger [9] suggested that the surface contamination flashover could be reduced by maintaining the insulator surface temperature by few degrees
# TABLE 1.1

## CLASSIFICATION OF POLLUTION AREA AND THE EXPECTED MAXIMUM EQUIVALENT SALT DEPOSIT DENSITIES OF VARIOUS INSULATORS

<table>
<thead>
<tr>
<th>Classification of pollution area</th>
<th>AA</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model pollution degree, mg/cm² (Based on 10&quot; x 5-3/4&quot; standard disc)</td>
<td>0.03</td>
<td>0.063</td>
<td>0.125</td>
<td>0.25</td>
<td>0.5</td>
<td>-</td>
</tr>
<tr>
<td>Approx. distance from sea coast, km</td>
<td>50 over</td>
<td>10-50</td>
<td>3-10</td>
<td>1-3</td>
<td>0-1</td>
<td>0-0.3</td>
</tr>
<tr>
<td>10&quot; x 5-3/4&quot; standard disc (under surface)</td>
<td>0.03</td>
<td>0.063</td>
<td>0.125</td>
<td>0.25</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>10&quot; x 5-3/4&quot; fog type disc (under surface)</td>
<td>0.021</td>
<td>0.044</td>
<td>0.088</td>
<td>0.175</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>Ordinary salt pollution mg/cm² (Expected values)</td>
<td>11&quot; x 6-1/8&quot; standard disc (under surface)</td>
<td>0.021</td>
<td>0.044</td>
<td>0.088</td>
<td>0.175</td>
<td>0.35</td>
</tr>
<tr>
<td>Cylindrical post (total surface)</td>
<td>0.015</td>
<td>0.03</td>
<td>0.063</td>
<td>0.125</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Porcelain shells</td>
<td>0.012</td>
<td>0.025</td>
<td>0.05</td>
<td>0.10</td>
<td>0.20</td>
<td></td>
</tr>
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</table>

Industrial Pollution mg/cm²: All of insulators - 0.125 - 0.25 - 0.25-0.5 out skirts Heavy industrial area of industrial area

Reprinted from Reference [6] pg. 322
### Table 1.2

**Required Leakage Distance per 1 kV of Nominal Line to Line Voltage for Disc Insulators**

<table>
<thead>
<tr>
<th>Classification of Pollution Area</th>
<th>*AA</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
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<tr>
<td>10&quot; x 5-3/4&quot; standard disc</td>
<td>0.75</td>
<td>0.90</td>
<td>1.00</td>
<td>1.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(19.1)</td>
<td>(22.9)</td>
<td>(25.4)</td>
<td>(28.0)</td>
<td></td>
</tr>
<tr>
<td>10&quot; x 5-3/4&quot; fog type disc</td>
<td>0.70</td>
<td>0.80</td>
<td>0.95</td>
<td>1.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(17.8)</td>
<td>(20.3)</td>
<td>(24.1)</td>
<td>(26.7)</td>
<td></td>
</tr>
<tr>
<td>Ordinary salt pollution</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11&quot; x 6-1/8&quot; standard disc</td>
<td>0.70</td>
<td>0.85</td>
<td>0.90</td>
<td>1.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>in./kV</td>
<td></td>
<td>(17.8)</td>
<td>(21.6)</td>
<td>(22.9)</td>
<td>(26.7)</td>
<td></td>
</tr>
<tr>
<td>(mm/kV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12-5/8&quot; x 7&quot; fog type disc</td>
<td>0.65</td>
<td>0.80</td>
<td>0.95</td>
<td>1.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(16.5)</td>
<td>(20.3)</td>
<td>(24.1)</td>
<td>(26.7)</td>
<td></td>
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Industrial Pollution

<table>
<thead>
<tr>
<th>Pollution Type</th>
<th>All of disc Insulators</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>in./kV</td>
<td></td>
<td>0.90</td>
<td>1.00</td>
<td>1.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(mm/kV)</td>
<td></td>
<td>(22.9)</td>
<td>(25.4)</td>
<td>(28.0)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*In this pollution area, insulation strength is determined by BIL*

**Class E is the location under direct spray of sea water. Therefore, polluted condition in this area is simulated by horizontal spray of 3% salt water of 0.3 mm/minute rate.*

Reprinted from Reference [6], pg. 322
above the ambient temperature. This suggestion was found to be useful in evaluating the correct kind of insulator material.

The above suggestion was used by Moran and Powell [10] in their proposal of resistance graded insulators, the ultimate solution to the contamination problem.

Robinson [11] stated that the flow of about 1 mA leakage current at normal operating voltage for a single suspension type unit, on the resistance graded insulator surface would generate sufficient heat to prevent formation of electrolytic film. This leakage current has been achieved by coating the insulators with a semiconducting glaze. The experimental results of semiconducting glazed insulators are limited to high voltage only. The semiconducting glaze is thermally unstable having negative temperature coefficient of resistance and thus is not very satisfactory.

Orbec and Niemi [12] have carried out research on the possibility of using polymers (silicon polymer) as an alternative material to ceramics but without specific results.

The means of special design of over-insulation, and alternative material have been tried but without much success in solving the basic problem of contamination flashover. Even the most recent semiconducting glaze has not been an acceptable alternative; thus search for new material continues.

Ciccotelli [13] studied the current-voltage characteristics, breakdown voltage, thermal properties, performance under polluted conditions, etc. with some encouraging results of silicon carbide filled adiprene. His major problem was the reproducibility of the sample insulator. Thus silicon carbide filled adiprene still needed extensive research to establish the
usefulness of this material as a replacement for ceramic insulators.

**PRESENT WORK**

The aim has been to find a suitable material which exhibits the following properties.

1. Have semiconducting property to avoid formation of electrolytic film.
2. Have positive temperature co-efficient of resistance which will ascertain the required thermal stability.
3. To act as a graded resistor thus having uniform voltage distribution along the insulation.
4. Have very high resistance to tracking to avoid deterioration due to surface discharges.
5. Have good insulation properties i.e. comparatively higher withstand voltage per unit length, making it more economical.
6. Easy to manufacture in shapes and sizes eliminating design limitations.
7. Have adequate mechanical properties comparably better than porcelain insulation giving the new material more flexibility in application.

The present research work has shown (see Chapter III) that silicon carbide filled adiprene possesses almost all the above mentioned properties. Thus silicon carbide filled adiprene insulators could be expected to perform well in contaminated atmospheres.
CHAPTER II

MATERIAL

Researchers have not yet been successful in finding any organic or inorganic material as a suitable substitute for porcelain. As mentioned in chapter 1 many types of polymers (epoxies) have been tried [13] but the main problem has been sensible economic manufacture.

An organic compound, adiprene LD-955, has been selected as an insulating material and silicon carbide of one hundred electrical grade grit as the semiconductor.

2:1 SILICON CARBIDE (SiC)

Silicon carbide, as a semiconductor, (i.e., having electrical conduction intermediate between conductor and insulator) has a wide range of applications in electrical, electronic and metallurgical industries. It has a crystalline structure with a series of polytypes; but it could be represented by two main types, i.e., α-SiC and β-SiC. The α-SiC has hexagonal unit cell and β-SiC cubic unit cell.

The minimum experimental values of the forbidden gap for α-SiC and β-SiC has been found [14] to be 3eV and 2.2eV respectively. Table 2:1 and 2:2 lists some of the general properties of commercially available silicon carbide [14], [15].

The electrical properties of silicon carbide have mostly been studied in its p-n junctions form. Silicon carbide's p-n junctions could be "natural" p-n junctions in commercial α-SiC single crystals or prepared by fusion method. Figure 2:1 shows current-voltage characteristics of α-SiC junctions as a diode [14]. Figure 2:2 also shows the current-voltage characteristics studied by rectifying junctions, made as a result
of heating silicon carbide in silicon or silicon aluminum [13]. The
current-voltage characteristics of silicon carbide does not obey Ohm's
law, although maximum efforts have been made to have better ohmic contacts
by minimizing electrical impedance at the interface of SiC material and leads.

2:2 POLYURETHANE

The elastomer family, polyurethane, is a reaction product of di-
isocyanates and polyhydroxyl. The chemical reaction [16] may be written as:
\[ n \text{HOROH} + n \text{NCO-R}-\text{NCO} \rightarrow H\text{D}+R-O-C-NH-C=O-R-O-C-NHR\text{NCO} \]

The reaction processes involve cross linking and chain extensions. This
family of urethanes is known as condensation polymers. The fully saturated
polyurethanes are very widely used in rubber industries and are finding
applications in electrical fields. General electrical properties are given
in table 2:3.

The adiprene LD-955, fully saturated urethane polymer, has been used
as insulating material in this research work. This is a product of Du Pont
De Nemours and Co. They manufacture a series of elastomers such as L-42, L-83,
L-100, L-167, L-200, L-213, L-420, LD-955, and sulphur curable urethane rubber.
The adiprene LD-955 has been selected for this study because of its comparatively longer working life, better compression properties etc. The
particularly desirable properties [18], [19] have been summarized in tables
2:4 - 2:9. These tables compares various properties of adiprene LD-955
as compared to other adiprenes mentioned above. It must be noted that
adiprene can be harmful to the human skin.

(Reprinted from reference #14)
FIG 2.2. Current - Voltage Characteristics of Silicon Carbide as a Rectifier. Solid lines indicate experimental values. Dotted lines indicate theoretical values.
2:2:1 HARDENER FOR POLYURETHANE

Moca [4,4' - Methylene -bis (2 - chloroaniline)] has been evaluated as a most favourable curing agent. Moca, when preheated to 121°C and mixed with polyurethane, results in good vulcanizates. This hardener bonds chemically with urethane and becomes part of the polymer. The reaction is exothermic and could raise the mix temperature by about 20°C (68°F). The general product description and properties [20] Moca, imparts to various types of adiprene's are shown in tables 2:10 - 2:12.

Moca should be handled with considerable care because it breaks down, thermally, at 205°C (400°F) and should never be heated beyond 140°C (285°F).

2:3 TEST SAMPLES

The geometry of the test samples was decided to be a cylindrical shape 4" long and 1" in diameter, to effect simplicity in manufacture, ease of calculations and similarity to the rod type insulators in use. The processing procedure as recommended by the polyurethane manufacturer, except degassing has been followed [19]. The moulding and manufacturing processes are described below.

2:3:1 THE MOULDING APPARATUS

The most desirable mould for the test samples should have the following properties:

1. The mould should exhibit non-adhesive properties.
2. The mould should be of a non-consumable quality.
3. The mould should be capable of a continued high quality of sample production.
FIG. 2:3 APPARATUS USED TO MOLD TEST SAMPLES
Bearing the above in mind, and considering the difficulties presented by ordinary plexy-glass tube mould, a Teflon mould was designed as shown in figure 2:3. The apparatus consisted mainly of a mixing bowl, stopper, mould chamber (1" I.D., 4 1/4" long) and end stopper all made of Teflon and designed to withstand temperatures up to 260°C (500°F) in a dry air oven. The top end of the Teflon stopper was connected to Crowley's Edward high vacuum pump. A temporary manual press with Teflon (31/32" dia., 1" long) was used to compress the sample material.

2:3:2 PROCEDURE

The predetermined amounts, by volume, of adiprene LD-955 and silicon carbide of 100 GGE were heated in a dry air oven with a capacity of 4 K.W., 0 - 500°F, for 3 - 4 hours at 73°C (164°F) to ascertain uniform temperature. The 73°C (164°F) temperature was selected to ensure the best properties. Silicon carbide was then mixed with urethane. The mixing was done by hand very slowly to avoid air bubbles entrapment but as thoroughly as possible to ensure uniform mixture. The mix was returned to the dry air oven to maintain the desired 73°C temperature.

The curing agent, moca, was heated separately to 121°C (250°F) in another oven. One, 1/4" O.D., 1" long, threaded brass rod, was fitted to the end cap of the mould and embedded in the sample to act as a conducting agent.

The silicon carbide and urethane mixture was put into a mixing bowl and stirred thoroughly but gently. The moca in its molten state at 121°C and of desired quantity, was introduced to silicon carbide and urethane mixture and mixed thoroughly with considerable alacrity. The vacuum pump
was simultaneously switched on for a few seconds to create a partial vacuum in the mould chamber. The stopper was then lifted at the appropriate time to allow the solution to enter the partially evacuated mould.

Once in the mould, the material was compressed manually and at the same time the 2nd electrode was emplaced. The applied pressure was kept in force for 3 - 4 hours after which time the sample was removed from the mould.

The sample was cured at 100°C (212°F) for six hours and at 70°C (158°F) for sixteen hours under controlled conditions. The sample was then allowed to cure for a further period of 3 days at room temperature and normal relative humidity before being tested in the laboratory.

2.3.3: ELECTRODES

Threaded brass rods 0f 1" length and 1/4" in diameter were embedded as electrodes in the test sample during moulding. Ciccotelli[1] drilled test insulators to accomodate the electrodes. That resulted poor electrical contact of electrode to insulating material. The improper contact would mean high localized electrical stresses, thereby affecting the performance of insulating material. The embedding will ensure good electrical contact.
## Table 2.1

**General Properties of Silicon Carbide**

[Commercially known as Carborundum]

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colour</td>
<td>Green (because of nitrogen impurity)</td>
</tr>
<tr>
<td></td>
<td>Blue or Dark black (aluminum impurity)</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>3.17</td>
</tr>
<tr>
<td>Melting point °F</td>
<td>4900 +</td>
</tr>
<tr>
<td>Specific heat (cal/g./°C)</td>
<td>0.143</td>
</tr>
<tr>
<td>Thermal expansion (0-2550°F)</td>
<td>2.17</td>
</tr>
<tr>
<td>per °F (x10^6)</td>
<td>4.7</td>
</tr>
<tr>
<td>per °C (x10^6)</td>
<td></td>
</tr>
<tr>
<td>Heat conductivity</td>
<td></td>
</tr>
<tr>
<td>(Btu/hr/ft^2/°F/in.)</td>
<td>293</td>
</tr>
<tr>
<td>(cal/sec/cm^2/°C/cm.)</td>
<td>0.49</td>
</tr>
<tr>
<td>Neutron Absorption Cross-section (cm^2/cm^3)</td>
<td>0.00647</td>
</tr>
<tr>
<td>Modulus of rupture psi (77°F)</td>
<td>24 \times 10^3</td>
</tr>
<tr>
<td>Modulus of elasticity psi (77°F)</td>
<td>68 \times 10^-6</td>
</tr>
<tr>
<td>Tensile strength psi (77°F)</td>
<td>25 \times 10^3</td>
</tr>
<tr>
<td>Compressive strength psi (77°F)</td>
<td>150 \times 10^3</td>
</tr>
<tr>
<td>Maximum Service Temperature</td>
<td></td>
</tr>
<tr>
<td>In Air (°F)</td>
<td>4000</td>
</tr>
<tr>
<td>In Inert Gas (°F)</td>
<td>3000</td>
</tr>
<tr>
<td>Refractive index</td>
<td>Approximately 2.65</td>
</tr>
</tbody>
</table>
### TABLE 2:2

**CHEMICAL STABILITY OF SILICON CARBIDE**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>In oxidizing media at temperature</td>
<td>1500</td>
</tr>
<tr>
<td>In steam</td>
<td>1300</td>
</tr>
<tr>
<td>In sulphur and sulphur dioxide up to</td>
<td>1000</td>
</tr>
<tr>
<td>In nitrogen up to</td>
<td>1100</td>
</tr>
<tr>
<td>In hydrogen and carbon dioxide</td>
<td>inert</td>
</tr>
<tr>
<td>In a mixture of nitric acid, Hydrofluoric acid and orthophosphoric acid of s.g. 1.75</td>
<td>becomes unstable only at 200 °C</td>
</tr>
<tr>
<td>Property</td>
<td>Temperature °C (°F)</td>
</tr>
<tr>
<td>-----------------------------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>Power factor (ASTM D150) percent</td>
<td>24 (75)</td>
</tr>
<tr>
<td></td>
<td>70 (158)</td>
</tr>
<tr>
<td></td>
<td>100 (212)</td>
</tr>
<tr>
<td>Dielectric Constant</td>
<td>24 (75)</td>
</tr>
<tr>
<td></td>
<td>70 (158)</td>
</tr>
<tr>
<td></td>
<td>100 (212)</td>
</tr>
<tr>
<td>Volume Resistivity ohm-cm</td>
<td>24 (75)</td>
</tr>
<tr>
<td></td>
<td>70 (158)</td>
</tr>
<tr>
<td></td>
<td>100 (212)</td>
</tr>
<tr>
<td>Dielectric Strength (ASTM D194) volts/mil</td>
<td>-</td>
</tr>
<tr>
<td>Arc resistance (ASTM D495) sec.</td>
<td>-</td>
</tr>
<tr>
<td>Parameter</td>
<td>Description</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Chemical Composition</td>
<td>Fully saturated urethane polymer</td>
</tr>
<tr>
<td>Physical Form</td>
<td>Viscous liquid</td>
</tr>
<tr>
<td>Color</td>
<td>Honey colored</td>
</tr>
<tr>
<td>Odour</td>
<td>Isocyanate odour</td>
</tr>
<tr>
<td>Available, Isocyanate content, %</td>
<td>9.0 % - 9.3 %</td>
</tr>
<tr>
<td>Brookfield Viscosity</td>
<td></td>
</tr>
<tr>
<td>30°C (86°F) cps</td>
<td>14000 - 22000</td>
</tr>
<tr>
<td>70°C (158°F) cps</td>
<td>Approximately 1000</td>
</tr>
<tr>
<td>80°C (176°F) cps</td>
<td>Approximately 800</td>
</tr>
<tr>
<td>Storage stability at room</td>
<td>Excellent in the absence of moisture</td>
</tr>
<tr>
<td>temperature</td>
<td></td>
</tr>
<tr>
<td>Solubility</td>
<td>Soluble in aromatic hydrocarbons, ketones, esters and chlorinated hydrocarbons.</td>
</tr>
</tbody>
</table>

TABLE 2:4

GENERAL DESCRIPTION OF ADIPRENE LD-955
<table>
<thead>
<tr>
<th>Property</th>
<th>LD-955 Typical values</th>
<th>LD-955 Range of Values</th>
<th>Adiprene L-315</th>
</tr>
</thead>
<tbody>
<tr>
<td>LD-955</td>
<td>100</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>Adiprene L-315</td>
<td>-</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>Moca (90% Theory based on % NCO)</td>
<td>25.8</td>
<td>25.8-26.6</td>
<td>27</td>
</tr>
<tr>
<td>Working Life at Mix temperature (158°F), seconds</td>
<td>150</td>
<td>150-190</td>
<td>70</td>
</tr>
<tr>
<td>Cure:</td>
<td>6 hrs/212°F</td>
<td>6 hrs/212°F</td>
<td>1 hr/212°F</td>
</tr>
<tr>
<td>Post Cure:</td>
<td>16 hrs/158°F</td>
<td>16 hrs/158°F</td>
<td>16 hrs/158°F</td>
</tr>
<tr>
<td>Condition before testing:</td>
<td>3 days/RT/3%RH</td>
<td>3 days/RT/50%RH</td>
<td>3 days/RT/50%RH</td>
</tr>
<tr>
<td>Hardness, Durometer D</td>
<td>72</td>
<td>70-75</td>
<td>72</td>
</tr>
<tr>
<td>100% Modulus, psi</td>
<td>3750</td>
<td>3500-5000</td>
<td>.4400</td>
</tr>
<tr>
<td>Tensile Strength at Break, psi</td>
<td>6800</td>
<td>6000-9300</td>
<td>9200</td>
</tr>
<tr>
<td>Elongation at Break, %</td>
<td>265</td>
<td>195-325</td>
<td>255</td>
</tr>
<tr>
<td>Flexural Modulus (ASTM D-790-61B), psi</td>
<td>85,000</td>
<td>78,000-93,000</td>
<td>100,000</td>
</tr>
<tr>
<td>Heat Distortion Temperature (66 psi), °F</td>
<td>293</td>
<td>257-320</td>
<td>320</td>
</tr>
<tr>
<td>Izod Impact Strength, lbs/in-notch</td>
<td>No Break</td>
<td>No Break</td>
<td>16</td>
</tr>
<tr>
<td>Comp. Set &quot;A&quot; (1350 psi/22 hrs/158°F), %</td>
<td>10</td>
<td>8-11</td>
<td>5</td>
</tr>
<tr>
<td>Bashore Resilience</td>
<td>58</td>
<td>51-58</td>
<td>48</td>
</tr>
<tr>
<td>NBS Abrasion Index</td>
<td>425</td>
<td>425-475</td>
<td>470</td>
</tr>
<tr>
<td>Solenoid Brittle Point</td>
<td>Lower than -94°F</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Dielectric Properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume resistivity, ohm-cm</td>
<td>$1.0 \times 10^{14}$</td>
<td>$3.2 \times 10^{14}$</td>
</tr>
<tr>
<td>Dielectric Strength, v/mil (25 mil specimen)</td>
<td>900</td>
<td>950</td>
</tr>
<tr>
<td>Dielectric Constant, 1000 cps, %</td>
<td>4.8</td>
<td>5.0</td>
</tr>
<tr>
<td>Power Factor, 1000 cps, %</td>
<td>2.98</td>
<td>2.90</td>
</tr>
</tbody>
</table>

1 Values shown in this column are based on a sample analyzing 9.0% NCO.
Range shown is based on fifteen separate determinations.

The types of mould and the moulding process used to produce specimens affect the results obtained in this test. In the case of bars compression moulded place the bars so that the direction of the testing force will be perpendicular to the direction of the moulding pressure. ASTM D-648-56

Cast bars have been shown to have all sides equivalent and to yield values essentially identical to those obtained from compression moulded bars tested on the side.

ASTM D-256; maximum value recorded 10 ft.-lbs. against 0.5 inch notched specimen.

Duplicate determinations.
**TABLE 2.6**

**EFFECT OF CURE TIME ON VARIOUS PROPERTIES**

of Adiprene

<table>
<thead>
<tr>
<th>Property</th>
<th>6 hrs/100°C</th>
<th>3 hrs/100°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>LD-955(^1)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Moca (90% Theory)</td>
<td>26.3</td>
<td>26.3</td>
</tr>
<tr>
<td>Cure:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition before testing:</td>
<td>3 Days/RT/50% RH</td>
<td>3 Days/RT/50% RH</td>
</tr>
<tr>
<td>Hardness, Durometer D</td>
<td>73</td>
<td>73</td>
</tr>
<tr>
<td>100% Modulus, psi</td>
<td>5000</td>
<td>4350</td>
</tr>
<tr>
<td>Tensile Strength at Break, psi</td>
<td>6500</td>
<td>6975</td>
</tr>
<tr>
<td>Elongation at Break, %</td>
<td>195</td>
<td>310</td>
</tr>
<tr>
<td>Flexural Modulus, psi</td>
<td>99,000</td>
<td>94,000</td>
</tr>
<tr>
<td>Izod Impact Strength, lb./in. notch</td>
<td>NB</td>
<td>NB</td>
</tr>
<tr>
<td>Heat Distortion Temperature (66 psi), °F</td>
<td>310</td>
<td>167</td>
</tr>
</tbody>
</table>

\(^1\)Data based on a sample analyzed 9.19% NCO.
### TABLE 2:7

**VULCANIZATE PROPERTIES OF ADIPRENE AT ELEVATED TEMPERATURE**

<table>
<thead>
<tr>
<th></th>
<th>75°F</th>
<th>158°F</th>
<th>212°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>LD-955</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moca (90% Theory)</td>
<td>26.5 (90)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measured at Temperature:</th>
<th>75°F</th>
<th>158°F</th>
<th>212°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness, Durometer D</td>
<td>73</td>
<td>63</td>
<td>59</td>
</tr>
<tr>
<td>100% Modulus, psi</td>
<td>4800</td>
<td>5550</td>
<td>4000</td>
</tr>
<tr>
<td>Tensile Strength at Break, psi</td>
<td>7650</td>
<td>9750</td>
<td>6300</td>
</tr>
<tr>
<td>Elongation at Break, %</td>
<td>270</td>
<td>285</td>
<td>310</td>
</tr>
</tbody>
</table>

Cure, 6 hrs/100°C + 16 hrs/70°C: Condition, 3 Days/RT/50% RH before testing.
TABLE 2:8
HEAT AGE RESISTANCE OF LD-9551 WITH MOCA 26.5%

<table>
<thead>
<tr>
<th></th>
<th>Original</th>
<th>7 Day/525°F</th>
<th>7 Days/302°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness, Durometer D</td>
<td>73D</td>
<td>97A</td>
<td>90A</td>
</tr>
<tr>
<td>100% Modulus, psi</td>
<td>4800</td>
<td>4700</td>
<td>3425</td>
</tr>
<tr>
<td>Tensile Strength at Break, psi</td>
<td>7650</td>
<td>7500</td>
<td>3450</td>
</tr>
<tr>
<td>Elongation at Break, %</td>
<td>270</td>
<td>280</td>
<td>.235</td>
</tr>
</tbody>
</table>

1 Cure, 6 hrs/100°C + 16 hrs/70°C; Condition, 3 Days/RT/50% RH before testing.

2 Specimens conditioned for 3 Days/RT/50% RH after aging and before testing.
<table>
<thead>
<tr>
<th>PROPERTIES</th>
<th>NATURAL RUBBER</th>
<th>ADIPRENE Polyurethane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength (psi) Pure gum</td>
<td>over 3000</td>
<td>over 4000</td>
</tr>
<tr>
<td></td>
<td>over 3000</td>
<td></td>
</tr>
<tr>
<td>Hardness Range (durometer A)</td>
<td>30-90</td>
<td>66-99</td>
</tr>
<tr>
<td>Specific Gravity (base material)</td>
<td>0.93</td>
<td>1.06</td>
</tr>
<tr>
<td>Vulcanizing Properties</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Adhesion of Metals</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Adhesion to Fabrics</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Tear Resistance</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Abrasion Resistance</td>
<td>Excellent</td>
<td>Outstanding</td>
</tr>
<tr>
<td>Compression Set</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Rebound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold</td>
<td>Excellent</td>
<td>Poor at very low temp.</td>
</tr>
<tr>
<td>Hot</td>
<td>Excellent</td>
<td>Good at R.T.</td>
</tr>
<tr>
<td>Dielectric Strength</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrical Insulation</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Permeability to Gases</td>
<td>Good - Excellent</td>
<td>Fair to Good</td>
</tr>
<tr>
<td>Acid Resistance</td>
<td></td>
<td>Fair</td>
</tr>
<tr>
<td>Dilute</td>
<td>Fair - Good</td>
<td>Fair</td>
</tr>
<tr>
<td>Concentrated</td>
<td>Fair - Good</td>
<td>Poor</td>
</tr>
<tr>
<td>Solvent Resistance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alephatic hydrocarbons</td>
<td>Poor</td>
<td>Excellent</td>
</tr>
<tr>
<td>Aromatic hydrocarbons</td>
<td>Poor</td>
<td>Fair - Good</td>
</tr>
<tr>
<td>Oxygenated (ketones etc.)</td>
<td>Good</td>
<td>Poor</td>
</tr>
<tr>
<td>Lacquer Solvents</td>
<td>Poor</td>
<td>Poor</td>
</tr>
<tr>
<td>Resistance to</td>
<td>Swelling in lubricating oil</td>
<td>Swelling in oil and gasoline</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>-----------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td></td>
<td>Poor</td>
<td>Poor</td>
</tr>
<tr>
<td></td>
<td>Poor</td>
<td>Excellent</td>
</tr>
</tbody>
</table>


### TABLE 2:10

**GENERAL DESCRIPTION OF MOCA**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Composition</td>
<td>4,4'-Methylene-bis-(2-chloroaniline)</td>
</tr>
<tr>
<td>Molecular Weight</td>
<td>267</td>
</tr>
<tr>
<td>Equivalent Weight</td>
<td>133.5</td>
</tr>
<tr>
<td>Physical Form</td>
<td>Pellets (100% through 1/2&quot; screen)</td>
</tr>
<tr>
<td>Colour</td>
<td>Yellow to light gray-tan</td>
</tr>
<tr>
<td>Odour</td>
<td>Slight</td>
</tr>
<tr>
<td>Specific Gravity, solid, at 75^°F (24^°C)</td>
<td>1.44</td>
</tr>
<tr>
<td>Specific Gravity, melt, at 225^°F (107^°C)</td>
<td>1.26</td>
</tr>
<tr>
<td>Melting Range</td>
<td>212 - 228^°F (100 - 109^°C)</td>
</tr>
<tr>
<td>Moisture content</td>
<td>Less than 0.5%</td>
</tr>
<tr>
<td>Storage Stability</td>
<td>Excellent - slight hygroscopic</td>
</tr>
<tr>
<td>Solubility</td>
<td>Soluble in ketones and esters</td>
</tr>
</tbody>
</table>

### TABLE 2:11

**SOLUBILITY OF MOCA AT 75^°F (24^°C)**

<table>
<thead>
<tr>
<th>Solvent</th>
<th>Solubility (% by Weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trichloroethylene</td>
<td>4.2</td>
</tr>
<tr>
<td>Toluene</td>
<td>7.5</td>
</tr>
<tr>
<td>Ethoxy-ethyl acetate</td>
<td>34.4</td>
</tr>
<tr>
<td>Methyl oxide</td>
<td>43.0</td>
</tr>
<tr>
<td>Methyl ethyl ketone</td>
<td>51.0</td>
</tr>
<tr>
<td>Tetrahydrofuran</td>
<td>55.5</td>
</tr>
<tr>
<td>Dimethyl Formamide</td>
<td>61.7</td>
</tr>
<tr>
<td>Dimethyl Sulfoxide</td>
<td>75.0</td>
</tr>
</tbody>
</table>
**TABLE 2:12**

**MOCA IN TYPICAL VULCANIZATES OF ADIPRENE L**

<table>
<thead>
<tr>
<th>Adiprene Polymer (%NCO)</th>
<th>L-42 (2.8)</th>
<th>L-83 (3.3)</th>
<th>L-100 (4.1)</th>
<th>L-167 (6.3)</th>
<th>L-200 (7.5)</th>
<th>L-213 (9.3)</th>
<th>L-315 (9.5)</th>
<th>L-420 (2.8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moca</td>
<td>8.9</td>
<td>1.5</td>
<td>12.4</td>
<td>19.0</td>
<td>22.6</td>
<td>26.6</td>
<td>27.1</td>
<td>8.8</td>
</tr>
<tr>
<td>Moca % Theoretical</td>
<td>100</td>
<td>100</td>
<td>95</td>
<td>95</td>
<td>95</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
</tbody>
</table>

---

**Mixing and Curing Conditions**

<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix Temperature °F</td>
<td>212</td>
<td>212</td>
<td>212</td>
<td>185</td>
<td>185</td>
<td>176</td>
<td>176</td>
</tr>
<tr>
<td>Cure, Hrs/212°F (100°C)</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Working life at Mix</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature, minutes</td>
<td>9</td>
<td>8</td>
<td>15</td>
<td>6</td>
<td>5</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

---

**Physical Properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>75-</th>
<th>80-</th>
<th>85-</th>
<th>93-</th>
<th>50D</th>
<th>600</th>
<th>750</th>
<th>750</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness, Durometer</td>
<td>80A</td>
<td>85A</td>
<td>93A</td>
<td>50D</td>
<td>600</td>
<td>750</td>
<td>750</td>
<td>800</td>
</tr>
<tr>
<td>Tensile Strength (psi)</td>
<td>2000+</td>
<td>4000+</td>
<td>4000+</td>
<td>5000+</td>
<td>8000+</td>
<td>8000+</td>
<td>7000+</td>
<td>3000+</td>
</tr>
<tr>
<td>Elongation at Break %</td>
<td>600</td>
<td>575</td>
<td>450</td>
<td>375</td>
<td>300</td>
<td>250</td>
<td>250</td>
<td>800</td>
</tr>
<tr>
<td>Tear Strength (ASTM D-470 lb./in.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Notched Izod Impact Strength ft-lb/in notch</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NBS Abrasion Index</td>
<td>70</td>
<td>85</td>
<td>75</td>
<td>130</td>
<td>135</td>
<td>145</td>
<td>115</td>
<td>70</td>
</tr>
<tr>
<td>Compression Set &quot;A&quot; (22 hr/158°F, 1350 psi) %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compression Set &quot;B&quot; (22hr/158°F) %</td>
<td>45</td>
<td>35</td>
<td>35</td>
<td>35-40</td>
<td>40</td>
<td></td>
<td></td>
<td>45</td>
</tr>
<tr>
<td>Bashore Resilience %</td>
<td>45</td>
<td>50</td>
<td>50</td>
<td>40</td>
<td>45</td>
<td>48</td>
<td>48</td>
<td>70</td>
</tr>
</tbody>
</table>

---

1 The effect of varying Moca concentration, mixing temperature and curing conditions is discussed in the individual Adiprene L bulletins.

2 As with other urethanes, the vulcanizate physical properties of Adiprene L polymers vary with the relative humidity at which the specimens are conditioned before testing. (Adiprene L Bulletin No. 5, Water Resistance of Liquid Urethane Vulcanizates). Specimens were conditioned for 3 days at 75°F (24°C) and 50% relative humidity.
CHAPTER III

EXPERIMENTAL PROCEDURE AND RESULTS

3:1 INTRODUCTION

Before a material is considered acceptable in any specific application, it is usually assessed experimentally in a laboratory as well as in service i.e. in the field for which the material is being considered. This study has been limited to laboratory testing in the form of a simulated model. The model as already mentioned was a 4" long cylindrical insulator 1" in diameter, made of silicon carbide filled adiprene LD-955 in varying formulation by volume as shown in table 3:1. The test performed could be classed into three categories:

1. Electrical
2. Mechanical
3. Thermal

The following sections give a precise discussion of the categories of tests performed.

3:2 ELECTRICAL TESTS

The following selected tests were performed to ascertain the applicability of this material, silicon carbide filled adiprene, for E.H.V. and U.H.V. power applications in contaminated environments.

Test #1 Voltage-Current characteristics under D.C. and A.C. voltages.
Test #2 Polarization effects, if any.
Test #3 Performance under cold switch on.
Test #4 Electrical breakdown (A.C. and D.C.)
Test #5 Electrical surface flashover (unfilled samples) (D.C.)

29.
<table>
<thead>
<tr>
<th>Type of Sample #</th>
<th>Silicon Carbide (100 GGE)</th>
<th>Adiprene&lt;sup&gt;2&lt;/sup&gt;LD-955</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>2.</td>
<td>40%</td>
<td>60%</td>
</tr>
<tr>
<td>3.</td>
<td>35%</td>
<td>65%</td>
</tr>
</tbody>
</table>

<sup>1</sup>The specific gravity for silicon carbide has been taken as 3.17 gm/cc

<sup>2</sup>The volume of adiprene corresponds to its volume at 73°C (164°F)
Test #6 Performance under direct flame.
Test #7 Tracking. (A.C. and D.C.)
Test #8 Flashover under contaminated conditions leading to breakdown. (A.C.
and D.C.)

3:2:1 HIGH VOLTAGE CIRCUITRY

Two transformers were used for D.C. and A.C. high voltage source respectively. For D.C. high voltage, a rectifying circuit was built into the x-ray transformer. For A.C. high voltage source, a drum type transformer was used. Specifications of both transformers are given below.

(1) D.C. High Voltage source

3 KVA, 220V/120KV x-ray high voltage unit modified to function as a half wave rectifier of 220V/60KV with primary 10.6 amps continuous rating and secondary 100 mAmmps.

(2) A.C. High Voltage source

8 KVA, 208-230V/50KV R.M.S., 1 phase, 50/60 Hz, primary 27 amps, secondary 170 mAmperes.

Figure 3:1 shows a simple block diagram of high voltage circuit for A.C. as well as D.C. systems. The only difference would be to switch in the capacitor bank for use on D.C. with a D.C. high voltage source; and switch off capacitor bank for A.C. with an A.C. transformer in circuit. A 25 KΩ resistor was connected in series with four additional 10 KΩ steps to change, if necessary, the value of the current limiting resistors. The capacitor bank comprises two 25 μf capacitor units connected in parallel to give capacitance of .5 μf. The capacitors ensured fairly constant voltage in testing i.e. they allowed minimal voltage drop during flashover and other heavy current testing activities. This also ensured
a smooth output from the rectifying circuit. A 600 M-Ω resistor was connected to the voltage measurement circuit. A 6 K-Ω resistor was connected in the discharge circuit. The low voltage side was grounded with a surge arrester of 200V and a paper gap of about 700V in parallel. This (LV. side) was further connected to a current measuring circuit with adequate protection. The surge arrester, paper gap protected the measuring circuit.

The high voltage source (A.C. or D.C.) was supplied from a single phase 220V power source, adjustable from 0 - 220V. The low voltage supply was controlled from a central cabinet with built-in protection for disengaging the test sample from high voltage in the event of:

1. Leakage current rising above the desired limits (through the tripping circuit).
2. Either fog chamber door or high voltage safety door opening or being opened while the high voltage system is in the on position. This has been achieved by providing an electrical interlock system.

3:2:2 HIGH VOLTAGE MEASURING CIRCUIT

The high voltage measuring circuit consists of a voltage divider of a 600 ± 15% M-Ω resistor and a 100K-Ω potentiometer connected to a high voltage source. The potentiometer was calibrated to give a ratio of 10V drop for 1 KV with respect to a drop at the high resistance. A D.C. vacuum voltmeter (by Hewlett Packard) was used for measuring the voltage across the potentiometer. A neon bulb of 90V and a paper gap of about 700V were connected in parallel across the voltmeter to ensure the limited voltage across the voltmeter as shown in figure 3:2.

The voltmeter for D.C. was calibrated with an electrostatic voltmeter
1. Control cabinet to supply primary of H.V. source.
2. High voltage source (A.C. or D.C.)
3. Current limiting resistor
3a. Discharge circuit resistor.
4. Capacitor bank (65 microfarads)
5. 600M-ohm resistor
6. High voltage measuring circuit.
7. Fog chamber with sample mounting arrangements housed in.
8. Protection circuit.

FIGURE 3:1 HIGH VOLTAGE (A.C. AND D.C.) CIRCUIT
1. High voltage source.
4. 600K-ohm resistor for voltage divider circuit.
5. 100 K-ohm potentiometer calibrated to 60 ± 15% K-ohm for voltage measurements.
6'. Capacitor bank (5 microfarads).
7. Neon lamp (90V).
8. D.C. vacuum tube voltmeter model 412A.

FIGURE 3:2 VOLTAGE MEASURING CIRCUIT
made by Electrical Instrument service, serial no. ES 6076, model ESH 23CX.
The electrostatic voltmeter has 10, 25, 50 - KV ranges with 0.5\% accuracy
over the full range. An accuracy of about 1\% was achieved with respect to
the electrostatic voltmeter.

3:2:2 LEAKAGE CURRENT MEASURING CIRCUIT

One of the most important aspects of this study was to monitor the
leakage current which plays the key role in the performance of antipollution
insulators. The leakage current is responsible for raising insulator
surface temperature and for avoiding contamination flashover. Figure 3:3
shows a simple circuit for the measurement of leakage current. Double
protection was provided on the low voltage side of the test samples. One
ground was connected directly through a paper-gap of about 700V and a surge
arrester of 200V in parallel, and the other through a 90V surge arrester in the
current measuring circuit. A digital multimeter, DMM2 (by Advance Instruments)
calibrated by the lab technician and having \( \pm \) .3\% accuracy was connected
for current measurement in service with the 1.66 K-ohm resistor as shown in figure
3:3. A three way switch was provided with a 10 ohm potentiometer and 8 ohm
resistor to connect a U.V. recorder type SE. 2005 and having an accuracy
of \( \pm \) 1\% used for continuous recording of current). The U.V. recorder
circuit though not used extensively was calibrated to give 0, 3, 20 mA
settings of the three point switch (\( '0' \) setting to bypass the U.V. recorder).
The Ultra Voltage recorder scale was calibrated against a DMM2 meter. A
1 A. 250Y, 3A. 125V potentiometer along with the two other resistors were
calibrated and were set to provide tripping signal for tripping the circuit
1. Surge arrester (200V).
3. Surge arrester (90V).
4. 1.66 K-ohm resistor.
5. Digital multimeter DMM2 (accuracy ± 0.3%).
6. U.V. recorder.
7. Three position switch for recorder (a for off, b for 3mA, c for 20 mA, i.e., three operational settings.)
8. 10 ohm 20 mA potentiometer for calibration (used at 2 ohms).
9. 8 ohm resistor.
10. 1A 250V, 3A 125V potentiometer for tripping signals (195 microamps - 20 mA).
11. 47 ohm resistor.
12. 100 ohm potentiometer (used 75 ohms) for maximum tripping current.

**FIGURE 3:3 CURRENT MEASURING CIRCUIT**
housed in the control cabinet. The mechanism was used for disengaging the high voltage source from the test samples in the event of leakage current exceeding the maximum value of 20 mA, prescribed range. The desired range was established at 125 microamps - 20 mA.

3:2:4 MOUNTING ARRANGEMENT FOR TEST SAMPLES

Figure 3:4 shows a simple but very efficient arrangement for mounting the test samples inside the fog chamber for high voltage application. The test sample (as #1) with pre-embedded electrodes is screwed into two (1-1/2" x 1/2") brass rods (#3). The #3 is threaded into a 4" long and 1/2" in I.D. aluminum conduit (#4) which fits over another 1/2" in diameter aluminum threaded rod. This arrangement is supported by the fog chamber walls.

3:2:5 ELECTRICAL CONDUCTION MECHANISM

In chapter II the voltage-current characteristics were prescribed for silicon carbide, a semi-conducting material, as having conduction intermediate between conductor and insulator. The semiconductors are more or less crystalline in nature and their unique properties are derived from the intentional creation of minute imperfections. The electronic conduction in semiconductors are generally described in terms of either the band or the hopping type [21].

In all conductors, semiconductors or insulating materials, or any mixture of these, two main bands exist. These are the valence and the conduction band, and are separated by an energy gap, generally known as the forbidden gap. The valence band refers to the band of energy/energies which corresponds to the electrons tied to the parent atom. The conduction
FIGURE 3.4 MOUNTING ARRANGEMENT FOR TEST SAMPLES

1. Test Sample (4") long and 1" in diameter
2. 1" x 1/4" Brass Electrode
3. 1/2" Brass Rod (1/2" long) threaded to fit in 2 and to screw in 1/4" Brass Electrode
4. 1/2" Aluminum conduit threaded both sides to fit on 1 and 5
5. 1/2" Aluminum rod threaded both sides to go in 4 and fog chamber walls for supporting the mounting arrangement.
band refers to the band in which the electrons, cross over the parent atom, after having acquired sufficient energy. Thus once an electron is in the conduction band, it is free to migrate through the material crystal to act further along with a number of the other free electrons, which constitutes a conduction current to flow.

The creation of a free electron or the displacement of an electron from the valence band to reach the conduction band, would need sufficient energy to cross the forbidden gap. This could be achieved by incorporating impurities or by thermal, photo, or field excitation. The total conduction current flowing would be determined by the number of free electrons and their movements from the valence band to the conduction band.

In the hopping type conduction, the electrons or charge carriers, would have to jump from one state of energy to another state by crossing the energy barrier [21]. A distinction between the types of conduction expected to be predominant in silicon carbide filled adiprene can be made by understanding the basic difference between band type and hopping type conduction.

Forster [21] showed that A.C. conductivity should be higher than D.C. conductivity for hopping type conduction, and that A.C. and D.C. conductivity should be nearly equal in band type conduction. He further showed that the A.C. conductivity will increase with an increase in frequency for the hopping type and it will decrease similarly for the band type. Finally he showed that in hopping type conduction the barrier energy required for the electrons to jump will decrease with decreasing temperature or it will increase with increasing temperature, while there will be no appreciable change for band type conduction.
Figure 3.5 D.C. Current - Voltage Characteristics of Rubber
Read and Stow [22] have performed a number of experiments to establish the kind of conduction in rubber. They have concluded that the hopping type conduction predominates in rubber. Figure 3:5 shows current-voltage characteristics established by them.

It has been found experimentally (see 3:2:6) that the conduction in silicon carbide filled adiprene could be safely assumed to be the hopping type. Figure 3:8 and figure 3:9 indicates that A.C. conductivity is higher than D.C. conductivity. Thermal tests discussed in section 3:6 show that conductivity decreases with increasing temperature and it increases with decreasing temperatures. The result of the first six tests conducted on a number of samples with varying formulation are reported below.

3:2:6 PROCEDURE AND RESULTS FOR TESTS 1 - 6

Sixty test samples of a particular formulation were first subjected to D.C. high voltage. The voltage was raised in steps of 2 KV every 15 minutes allowing sufficient time for the current to be steady at a particular stage. The leakage current was recorded. The above steps were repeated to attain working voltage of 20 - 24 KV for a 4" sample.

Figures 3:6-3:10 show the current-voltage characteristics of various samples of different/same formulation under D.C. and A.C. fields. The A.C. testing was carried out using the same method and procedure, but the following changes were required:

a) From D.C. voltmeter to A.C. voltmeter.
b) From D.C. high voltage source to A.C. high voltage source (drum transformer, 8KVA 220/50KV).
c) Disconnecting the capacitor bank.

Figure 3:6 shows current-voltage characteristics for one sample under
FIGURE 3:6 CURRENT VOLTAGE CHARACTERISTICS OF SILICON CARBIDE FILLED ADATENE SHOWING INITIAL AND FINAL STEADY STATE VALUES.

1. The instant voltage was increased by one step.

2. Steady state, 15 minutes after raising the step, of 2 KV.
FIG. 3.7 Current-Voltage Characteristics of Silicon Carbide Filled Polyurethane Cylindrical Insulator 1" dia. and 4" Long for Different Mixtures by Volume.

(1) 50:50; (2) 40:60; (3) 35:65.
FIGURE 3:8 CURRENT-VOLTAGE CHARACTERISTICS OF SILICON CARBIDE FILLED ADIPRENE CYLINDRICAL SAMPLE INSULATORS 1" DIAMETER, 4" LONG UNDER AN A.C. FIELD

Formulation used by volume:

1. (50:50)
2. (40:60)
3. (35:65)
FIGURE 3:9 COMPARISON OF CURRENT - VOLTAGE CHARACTERISTICS OF 40:60 SAMPLE OF SILICON CARBIDE FILLED ADIPRENE INSULATORS

1. Under A.C. Field (R.M.S.)

2. Under D.C. Field
FIGURE 3:10 CURRENT - VOLTAGE CHARACTERISTICS OF SILICON CARBIDE FILLED EPOXY IN 2:1 RATIO BY WEIGHT
(Epoxy # 2211, and 2320 were tested).
the same test conditions. Curve #1 corresponds to the values taken just
after increasing the voltage and curve #2 corresponds to the values taken
after the leakage current had attained the steady state condition. Figure 
3:7 shows the voltage - current characteristics of steady state values of 
samples with different formulation as indicated on the diagram. The ratio 
40:60 pertains to the amounts by volume of silicon carbide and adiprene 
LD-955 used in the preparation of test samples. The testing was confined 
to these ratios because of too low and too high conduction outside the 
selected range as already confirmed by Ciccotelli [1].

Figure 3:8 shows the voltage - current characteristics of 40:60 
(silicon carbide to adiprene) sample insulators of silicon carbide filled 
adiprene under an A.C. field. The pattern of conduction was observed to be 
similar except that the higher leakage current was recorded due to the 
predominance of hopping type conduction. Figure 3:9 gives a better evaluation 
of the difference between A.C. and D.C. conductivity in silicon carbide 
filled adiprene. For this examination a number of samples of 40:60 formulation 
were selected and tested first under D.C. and then A.C. high voltage. The sequence 
was reversed to examine the effect of field change. There was no noticeable 
damage to the samples. Curves #1 for A.C. and #2 for D.C. were obtained.

Epoxides filled with silicon carbide were also evaluated. The conduction 
phenomenon appeared to be quite similar at first as shown in figure 3:10, but 
epoxides proved to be unacceptable material due to sudden increase in conduction 
They were found unacceptable especially for EHV and UHV projects. Epoxides 
of various grades and varying formulation of silicon carbide of 100 CGE were 
tested under A.C. and D.C. high voltage for electrical conduction: Their
behaviours was found to be identical. Although the compound contained smaller amounts of silicon carbide, the conduction started at higher applied voltage. The conduction progressed slowly, but then increased from 30 micro-amps to the value of 300 - 500 microamps over a small change in applied voltage as indicated by points A, B on fig. 3:10, p. 46. This fact was also confirmed by one of the researchers while checking filled epoxy (with silicon carbide) for evaluation of track resistance. The behaviour of silicon carbide filled epoxides (AP 2320, AP 2211) was found to be unpredictable. Thus, it could be safely stated that the results of this research proved that silicon carbide filled adiprene is superior to silicon carbide filled epoxides.

In addition to current-voltage characteristics, the material was evaluated for any permanent polarization effect. The polarization term is defined as: "the moment of the charged atom under the influence of an electrical field". The polarization effect was checked under D.C. and under A.C. fields. The sample was maintained at 24KV D.C. voltage, for a period of 24 hours. The polarity was then reversed suddenly. No appreciable change was observed except a slight increase in conduction of about 5 microamps against 90 microamps. This checking of polarization effect was repeated by changing polarity in varying intervals of one hour to 7 days. The percentage increase in conduction did no change significantly. Finally the samples were subjected to A.C. high voltage but showed no sign of usual polarizations effect. If the material had any polarization effect, the conduction pattern under the A.C. field would not have been similar to the D.C. field. Thus, it can be concluded that the material does not exhibit any permanent polarization effect.

Seven randomly chosen samples were time tested to check any conditioning effect.
under applied voltage. The results were found to be satisfactory. Further assessment of the material was made by subjecting a few samples to A.C. and D.C. high voltage for varying intervals of 10 minutes, 6 hours, 24 hours, 7 days, and 15 days. Again the results were found to be satisfactory. This confirms that insulators manufactured from silicon carbide filled adiprene would not be less superior than conventional insulators.

The material was also checked for electrical breakdown under A.C. and D.C. voltages and for any recovery from breakdown. The breakdown voltage ranged from 44 - 48 KV with two samples at 56 KV. The recovery was found to have a declining trend of 75%, 50%, 40%, etc. of breakdown values of voltage. This is an acceptable recovery rate but it also depends on the degree of destruction that the insulator has undergone. The tendency of breakdown has been in general as shown in figure 3:10. It was further noticed that the breakdown voltage range was the same with or without fibre glass reinforcement. Thus there was no interface problems with this material (filled adiprene).

The unfilled adiprene LD-955, was evaluated for surface flashover. 30 mm. long and 25.4 mm. in diameter samples of unfilled adiprene were moulded and cured using the same moulding technique and were tested under high voltage for surface flashover. The flashover voltage ranged from 27.6 KY to 28.4 KY. Every sample was checked for 20 - 25 flashovers even repeatedly, but the same results were obtained. This means that the dielectric strength of adiprene is 920V/mm to 946V/mm. This agrees with 900 - 950 V/mm value given in literature mentioned in table 2:5. There was also no appreciable damage on the surface.

The material was further checked for direct flame effect. For comparison, silicon carbide filled and unfilled adiprene, filled and unfilled epoxy,
Teflon and phenolic were checked for performance under direct flame. A high temperature propane torch was used for the flame. Table 3:1A shows a comparative statement of results obtained. It can be concluded that filled adiprene is certainly better than phenolic and epoxy already in use for insulation purposes.

3:2:7 DISCUSSION OF RESULTS FROM 3:2:6

The main objective of this research was to evaluate and establish a material having the desired properties for use as antipollution insulators. One of the main qualities required in the material is conduction. It must have a positive temperature co-efficient of resistance to be thermally stable. It should resist the formation of an electrolytic film over the polluted insulator surface. Where film formation is unavoidable it should retain acceptable uniform conduction with graded type resistance. This would ensure wide dry band formation with required series resistance to avoid flashover in contaminated atmospheres.

From the results so far presented it is clearly seen that silicon carbide filled adiprene does have desirable and controllable electrical conduction depending upon the material formulation used as shown in table 3:2. Because of electrical conduction, the material would certainly exhibit some electrical energy loss, which converts into heat energy. This heat will keep the surface temperature well above the ambient temperature. The conduction phenomenon has already been explained in 3:2:5 and an examination of figures 2:1, 2:2 and 3:5 would reveal certain current - voltage characteristics anticipated for silicon carbide filled adiprene. This anticipated behaviour has already been shown in figures 3:6 - 3:9. So far the material was found
**TABLE 3:IA**

**COMPARATIVE PERFORMANCE OF VARIOUS INSULATING MATERIALS UNDER DIRECT FLAME**

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>COMPARATIVE TIME</th>
<th>EXTINGUISHABILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Unfilled adiprene</td>
<td>Longer than items 3, 4, 5</td>
<td>Quick self extinguishing</td>
</tr>
<tr>
<td>2. Filled adiprene</td>
<td>Almost same as item 1</td>
<td>Same as item 1</td>
</tr>
<tr>
<td>3. Unfilled epoxy</td>
<td>Very quick wrt. items 1, 2, 6</td>
<td>Took more time than items 1 and 2</td>
</tr>
<tr>
<td>4. Filled epoxy</td>
<td>Almost same as item 1</td>
<td>Same as item 3</td>
</tr>
<tr>
<td>5. Phenolic</td>
<td>Very quick as compared to items 1, 2, 6 and 3, 4</td>
<td>Much worse as compared to items 1-4, 6</td>
</tr>
<tr>
<td>6. Teflon</td>
<td>Much more than 1-5</td>
<td>Very quick to get extinguished (self)</td>
</tr>
</tbody>
</table>
**TABLE 3:2**

**CONDUCTION RANGE FOR DIFFERENT FORMULATION OF SILICON CARBIDE TO ADIPRENE**

<table>
<thead>
<tr>
<th>Sample number (type)</th>
<th>% Concentration of Silicon Carbide</th>
<th>Conduction Range mA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>By Weight</td>
<td>By Volume</td>
</tr>
<tr>
<td>1.</td>
<td>146</td>
<td>50</td>
</tr>
<tr>
<td>2.</td>
<td>120</td>
<td>40</td>
</tr>
<tr>
<td>3.</td>
<td>102</td>
<td>35</td>
</tr>
</tbody>
</table>

Note: Sixty samples of each type were tested to ascertain the validity of results. The conduction refers from linear to steady state condition as shown in figs 3:6-3:9.
### TABLE 3:3

**ELECTRICAL PROPERTIES OF SILICON CARBIDE**

**FILLED ADIPRENE WITH VARYING FORMULATIONS**

<table>
<thead>
<tr>
<th>Type of Sample #</th>
<th>Total Arga Sq.&quot;/cm.&quot;</th>
<th>Working Voltage (KV)</th>
<th>Range of Resistance MΩ</th>
<th>Range of Power Loss mW/cm.² (mM/Sq.&quot;),</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>12.57/81.07</td>
<td>8-16</td>
<td>267-89</td>
<td>2.96-35.5 (19.1-229)</td>
</tr>
<tr>
<td>3.</td>
<td>12.57/81.07</td>
<td>26-36</td>
<td>1400-480</td>
<td>6.90-33.30 (44.5-214.86)</td>
</tr>
</tbody>
</table>
to have acceptable conduction. Moreover, the conduction tends to a saturation level around the working voltage of 5-6 KV/inch. It also has breakdown voltage of 11-12KV/inch. The values are far superior to porcelain. Another point worth while mentioning is that the material has uniform voltage distribution along the insulation length. It has further been found to have a temperature gain of about 5-6°C with 40-60 microamps conduction at 20-24 KV. Table 3:3 shows the electrical properties i.e. energy dissipated per unit area.

The other beneficial properties are listed below:

1. No permanent polarization effect.
2. Excellent performance for surface flashover.
4. Excellent self-extinguishing property.
5. Uniform temperature for contamination resistance.
6. Works well under cold switch on codition.

3:3 TRACKING
3:3:1 INTRODUCTION

Tracking is the "formation of a permanent conducting path across a surface of the insulation." [24]

This conducting path in most cases, especially in organic material results from the degradation of insulating properties of the insulating material. This degradation could be due to high temperature, due to arcing.

The three essential conditions of the tracking phenomenon are:

1. The presence of a conducting film across the surface of the insulation.
2. A mechanism whereby leakage current is interrupted with the production
of a spark. (The interruption here refers to narrow 'dry bands'.)

3. Degradation caused by high temperature due to arcing.

Track resistance controls the formation of sparks across the insulation surface. The conducting film due to moisture absorbed by hygroscopic or other pollutants, creates a narrow 'dry band' and established very high voltage across a limited insulation. This dry band breaks down and forms an electric arc. The arc can further elongate and bridge the electrodes, thus forming a permanent conducting path.

Theoretically [24], the tendency to track depends on the proportion of the bonds, which produce free carbon on pyrolysis if:

\[
\Delta H_c = \text{the energy of all bonds which, on breaking produce free carbon}
\]

\[
\Delta H_{cpd} = \text{the Total bond energy of the molecule}
\]

Then ratio \( R = \Delta H_c / \Delta H_{cpd} \)

Thus lowering the value of \( R \), will reduce the likelihood of the material tracking as shown in figure 3:11. Considerable amount of research has been conducted to find the most effective method to evaluate the tracking resistance of the insulating materials, and to interpret the results thus obtained. Nato and Kawamura [25] have made use of a capacitor discharge method to produce an arc at 5kV and 5mA discharge current at different cycles. They used tungsten electrodes placed 2 mm apart on the surface of a specimen of insulating material.

They attempted to analyze the results by finding the gassification factor and weight of the various components such as:

1. Total weight of degraded material.
FIGURE 3.11 RELATION BETWEEN DUST/FOG LIFE AND CARBON FORMING TENDENCY FOR VARIOUS INSULATING MATERIALS [FROM ALSTON]
2. Weight of solid carbon if any.
3. Weight of decomposition gases and volatile components.
4. Weight of inorganic residue.

They claimed the method is satisfactory since it has less tendency of eroding the material. The method of analysis was found to be inadequate in finding different by product weights mentioned above. As an example, the weight of free carbon is very difficult to establish. The discharge method has its own limitations. They suggested the energy ratio evaluation method. This method is found to be limited to unfilled materials.

Hino [26] has used the trigger discharge method for finding the effective value of track resistance of insulating materials. He used gas analysis as a basis for evaluating the tracking weakness in a selected material. He stated that the tracking characteristics is a strongly related to the applied voltage, and that tracking properties should be studied under the expected working voltage of the material being tested. He has shown that "the addition of Al₂O₃·3H₂O (Aluminum hydroxide) to an organic insulating material inhibits deterioration by oxidation considerably."

Kurtz [27] presented a complete review of the results obtained for tracking resistance by the use of various methods, but has not been able to conclude the most reliable method for track resistance evaluation.

In this study, electrolyte drop method and inclined plane track methods have been used because of their simplicity and their standardized procedure.

3:3:2 COMPARATIVE TRACKING INDEX (B.S. 3781 (1964))

This method "comparative tracking index of solid insulating materials (B.S. 3781 (1964))", is given in IEC 112 publication. [For details see
Appendix A). The procedure was followed very closely as recommended in the publication. Figure 3:12 gives a simple circuit diagram, where two brass electrodes of standard dimension were placed 4 ±0.1 mm. apart on the surface of the test sample (50 x 50 x 5 mm). 100 Volt A.C. was applied, controlled by a 135V 5 amperes autotransformer, and 115/375 volts 500 milliamperes instrument transformer. It should be noted that the material would fail at 500mA persisting for a minimum period of two seconds at 100 - 500 volts, and 500mA for 10 seconds for any other high voltage during 100 drops. The electrolyte of 0.1% ammonium chloride solution at one drop every 30± 5 seconds was allowed to drop from the pipet placed 25 ± 5 mm. above the surface. The conduction was recorded just before and after the fall of the drop. The experiment was completed for 100 drops although IEC recommendation requires only for 50 drops. Then the voltage was raised in 50 volt steps and the entire procedure was repeated to 450V after cleaning the sample and electrode after each step. A maximum conduction 260 mA was observed. The material showed no erosion or any kind of deterioration up to 400 volts. Some insignificant burning was noticed at 450 volts. This burning was self-extinguishing. Due to this burning subsequently some surface erosion was also observed. The test was repeated for a number of samples and different spots on the same sample.

The results are considered to be satisfactory.

The experiment was also conducted for phenolic, filled and unfilled epoxides, Teflon and ceramic. The adiprene results are tabulated in table 3:4. The comparative results are shown in table 3:5. An examination of these tables reveals at least for preliminary purposes the acceptability of silicon carbide filled adiprene.
T₁ 135V 5A Auto-Transformer
T₂ 115/375, 500mA Transformer
V Voltmeter (0 - 500V)
A Ammeter (0 - 100, 0 - 1000 mA)
S Test sample (50 x 50 x 5 mm)
E Brass electrode (standard size)
C 0.1% Ammonium chloride drops @ 30 sec.

FIGURE 3:12 CIRCUIT FOR COMPARATIVE TRACKING INDEX OF SOLID INSULATING MATERIALS
<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>REPORT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Each voltage applied and associated. No: of drops either tabulated or as curve</td>
<td>See table 3:5</td>
</tr>
<tr>
<td>2) The comparative tracking index</td>
<td>No tracking</td>
</tr>
<tr>
<td>3) Thickness of test piece</td>
<td>5mm.</td>
</tr>
<tr>
<td>4) Nature of surface tested</td>
<td>Flat and almost smooth</td>
</tr>
<tr>
<td>5) Any loss of material during the test and if no failure by tracking occurred, the maximum depth of erosion occurred</td>
<td>No tracking, erosion about 1.5 mm. maximum depth</td>
</tr>
<tr>
<td>6) Any other effect, other than tracking and erosion.</td>
<td>Burning, smoking and a minor fire at 450V but self extinguishing</td>
</tr>
</tbody>
</table>
### TABLE 3:5
RESULTS OF COMPARATIVE STUDY OF TRACKING
BY THE DROP METHOD
(100 drops)

<table>
<thead>
<tr>
<th>Material Used</th>
<th>Performance at: (Voltages)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Unfilled Adiprene</td>
<td>No Tr.</td>
</tr>
<tr>
<td>Filled Aliprene</td>
<td>No Tr.</td>
</tr>
<tr>
<td>Phenolic</td>
<td>No Tr.</td>
</tr>
<tr>
<td>Unfilled Epoxy</td>
<td>No Tr.</td>
</tr>
<tr>
<td>Filled Epoxy</td>
<td>No Tr.</td>
</tr>
<tr>
<td>Ceramic</td>
<td>No Tr.</td>
</tr>
<tr>
<td></td>
<td>No Er.</td>
</tr>
<tr>
<td>Teflon</td>
<td>No Tr.</td>
</tr>
<tr>
<td></td>
<td>No Er.</td>
</tr>
</tbody>
</table>

Note: No Er. - No Erosion
No Tr. - No Tracking
3:3:3 INCLINED PLANE TRACKING (ASTM 2303D-68) TESTS

The method "Liquid - Contaminant" inclined plane, Tracking and Erosion of Insulating Material" was used to confirm the results obtained previously in BS 3781 (1964), electrolyte drop method.

Day [28] has done extensive study of track resistance characteristics of filled and unfilled material under various conditions using the inclined plane method. He stated that this method though useful in evaluating the life expectancy of the material but it cannot be safely depended upon because of varying conditions in service. He used silicon carbide of 50 GGE as filler and performed a number of experiments on filled and unfilled epoxy and found that very few samples survived. They all failed at 1 - 7 KV. He concluded that the effect of silicon carbide as a filler in epoxy is still unpredictable. Such epoxides being satisfactory for low voltage only and may continue to be used for want of a better product.

Figure 3:12A shows a single line diagram of various components used in this study [see Appendix B]. This study also used standard electrodes, electrolyte and test samples.

The electrolyte, 0.1 ±0.002% of ammonium chloride with 0.02% of photo flow solution, was regulated with a pressure equalizer and a regulating valve. The quantity of the electrolyte was calibrated in terms of drops/mil and was checked every hour during the experiment. The rest of the components such as current limiting resistor and fuse resistor were as per ASTM 2303-68.

To check the initial tracking voltage the experiment was initiated at 3KV with appropriate rate of flow of electrolyte. The voltage was raised in 250V steps at an hourly-interval as per standard method. The voltage
was raised to 7.5Kv and no tracking was observed.

There was significant amount of scintillation from the start of the experiment at 3 KV. This is shown in the pictorial view in figure 3:13. The sample showed minor burnings and smoking with about 5% increase in conduction. The minor surface fires were self extinguishing. It was not necessary to switch off the high voltage source. This unstable condition continued for about 30 minutes and then corrected itself. The loss of material due to erosion continued slowly during the first 4 hours of the test up to 4 KV and later stabilized itself. The test was allowed to run for 22 hours continuously. The only physical observation was erosion of about 2.5 mm deep and residue of light creamish/yellowish colour on the edges of the eroded surface close to the electrode. The final pictorial view of the tested sample is given in figure 3:14. This clearly shows how urethane burns out under a high temperature electrical arc.

Cessation of erosion could be due to the formation of silicon carbide layers after the urethane had decomposed into its various constituents such as H₂O, CO, CO₂, etc. Silicon carbide is not affected below 2000° C. The report is presented in table 3:6. The conduction and activities, step wise is shown in table 3:7.

These tests were conducted on other samples having varying amounts of filler to confirm the results. These tests were conducted at 7.5KV for 6 - 10 hours. The maximum conduction was 47 - 53 mA, during which mainly erosion was observed.

For comparison, filled and unfilled epoxy was evaluated for track resistance with the same standard test method. The failure voltages with
1. Electrolyte Container
2. Pressure Equalizer
3. Regulating Valve
4. Electrolyte Supply Line
5. 50 K-ohm/200W Resistor of H.V. Side
6. Test Sample at 45 degrees to ground.
7. 1/2 Watt 330 Ohm Spring loaded fuse resistor

FIGURE: 3.12A SINGLE LINE DIAGRAM FOR INCLINED PLANE TRACKING METHOD (ASTM 2303D-68)
FIGURE 3.13: VIEW OF SCINTILLATIONS ON THE SURFACE OF THE SILICON CARBIDE FILLED ADIPRENE'S STANDARD SAMPLE AT 3 KV, A.C., RMS.
FIGURE 3:14 VIEW OF SILICON CARBIDE FILLED ADIPRENE SAMPLE AFTER TESTING FOR TRACK RESISTANCE
<table>
<thead>
<tr>
<th>Description</th>
<th>Report</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Type and designation of material used.</td>
<td>100% CF E silicon carbide filled Adiprene LD-955.</td>
</tr>
<tr>
<td>2. Details of specimen fabrication including size, thickness, cleaning procedure, solvent used, surface finish if any, preconditioning, etc.</td>
<td>The fabrication procedure same as for other samples except mould, mould was for the desired size 5&quot; x 2&quot; x 2&quot;. The cleaning was done with methanol and distilled water and moulded surface (with no grinding, no machining) was used.</td>
</tr>
<tr>
<td>3. Orientation of specimen in respect of electrodes (i.e. machining direction or fill direction etc.)</td>
<td>Filler (SiC) was mixed as thoroughly as possible and moulded horizontally but no machining.</td>
</tr>
<tr>
<td>4. Contamination concentration Contamination conductivity Temp. during conductivity</td>
<td>0.1% Ammonium chloride solution 380 Ohm-cm. 24°C</td>
</tr>
<tr>
<td>5. Test voltage or voltages and associated rate of contamination liquid applicable</td>
<td>See Table 3:7 and Appendix B</td>
</tr>
<tr>
<td>6. Initial tracking voltage and No. of steps used including at which continuous tracking occurred</td>
<td>No tracking noticed in continuous form and 18 steps taken to reach 7.5KV from 3KV</td>
</tr>
<tr>
<td>7. Time to progressive tracking during the last voltage step.</td>
<td>No tracking thus not applicable.</td>
</tr>
<tr>
<td>8. Appearance of test specimen and the track including a notation as to the qualitative degree of erosion.</td>
<td>See Figure 3:14 for appearance. Erosion 2-2.5 mm. deep in 22 hrs.</td>
</tr>
<tr>
<td>9. For time to track test.</td>
<td>Almost all the specimens behaved identically even on direct start at 7.5 KV and keeping this voltage and 0.9mil/min rate of electrolyte flow for 6 - 10 hrs. Thus no question of time to track arises under the present circumstances.</td>
</tr>
<tr>
<td>Applied Voltage (KV)</td>
<td>Leakage Current (mA)</td>
</tr>
<tr>
<td>----------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>3.00</td>
<td>8-20</td>
</tr>
<tr>
<td>3.25</td>
<td>50-55</td>
</tr>
<tr>
<td>3.50</td>
<td>50-57</td>
</tr>
<tr>
<td>3.75</td>
<td>Approx. 50</td>
</tr>
<tr>
<td>4.00</td>
<td>11-13</td>
</tr>
<tr>
<td>4.25</td>
<td>Approx. 11</td>
</tr>
<tr>
<td>4.50</td>
<td>Approx. 25</td>
</tr>
<tr>
<td>4.75</td>
<td>Approx. 33</td>
</tr>
<tr>
<td>5.00</td>
<td>Approx. 35</td>
</tr>
<tr>
<td>5.25</td>
<td>36</td>
</tr>
<tr>
<td>5.50</td>
<td>36.5</td>
</tr>
<tr>
<td>5.75</td>
<td>39</td>
</tr>
<tr>
<td>6.00</td>
<td>40</td>
</tr>
<tr>
<td>6.25</td>
<td>43-44</td>
</tr>
<tr>
<td>6.50</td>
<td>45-46</td>
</tr>
</tbody>
</table>
Continuation of Table 3:7

<table>
<thead>
<tr>
<th>Value</th>
<th>Range</th>
<th>Current</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.75</td>
<td>46-46.5</td>
<td>0.90</td>
<td>Simple arc in eroded part</td>
</tr>
<tr>
<td>7.00</td>
<td>47</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>7.25</td>
<td>48</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>7.50</td>
<td>50</td>
<td>0.90</td>
<td>The sample was further allowed to continue for 4 hours but no apparent change.</td>
</tr>
</tbody>
</table>

Note: With the other samples starting at 7.5 KV leakage current ranged from 47-54mA. The behaviour remained almost the same in most of the samples.
<table>
<thead>
<tr>
<th>Material</th>
<th>Starting Voltage (KV)</th>
<th>Final Voltage (KV)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Unfilled Adiprene</td>
<td>3.00</td>
<td>7.5</td>
<td>No tracking mainly erosion 250V step. Test time 20-22hrs.</td>
</tr>
<tr>
<td>2. Unfilled Epoxy</td>
<td>3.00</td>
<td>6.0</td>
<td>Tracked after 12 hrs. at 6KV rest behaviour same as 1.</td>
</tr>
<tr>
<td>3. Filled Adiprene</td>
<td>3.00</td>
<td>7.0</td>
<td>No tracking after 22 hrs. but erosion as in figure 3:14</td>
</tr>
<tr>
<td>4. Filled Epoxy</td>
<td>3.00</td>
<td>3.50</td>
<td>Tracked at 3.5 KV after 2 1/2 hrs. Fire and tracking combined. Tried after switching off, does not work</td>
</tr>
</tbody>
</table>
time for filled and unfilled sample of epoxy are shown in table 3:8, which clearly shows the superiority of adiprene over epoxy in both filled and unfilled specimens.

3:3:4 DISCUSSION OF TRACKING RESULTS

After a comparison of the various results on tracking observed so far, it could be safely stated that silicon carbide filled adiprene is a promising material for the replacement of the latest semiglazed insulators. It behaved equally well in tracking test as compared to Teflon and ceramic insulation and decidedly much better than phenolic and epoxy. Epoxies were also evaluated in various formulation and the results were found to be similar to Day's findings [28].

Erosion remains the primary concern. In actual service, erosion may be negligible. The search for material was for one with adequate and controllable conduction. This material should resist the formation of electrolytic film, but it should always be checked for the worst situations.

Erosion could be due to electrochemical deterioration. The process could be related closely to Faraday's law of electrolysis; since electrolyte and urethane have a tendency to disintegrate giving rise to water, carbon monoxide, carbon dioxide etc. In such cases a number of stabilizers have been suggested [24]. The erosion is a primary factor in reducing the life expectancy of a material. The stabilizers tested to date show promising effects in increasing the life expectancy up to 50 times eg. with 2% of Azo- benzene a mean life may be extended up to 50 times. The other generally used stabilizers are Anthraquinone, azoxybenzene, Benzil, etc.

It is concluded that silicon carbide filled adiprene has proved to be a promising material.
3:4 Flashover Under Contaminated Conditions

There has been an extensive research into this problem all over the world. There is much continuing research to reproduce in service flashover contamination mechanism in the laboratory. The problem is quite complicated, since the quantity and type of contamination varies from place to place during a year. The primary thrust has been to find most common pollutants which aid in the formation of electrolytic film. Researchers have tried to solve the problem by dividing the pollutants into cultures. This has been shown in chapter I, table 1.1, pg.5.

The cause of pollution deposit plays another major role. Research done in this subject area has established wind effect as being responsible for most of the pollution deposits. Several researchers have attempted to explain that the rate of pollutant deposit is higher in D.C. high voltage than A.C. high voltage. Kimota, Fujmura, and Naito [30] have stated "that the equivalent sodium chloride density in the case of D.C. voltage application is about 3 times that in the case of A.C. voltage application." They ignored wind effect in the calculations.

There are other factors affecting contamination flashover testing in the laboratory.

1. Method of application of pollutant to insulators.
2. Uniformness of pollutants.
3. Condition of pollution layer at the time of voltage application, such as wet, dry or damp.

High voltage stresses in application on polluted wet conducting insulators could give rise to [1].
1. Leakage current
2. Arcing
3. Corona
4. Ultra violet light
5. Erosion

The process causing stresses on the insulator surface involves [1].

1. Deterioration of insulation surface.
2. Formation of electrolytic film over entire insulator surface.
3. Arcing and deterioration because of leakage current.
4. Dry bands, leading to non-uniform distribution of voltage along the insulator surface.
5. Instability and flashover.

This all leads to discharges. Nasser [31] has divided the discharge into three parts:

i) Arc
ii) Streamer
iii) Glow

but he believes the causes could be the same as mentioned earlier.

While testing these insulators in laboratory conditions and trying to produce service conditions, researchers have developed the following procedures:

a. The surface should be wet and polluted before application of high voltage.

b. Polluted and dried insulator should be subjected to high voltage and then the fog applied.

c. In Japan [32] researchers believe the conditions would be more natural when clean insulators are subjected to high voltage and then polluted.
fog applied.

During this testing, all the conditions have been tried to ascertain dependable results.

**3:4:1 TEST SAMPLES**

Test samples were fabricated the same way as explained in moulding and size (4" x 1") have been kept as standard model. Each sample was contaminated with varying degrees of pollution as explained below.

**3:4:2 TEST EQUIPMENT INCLUDING FOG GENERATION**

The high voltage source and other equipment were described earlier. The tests were conducted in a 6' x 4' x 4' fog chamber with the samples mounted in the middle at 3' above the base. Fog generation was done through two nozzles arranged to be supplied with distilled water at constant head and with air regulating valve from 0 - 60 psi as shown in the single line diagram in figure 3:15. Three ranges of pressure were selected and applied. These are 20, 40, 60 psi as slow, normal and quick wetting rate.

No other changes in measuring circuits, except tripping, was affected in studying this problem.

**3:4:3 APPLICATION OF POLLUTANTS**

Bentonite as inert material and sodium chloride as conducting salt were used to prepare a slurry in distilled water. Three types of slurry solutions were used to represent light, medium and heavy pollution [33,2].

1. Light pollution: 400 cc. of distilled water
   
   6 grams of Bentonite.

   6 - 30 grams of salt

   Few drops of photo flow solution
W.S. Water Storage Tank
F.T. Float Tank
W.L. Water Line
P. Copper Piping
S.H. Siphoning Head
N. Spray Nozzle
R. Air pressure regulator and gauge
S. Shut off valve.
F. Air Filter

FIGURE 3:15 FOG GENERATING SYSTEM

Reprinted from [1].
2. Medium Pollution: 400 cc. of distilled water
   30 grams of Bentonite
   6 - 30 grams of salt
   Few drops of photo flow solution

3. Heavy Pollution: 400 cc. of distilled
   70 grams of Bentonite
   6 - 30 grams of salt
   Few drops of photo flow solution

The density of bentonite deposit could be varied depending upon
no. of sprays and was kept as 0.028, 0.098, 0.370 mg/cm² (±20%) corresponding
to slurries containing 6, 30, 70 grams of bentonite.

Slurry was prepared and sprayed keeping the following points in mind
to obtain uniform layers.
1. Slurry to be well shaken before use every time.
2. Angle of spray to be constant.
3. Distance of nozzle of spray gun from insulator surface to be constant
4. No. of sprays and interval to be constant for reproducibility.

Thus using the above mentioned criteria it becomes a standard spray.

This would enable determining salt density with sodium chloride's
 calibration curve [1] [Reproduced as Appendix 1C]\n
The samples were left on a rack overnight to dry in the laboratory
atmosphere.

3.4.4 TESTING PROCEDURE AND RESULTS

Tests were carried out under D.C. and A.C. voltages. First the sample
was subjected to 4 KV DC and the voltage was raised in 2 KV steps to check that
no flashover take place in fog conditions. After establishing the range of
voltage over which no flashover occurred, the following methods were used to check the various parameters affecting the results and to ensure reliable results.

1. Samples were subjected to high voltage and fog was generated simultaneously.
2. Dry samples were first allowed to get wet in varying degrees of fog for varying lengths of time, 5 - 15 minutes, and then subjected to high voltage.
3. Dry and clean samples were subjected to polluted fog. [feed to fog generation changed from distilled water to polluted solution].

Voltage application varied from 20 - 25 minutes [34]. The following observations were made during the entire testing process:

1. Scintillation (very minor) occurred for a very short period of time in the case of no. 2 above but practically no flashover at working voltage in the case of 40:60 (silicon carbide to adiprene) samples.
2. Drying out was quick with higher leakage current than the normal current.
3. Samples with higher percentage of filler failed due to too much leakage current.
4. Samples with less filler flashed over due to less heating.
5. Normal samples broke down internally at 32-35 KV.

3:4:5 DISCUSSION

The above results are encouraging and considered satisfactory. These were anticipated results based on conduction experiments discussed earlier. There is room for improving breakdown voltage and performance by adopting more closely controlled method of manufacturing. Proper moulding/manufacturing process with proper formulation of material would result in better insulators generating sufficient heat loss to maintain surface temperature 5-6°C.
above the ambient temperature. This would prevent formation of electrolytic film and would dry out any existing ones under cold switching conditions. With the correct type of material, the insulators will withstand any working conditions. Thus these test results bring us a step closer to establishing the type of material which will operate under polluted conditions. The conventional insulators are working satisfactorily in clear weather.

3:5 MECHANICAL RESULTS

By reviewing the mechanical properties of silicon carbide and adiprene individually, the mechanical properties of silicon carbide filled adiprene compound could be established. This would not be sufficient, since a tensile strength of 2000-5000 psi a nominal figure and the requirements are in the 10,000 - 100,000 psi range to make the insulators suitable for various applications on EHV and UHV power systems; thus the material needs reinforcement. The most suitable reinforcement could be fibre glass or resin bonded glass fibre (RBGF). These materials possess the required mechanical properties. The most important property would be adhesive strength.

Two materials, steel and fibre glass were used for reinforcement. 1/2" diameter rods of reinforcing material were embedded during moulding. The samples were checked on Tinus Olsen Machine. Every time the sample would break at the junction embedded end of the reinforcement, being the weakest point comparatively. There appear to be no problems as far as the mechanical properties are concerned. The other properties checked were:

1. Tensile strength.
2. Torque strength.

3. Deformation under load:

All the results were found to be excellent and the material was considered to have the desired mechanical properties.

The material was checked for below zero temperatures. The behaviour was also satisfactory.

3:6 THERMAL TESTS

An examination of current-voltage characteristics and other results revealed that the material, silicon carbide filled adiprene, has a positive temperature co-efficient of resistance. This implies that the resistance of the material will increase with temperature increase, regardless of the cause of the increase in thermal energy. The heat energy could be caused by conduction as already observed, see figure 3:6. The temperature co-efficient could be calculated from previous results, but there were many variables involved such as voltage, current, resistance, time, etc.

It is also desirable to know the thermal properties of a material. The thermal properties are important in establishing the thermal stability of the insulating material. The conduction was concluded to be a hopping type, since the conductivity decreased with increasing temperature. This is a vital property.

The conductivity phenomenon is very complex. Conduction could result from various impurities. Impurities can be classified on the basis of their concentration. The classifications are listed below:

1. Majority impurity concentration.

2. Minority impurity concentration.
Pollak and Geballe [34] have stated that "at the low-temperature
end the conductivity is roughly proportional to minority impurity concentration
and is almost independent of majority impurity concentration and at
higher temperatures the conductivity becomes approximately proportional
to the product of both concentrations."

Most of the theoretical work performed on impurity conduction phenomenon
has been done on impurity based-conduction with the Mott-Conwell model. This
model is applicable only for the case of low concentrations. According to
that model, the transport occurs by electrons hopping between states,
localized around acceptors and donor impurities. For the hopping to
take place it is necessary to have some vacant states and thus compensation
of the majority impurity becomes an essential feature of impurity conduction.
They further stated that because of the Coulomb's forces between the
ionized impurities, the state of lowest energy is achieved when the majority
impurity nearest a given minority impurity is ionized. Thus thermal energy
is required in order to overcome these Coulomb's forces. Even though the
electrons have the thermal energy but the field is changed, then it requires
some time for equilibrium.

Pollak [35] explains that as per Conwell-Mott model for the treatment
at higher temperatures, the majority impurities becomes more separated from
minority impurities, i.e. distance increases and thus electrons cannot be easily
transported from one state to another without sufficient energy.

Pollak [36] also states that at increased temperature, whenever two
majority impurities are sufficiently close, the existence of resonance
energy between them will introduce traps.
Silicon carbide filled adiprene was evaluated for:
1. Current–voltage characteristics at ambient temperature.
2. Temperature gain by test sample at working voltage.
3. Resistance–temperature characteristics at a particular voltage.
4. Current–voltage characteristics at elevated temperatures.

**3:6:1 APPARATUS, PROCEDURE AND RESULTS**

A 1.5 gallon capacity container was used to house the test samples as shown in figure 3:16. The necessary provisions were made for stirring, heating the sample through the transformer oil in the container, temperature measurements etc. The apparatus was placed in the fog chamber. The container was 3/4 full of transformer oil.

The sample was subjected to the working voltage of 22KV for 12 hours. The temperature gain by the sample was observed to be 4–5°C. The conduction at various levels of temperature was recorded. The test was conducted at a constant voltage. The voltage was then increased in steps of 5 KV up to 25 KV and the test repeated.

The above test was repeated for increasing rate of temperature increase. There was no significant difference in the results. The experiment was repeated for various samples. Each time the results were quite similar. Tested samples were re-evaluated for their thermal properties at an interval of one week. No significant difference was observed during re-testing. Resistance temperature characteristics are shown in figure 3:18.

The material was evaluated for current–voltage characteristics at elevated temperatures. The results are shown in figure 3:19. A number of experiments were conducted to establish the reproducibility of current–
1. H.V. Supply Lead
2. Insulation
3. Test Sample
4. Stirrer
5. Thermometer
6. 1.5 Gallon Container
7. Heating Elements

FIG. 3:16 APPARATUS USED IN THERMAL TEST
FIGURE 3:17 RESISTANCE - TEMPERATURE CHARACTERISTICS OF SILICON CARBIDE FILLED ADIPRENE AT VARIOUS CONSTANT VOLTAGES.
FIGURE 3:18 R/T CHARACTERISTIC OF SIC FILLED ADIPRENE
FIGURE 3:19 CURRENT-VOLTAGE CHARACTERISTICS OF SILICON CARBIDE FILLED ADIPRENE CYLINDRICAL INSULATORS 1" IN DIAMETER 4" LONG NO. 2 (40:60) AT ELEVATED TEMPERATURE
3:6:2 DISCUSSION

The current-voltage characteristics at ambient temperature have been discussed in 3:2:7. An examination of Resistance-temperature characteristics of silicon carbide filled adiprene reveals that the material has a positive temperature co-efficient of resistance. Table 3:9 shows temperature co-efficient of resistance calculated at various voltages.

The resistance-temperature characteristics exhibit the following properties.

1. Approximate linear relation of resistance-temperature and lower value of temperature co-efficient of resistance up to 20KV. compared to 25KV.
2. Significant increase in temperature co-efficient of resistance at 25KV compared to values at lower voltages.
3. Increase in resistance with temperature increase or decrease in conduction with temperature increase.

Re-examination of current-voltage characteristics shown in figure 3:6-3:9 would verify the results 1., 2 and 3. Increase in electric field resulted in increased leakage current. The current-voltage relationship is also approximately linear up to about 20-22KV and tend to be non-linear beyond 20-22KV. The increase in conduction beyond 20-22KV decreases significantly. The leakage current becomes almost saturated. This explains the difference observed in figure 3:18.

The decrease in conduction due to increase in material temperature has been explained earlier. This is mainly due to the predominance of hopping type conduction.

Figure 3:19 shows current-voltage characteristics of silicon carbide.
### Table 3:9

**TEMPERATURE COEFFICIENT OF RESISTANCE OF SILICON CARBIDE FILLED ADIPRENE AT VARIOUS VOLTAGES**

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Temperature Range °C</th>
<th>Resistance Ω</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>50-100</td>
<td>641-709</td>
<td>0.0018</td>
</tr>
<tr>
<td>10</td>
<td>50-100</td>
<td>665-735</td>
<td>0.0021</td>
</tr>
<tr>
<td>15</td>
<td>50-100</td>
<td>640-700</td>
<td>0.0019</td>
</tr>
<tr>
<td>20</td>
<td>50-100</td>
<td>439-488</td>
<td>0.0021</td>
</tr>
<tr>
<td>25</td>
<td>50-80</td>
<td>785-1820</td>
<td>0.0440</td>
</tr>
</tbody>
</table>

\[
\alpha = \frac{R_{T_2} - R_{T_1}}{R_{T_1} (T_2 - T_1)}
\]

\(\alpha\) = Temperature coefficient of resistance

\(R_{T_1}\) = Resistance at temperature \(T_1\)

\(R_{T_2}\) = Resistance at temperature \(T_2\)
filled adiprene at elevated temperature. The current-voltage relation tended to be linear over a wide range. The increase in conduction due to increase in applied voltage at the elevated temperature has insignificant effect on any temperature increase due to conduction itself.

The decrease in conduction at higher temperature could also be due to the increase in barrier energy. The barrier energy ΔE required for electrons increases with increasing temperature; thus conduction decreases. A similar explanation has been given by Pollak. This has been explained earlier on p.37f.

These results prove that silicon carbide filled adiprene has excellent potential as an antipollution insulator material.
CHAPTER IV
CONCLUSIONS AND SUGGESTIONS
FOR FUTURE STUDIES

The main objective of this study was to evaluate silicon carbide filled adiprene as a prospective material for antipollution insulators, and a replacement for conventional insulators. With this objective in mind, a systematic approach to the problem was initiated. A better moulding technique was designed and developed.

Improved test samples showed more positive results as compared to previous sample results [from (1)]. There is room for improvement in the reproductivity of silicon carbide filled adiprene insulators.

The silicon carbide filled adiprene model has been evaluated for its electrical, mechanical and thermal properties. The results are summarized below:

1. An appropriate value of the resistivity of the silicon carbide filled adiprene model appears to be in the range of 700-800 M Ω·cm at field strength of 5.5KV/inch (2.17KV/cm). These values are still tentative and would change with better manufacturing/moulding processes. Depending upon the formulation of silicon carbide to adiprene, any desired value of leakage current and heat dissipation could be attained. The working voltage was determined from current-voltage characteristics of 40:60 (silicon carbide to adiprene by volume) test samples, and the value corresponds to the starting point of saturation level, leaving good margin for fluctuation.

2. It was found that silicon carbide filled adiprene and fibre glass presents no interface contact problem. The value of breakdown voltage

89.
with or without fibre glass reinforcement was unaltered. The breakdown mechanism is still not very clear, since only internal breakdown was observed. The cause of internal breakdown could be:

a) air/gas pockets entrapped during moulding. The cavity content in general has lower electric strength than the material. Thus the air/gas entrapped in the pocket could breakdown, causing arcing, internal localized heating, leading to breakdown of the insulator.

b) Non uniformity of silicon carbide in adiprene. There could be lumps of silicon carbide and those parts would have less resistance. The sample would get heated up first at that part and finally would break depending upon field strength and leakage current. These breakdown causes need macroscopic and microscopic study of the mixed material to have an understanding of the breakdown phenomenon.

3. Experimental results proved that silicon carbide filled adiprene conducts more under A.C. than a D.C. voltage. This is attributed to the predominancy of hopping type conduction in silicon carbide filled adiprene. The prevalence of hopping type conduction in filled adiprene is desirable in:

a) Accomplishing saturation of the leakage current.

b) having positive temperature coefficient of resistance.

c) acquiring thermal stability.

These qualities are very well evident from the results discussed in chapter III.

4. The non-tracking property established, certainly, makes this material superior to other polymeric insulating materials in present use. The
erosion could act as a life diminishing agent. Electro-chemical deterioration could be the cause of erosion. The stabilizers could be used to enhance the life of the material as mentioned in chapter III, pg. 71.

5. Mechanical testing proved very encouraging. The adhesive property is one of the most important since the tensile strength would greatly depend upon proper adhesion of silicon carbide filled adiprene to its reinforcing material. Thus there would be no problem as far as mechanical strength of antipollution insulators is concerned.

6. Tests were also performed on a number of test samples having varying formulation of silicon carbide to adiprene, with varying degrees of pollution and fog. Almost all the possibilities were explored while performing these tests. The results were very useful. The right kind of insulator exhibited practically no scintillation and no flashover. The evaluation of leakage current as per service conditions is a must which could very well affect the performance of antipollution insulators in service.

7. The new insulation material for antipollution insulators has excellent thermal properties. The increase in resistance with increase in temperature confirms current-voltage characteristics discussed in section 3. This test further confirmed that the material has positive temperature coefficient of resistance, which is a vital property. The results also ensure that the material would be highly stable in varying conditions of weather in service. The increase/decrease in resistance with temperature is quite linear over the working voltage range. The higher value of temperature coefficient of resistance at higher voltage with increasing temperature is another good aspect of this new material.
Thus the summary of results reveals clearly a positive step towards
the use of silicon carbide filled adiprene for manufacture of antipollution
insulators to replace the present porcelain insulators.

The manufacturing process of silicon carbide filled adiprene's
antipollution insulators is much simpler than semiconducting glazed
insulators. The problem of attaining uniformity is common for both of these
materials.

Dey [8] stated that "the investment in overhead lines is 20-40% of the
total expenditure. Insulation accounts for about 10% of the line cost at
132KV, rising to approximately 25% at 750 KV." He has drawn a comparison
of performance and cost for RBGF cored insulators with respect to porcelain
insulators. He further stated that RBGF cored material is economical. The
facts stated are listed below:

1. The RBGF cored material is useful in manufacturing the following:
   a) Cantilevers or beams for single member cross arms.
   b) Tension members for suspension, tension and framed insulation of a transmission
      system.
   c) Compression members of transmission structure for use as struts.

2. The ease in manufacture satisfactory performance of the above listed
   structure members of the transmission could drastically cut the voluminousity
   of the present structure, ie:
   a) The height and maximum width of the cross arm of 132Kv transmission structure
      would reduce from 89' and 30' - 6" to 75' and 23' respectively.
   b) The height and maximum width of cross arm of 400 KV double circuit
      transmission tower would reduce from 164' - 8" and 66' - 8" to 136' and 53'
      respectively.
The above example means:

i) Economy in material cost.

ii) Ease of augmentation of exiting lower voltage lines to higher voltage lines.

The main idea in giving the above detailed useful information on application of RBGF cored insulators is to establish that:

1. The fibre glass reinforced silicon carbide filled adiprene insulators would be equally useful on all applications stated above because of:
   
a) Ease in manufacture.
   
b) No limitation of design for shapes and sizes.
   
c) Equally strong in mechanical strength due to the same reinforcing material.
   
d) Better performance in contaminated conditions.
   
e) Non-tracking properties.

2. These new antipollution insulators would be more economical because of higher withstand voltage per unit length.

Table 4:1 shows a comparative statement of various properties of various insulating materials such as silicon carbide filled adiprene antipollution insulators, porcelain insulators, and RBGF cored epoxy insulators.

Finally it is concluded that silicon carbide filled adiprene be given practical shape and be tested for performance in service.

SUGGESTIONS FOR FURTHER STUDIES

The performance of the silicon carbide filled adiprene is satisfactory.

The performance could further be improved by:

1. Degassing of material before and after mix. Because of viscosity and surface tension, adiprene L polymers entrap air and other gases during
<table>
<thead>
<tr>
<th>Property Description</th>
<th>Reinforced Filled Adiprene</th>
<th>Semiconducting Glazed Insulators</th>
<th>RBGF Cored Epoxy Insulators</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Design limitations</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>2. Manufacturing Process</td>
<td>Easiest</td>
<td>Difficult</td>
<td>Difficult</td>
</tr>
<tr>
<td>3. Performance in Contaminated atmosphere</td>
<td>Excellent</td>
<td>Poor</td>
<td>Poor</td>
</tr>
<tr>
<td>4. Working Voltage</td>
<td>5.5KV/inch</td>
<td>2-2.5KV/inch</td>
<td>2-2.5KV/inch</td>
</tr>
<tr>
<td>5. Electrical conduction</td>
<td>Excellent</td>
<td>Good</td>
<td>Poor</td>
</tr>
<tr>
<td>6. Thermal Stability</td>
<td>Excellent</td>
<td>Poor</td>
<td>Poor</td>
</tr>
<tr>
<td>7. Track resistance</td>
<td>Excellent</td>
<td>Satisfactory</td>
<td>Satisfactory</td>
</tr>
<tr>
<td>8. Voltage distribution along surface</td>
<td>Excellent</td>
<td>Good</td>
<td>Poor</td>
</tr>
<tr>
<td>9. Temperature coefficient of resistance</td>
<td>+ve</td>
<td>-ve</td>
<td>-ve</td>
</tr>
<tr>
<td>10. Resistance to Corrosion</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>11. Mechanical properties</td>
<td>Excellent</td>
<td>Normal</td>
<td>Excellent</td>
</tr>
<tr>
<td>12. Field of application</td>
<td>Very wide</td>
<td>Limited</td>
<td>Wide</td>
</tr>
</tbody>
</table>
shipping and handling. To ensure uniform, void free vulcanizates, the polymer must be degassed prior to addition of the curing agent. Whenever possible degassing be continued:
a) Adiprene alone
b) After mixing silicon carbide
c) Before and a little after mixing the curing agent.

The mixing equipment and other related components must be cleaned as soon as possible after casting the material. Xylene or toluene may be used for the final cleaning.

2. Standardizing the various constituents of the material in quantity and quality. This would ensure better productivity of antipollution insulators.

3. Depth wise grading of insulating material. In moulding/manufacturing, silicon carbide should be used in ascending order of density from the core. The resistance graded insulator would have maximum conduction of the surface of the insulator. The surface conduction would ensure:
a) better heat dissipation
b) improvement in withstand voltage
c) minimization of internal breakdown, thereby increasing breakdown voltage significantly
d) reducing the time required for the leakage current to get stabilized, i.e. lowering of leakage current stabilizing time constant. This would further improve withstand voltage in the cold switch-on conditions.

4. Introducing better controlled manufacturing/moulding processes.

Erosion is the primary concern in the performance of silicon carbide filled adiprene insulators. The surface discharge phenomenon should be
studied in detail. The surface discharges could be the cause of electrochemical deterioration, mainly due to oxidation. A number of stabilizers have already been suggested to minimize the electro-chemical deterioration. These stabilizers would have to be tested for long term performance.

Erosion could also be reduced by raising the heat-resistance of the material. The heat-resistance of adiprene might improve significantly with radiation. The type and dose of radiation would have to be determined. Hook, Week and Berbeco [37] have stated that "Radiation crosslinked plastics have been used in electrical insulation for improved heat-resistance, solvent resistance and mechanical and electrical properties." They claimed to have obtained the following characteristics in irradiated polymers.

1. Raising of softening temperature. For example, conventional heat-resistant, general purpose PVC melts below 150°C; with adequate crosslinking the PVC is insufflible.
2. Improvement in solvent resistance due to the crosslinked structure of the polymer.
3. Maintaining and improving the electrical properties.
4. Improvement of mechanical properties such as tensile strength.
5. Improved thermal and oxidative stability as compared to chemically crosslinked polymers.

The use of proper radiation could greatly improve the electrical and mechanical properties of silicon carbide filled adiprene. It would be worth mentioning here that the non-bonded electrons of NH₂ could conceivably enter into the empty d-orbitals of the silicon atoms of silicon carbide
altering the properties. This might not have much effect on the radiation process since radiation mainly ensures better crosslinking.

The degassing results in void-free adiprene; this would actually reduce the sizable voids to micro voids. Air/poor dielectric gas, filled micro voids would degrade the material leading to breakdown and reduction in life expectancy. This type of degradation of material could be avoided by impregnating the antipollution insulator material with an electro-negative gas. Kojima claimed to have successfully impregnated polyethylene. They[38] have further stated that the breakdown voltage of SF₆ impregnated polyethylene improved by 50%. The improved values of breakdown voltage of impregnated polyethylene is shown in table 4:2. Thus adiprene may be impregnated in SF₆ before and after mixing of the curing agent.

The recommended steps for the improvement are shown in figure 4:1. Finally it is recommended to design the antipollution insulator for on line tests. The designed insulator should be manufactured as recommended. A well designed and improved version of an antipollution insulator may then be tested in the laboratory and field for contamination resistance. That would give a decisive picture of the performance of this new antipollution insulating material i.e. silicon carbide filled adiprene.
1. Adiprene heated to 73°C (164°F) and degassed. Silicon carbide mixed to adiprene and degassing continued.

2. Impregnating mixture in SF₆.

3. Moca introduced to mixture.

4. Solution poured into mould.

5. Radiation process introduced after preliminary curing.

6. Natural curing at R. Temperature =50% R.H.

7. Field testing

**FIGURE 4:1 VARIOUS STAGES SUGGESTED FOR 2ND STAGE DEVELOPMENT OF SILICON CARBIDE FILLED ADIPRENE ANTI-POLLUTION INSULATORS**
<table>
<thead>
<tr>
<th>Specimen</th>
<th>B.D.V. (kV/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original PE (NYC 9025)</td>
<td>65.0</td>
</tr>
<tr>
<td>Freon C3.8 impregnated PE (0.5%)</td>
<td>71.8</td>
</tr>
<tr>
<td>Freon 114</td>
<td>71.5</td>
</tr>
<tr>
<td>Freon 12</td>
<td>68.5</td>
</tr>
<tr>
<td>SF₆</td>
<td>98.0</td>
</tr>
</tbody>
</table>
APPENDIX 'A'
[Reprinted from B.S. 3781:1964]

BRITISH STANDARD METHOD FOR DETERMINING

THE COMPARATIVE TRACKING INDEX OF

SOLID INSULATING MATERIAL

Foreword

This British Standard is based upon IEC Recommendation No. 112
"Recommended method of determining the comparative tracking index of solid
insulating materials under moist conditions". It has, however, been found
desirable to include definitions of 'Tracking' and 'Failure by tracking'
and a more precise definition of 'Comparative tracking index'.

The definition of failure by tracking has been introduced to avoid
uncertainty in the endpoint by defining the magnitude and duration of the
current which constitutes failure. This British Standard and the IEC
Recommendation 112 are based on the existence of an asymptote to an
electrolyte drop-voltage curve, but for convenience the I.E.C. Recommendation
refers only to the 50 drop level. For most materials the recommendation
that the 50 drop level coincides with the asymptote is justified but cases
have arisen where this is not so and to meet the difficulty the asymptote
is used to obtain the comparative tracking index in this standard.

Although IEC Recommendation 112 includes an alternative procedure at
fixed voltages with a requirement of a minimum of 50 drops of electrolyte
without failure, this procedure is not included in this standard as it is
less satisfactory than obtaining the comparative tracking index by the
method given herein.
METHOD

Scope

1. This British Standard describes a method of test for indicating the relative behaviour of solid electrical insulating materials as regards their liability to form a permanent track on the surface when stressed electrically and at the same time exposed to moisture which may be contaminated by dirt or dust from the surrounding medium. The liability to track is expressed numerically as the comparative tracking index (C.T.I.).

Account is taken of other forms of damage such as erosion which may occur during the test even when there has been no failure by tracking.

NOTE 1. The method described does not enable materials to be classed rigidly as 'non-tracking' or otherwise. The comparative tracking index indicates the relative behaviour of material when under alternating electric stress and exposed to moisture, and could not be used directly for establishing safe creepage distances in the design of electrical apparatus.

NOTE 2. The grading of materials by this method may differ from that obtained by utilizing other testing methods for the measurement of tracking resistance, for example tests based on the use of high voltage sparks or low voltage medium current arcs.

2. For the purposes of this British Standard the following definitions apply:

   Tracking. The progressive formation of electrically conducting paths which are produced on the surface of a solid insulating material by the combined effects of an electric field on the surface and of electrical leakage due to the electrolyte.

   Failure by tracking. The condition in the test in which an alternating current of 0.5 ampere flows between the electrodes across the surface of
test pieces for not less than two seconds at test voltages up to and including 500 volts, and for not less than 10 seconds at any higher voltage.

Comparative tracking index (C.T.I.) The numerical value of the voltage corresponding to the asymptote to a curve produced from the results of tests carried out in accordance with this specification.

Test Piece

3. Any smooth flat surface may be tested provided that the area is sufficient to ensure that, during the test, no electrolyte overflows the edges of the test piece. In special cases, the flat surface may be obtained by machining, but, if this is done, mention of the fact shall be made in the test report.

Note. A convenient minimum size of test piece has been found to be 15mm x 15mm x 2mm.

Unless specially required, the test piece shall not be conditioned in any way prior to the test, except that it shall be cleaned with a dry cloth.

Apparatus

4. a. Electrodes. Two brass electrodes of rectangular cross section 5 mm x 2mm and approximately 20 mm long shall be used. They shall be bevelled at an angle of 30 degrees, the edge so formed being slightly rounded (see Fig.A1, Electrode).

Where it is desired to use other metals, e.g. to simulate applications employing these metals, this may be done provided it is reported and it is recognized that the C.T.I. values so obtained may differ from those obtained with brass electrodes.

Note. Brass has been chosen for standard electrodes so as to be representative of normal practical conditions. Brass to B.S. 1949* is satisfactory for *B.S. 1949, "60/40 brass rods, sections, forging stock and forgings".
this purpose.

b. **Electrode arrangement.** The electrodes shall be applied to the test piece as shown in Fig. A2. Each shall bear on the surface with a force of 100 ± 10 grammes.

Note. This may be done conveniently by a pivoted horizontal arm of appropriate weight.

c. **Supply to electrodes.** The supply to the electrodes shall be from a controllable source of alternating voltage at a nominal frequency of 50 cycles per second. At all voltages used, the supply shall be capable of providing a current of 1 ampere at a power factor not less than 0.9 when the electrodes are short-circuited.

Note. The majority of tests will be carried out between 100 and 500 volts. The test is not suitable for voltages above 1000 volts.

d. **Circuit arrangement.** Arrangements shall be made to disconnect the supply when a current greater than 0.5 ampere has persisted for two seconds at test voltages up to and including 500 volts and for 10 seconds at higher voltages. This may be done manually, or by means of an over-current switching device as is indicated in the typical circuit shown in Fig. A3.

e. **Electrolyte.** The electrolyte shall be a 0.1 ± 0.002 per cent solution of ammonium chloride (A.R. grade)* in distilled or deionized water.

f. **Electrolyte dropping arrangements.** The apparatus shall be capable of depositing electrolyte in drops of size $20 \pm 5 \, \text{mm}^3$ from a height of $30\pm 10 \, \text{mm}$ above the test piece, at intervals of $30 \pm 5 \, \text{seconds}$.

Note. It has been found that an hypodermic needle having an outside diameter of 0.9-1.1 mm with the tip cut off square provides drops of the required size.

* A.R. - Analytical reagent, or recognized analytical quality
Procedure

5. The test shall be carried out at 20 ±5°C.

The drop size and dropping rate shall be checked for compliance with the requirements of Subclause 4f. The source voltage having been set to a chosen value and the over-current switching device if any, made inoperative, the short-circuiting switch shall be closed and the variable resistor shall be adjusted until the current through the ammeter is I ± 0.1 ampere.

The test piece shall be supported with the test surface horizontal and with the electrodes on it as required in Subclause 4b. The edges of the electrodes in contact with the test piece shall be even and smooth at the start of each test. Contact of the electrodes with the test piece shall be such that, when a light source is so placed that the light reaches the observer’s eye along the surface of the test piece, no light is visible between the test piece and the electrodes.

With the short-circuiting switch open and the overcurrent device, if any, in operation, the supply shall be switched on. Drops of electrolyte of size 20 +5 -0 mm³ shall then be allowed to fall on the test surface midway between the electrodes at intervals of 30 ± 5 seconds until failure by tracking occurs, or until at least 100 drops have been deposited without giving rise to failure.

An area unaffected by previous test shall be used for each test.

Tests shall be carried out at a range of voltages and a curve plotted showing the number of drops required to cause failure by tracking as a function of voltage (see Fig. A4). The voltages chosen shall enable this curve to be drawn with sufficient accuracy to enable the asymptote to be determined;
near the asymptote the voltage steps should not be greater than 10 per cent.

The numerical value of the voltage corresponding to the asymptote is the comparative tracking index.

For most materials it will be found satisfactory to take as the comparative tracking index the numerical value of the voltage corresponding to failure at 50 drops (see Fig. A4), provided that when the voltage is reduced by 10 per cent the number of drops to cause failure at this voltage is at least doubled.

Tests in which the electrolyte flows over the edge of the test piece shall be ignored.

**Examination of Test Piece**

6. After the tests, the pieces shall be examined for effects other than tracking. On test pieces which have not failed by tracking, the depth of any erosion shall be measured.

**Report**

7. The report shall give the following itemized information together with any other additional information which might be relevant.

(i) Each voltage applied and the associated number of drops either tabulated or as a curve.

(ii) The comparative tracking index.

Note. By definition this is a number, and should not be expressed as a voltage.

(iii) The thickness of the test piece.

(iv) The nature of the surface tested.

(v) Any appreciable loss of material during the test and if no failure by tracking occurred, the maximum depth of erosion.

(vi) Any effects other than tracking and erosion.

(vii) The material of the electrodes if other than brass.
Figure A1. ELECTRODE

Figure A2. ELECTRODE ARRANGEMENT

All dimensions in millimetres
Figure A3 TYPICAL CIRCUIT DIAGRAM
Figure A4. Examples of two types of curves for determining the comparative tracking index.

a. Curve obtained with a material having a C.T.I. coinciding with the 50 drop point.

b. Curve obtained with a material where the 50 drop point cannot be used to establish the C.T.I.
APPENDIX 'B'

[Reprinted from American Standard §59 135-1971]

STANDARD METHOD OF TEST FOR
LIQUID-CONTAMINANT, INCLINED-PLANE
TRACKING AND EROSION OF INSULATING MATERIALS

1. Scope

1.1 This method covers the evaluation of the relative tracking and erosion resistance of insulating material using the liquid-contaminant, inclined-plane test. ASTM Method D 2132, Test for Dust-And-Dog Tracking and Erosion Resistance of Electrical Insulating Materials, and ASTM Method D 2302, Test for Differential Wet Tracking Resistance of Electrical Insulating Materials With Controlled Water to Metal Discharges, may also be used to evaluate materials.

1.2 Two tracking and one erosion test procedures are described:

1.2.1 A "variable voltage method" to evaluate resistance to tracking
1.2.2 A "time to track method" to evaluate resistance to tracking
1.2.3 A method of quantitative determination of erosion

1.3 While a definite contaminant solution is specified, other concentrations or types of contaminants with suitable voltages may be used to simulate different service or environmental conditions.

2. Definitions

2.1 Initial tracking voltage – the applied voltage at which continuous tracking can be initiated in a specified time.

2.2 Time-to-track – the time in which tracking proceeds a specified distance between the test electrodes at a specified voltage.

2.3 Other definitions pertinent to this method are given in ASTM Method D 2132, Test for Dust-and-Fog Tracking and Erosion Resistance of Electrical Insulating Materials.²

3. **Significance**

3.1 These methods differentiate among solid electrical insulating materials on the basis of their resistance to the action of voltage stresses along the surface of the solid when wet with an ionizable, electrically conductive, liquid contaminant.

3.2 This method quantitatively evaluates the relative ability of insulating materials to withstand the action of electrical discharges on the surface which are similar to those which may occur in service under the influence of dirt and moisture condensed from the atmosphere. In the field, the critical conditions and the resulting electrical discharges occur sporadically. Degradation, often in the form of a conducting "track", develops very slowly until it ultimately bridges the space between conductors to cause complete electrical breakdown. In this method, the conducting liquid contaminant is continuously supplied at an optimum rate to the surface of the test specimen in such a fashion that essentially continuous electrical discharge can be maintained. By producing continuous surface discharge with controlled energy, it is possible to cause specimen failure within a few hours which is similar to that occurring under long-time exposure to the erratic conditions of service. The test conditions, which are standardized and accelerated, do not reproduce all the conditions encountered in service. Therefore, inferences made from results of tracking tests, concerning either direct or comparative service behavior, should be made with caution.
3.3 The time-to-track a 1-in. (25mm) distance at a specified voltage between electrodes separated 2 in. (50mm) has also been found useful in categorizing insulating materials for indoor and protected outdoor applications, such as metal-clad switchgear.

3.4 The initial tracking voltage has been found useful for evaluating insulating materials to be used at high voltages or outdoors and unprotected, as well as for establishing (see 8.11) the test voltage for the time-to-track test.

3.5 In service many types of contamination may cause tracking and erosion of different materials to different degrees. This method recognizes the importance of such variability and suggests the use of special test solutions to meet specific service needs. For example, an ionic contaminant containing, in addition, a carbonaceous component such as sugar may be used to cause tracking on very resistant materials like polymethylmethacrylate. Such contamination may be representative of some severe industrial environments. In this case, the time-to-track technique is used, since time is required to decompose the contaminant solution and build up conducting residues on the sample surface.

3.6 Very track-resistant materials, such as polymethylmethacrylate, may erode rather than track under more usual contaminant conditions in service. The use of this method for measuring erosion is consequently important. For erosion studies, only tests as a function of time at constant voltage are useful.

4. Test Specimens

4.1 Insulation specimens with a flat surface approximately 2 by 5 in. (50 by 130 mm) shall be made as shown in Fig. B1. In the case of sheet or other
materials with two or more surfaces which may have different characteristics, separate specimens shall be prepared exposing each surface to test. The surface shall be carefully identified so far as possible, that is, mold face, press face, etc. For surfaces that have noticeable directional characteristics, two sets of specimens shall be prepared with the predominant directional characteristic in line with the electrodes for one set of specimens, and at right angles to the other set. The sample direction shall be carefully identified as far as possible; that is, machine direction, cross-machine direction, warp or fill direction (for textile reinforced products) etc.

4.2 Preparation of Specimens—The sample face shall be cleaned with a suitable solvent and rinsed with distilled water. Unless otherwise specified, the natural surface finish of the specimen must not be mechanically destroyed that is, by sanding, abrading, etc., for specimens to be used in the time-to-track method. However, with the variable-voltage method the surface of the test specimens should be lightly but completely sanded under flowing tap water with 400A-grit wet silicon carbide paper and rinsed with distilled water. Such sanding removes gloss and contaminants to provide a surface that is wet more easily and rapidly by the contaminant. Loss of gloss and slight erosion of the surface usually occurs in service, particularly outdoors. The specimen are under the bottom electrode shall be generously covered with a conducting silver paint \(^4\) and the 1-in. (25mm) tracing reference marks shall be added as shown in Fig. B2. For all tests, other than the time-to-track test soak the test specimens prepared as above for 24 to 48 h in the specified contaminant solution before test.

4.3 For each determination five specimens shall be prepared and evaluated.

\(^4\) DuPont silver paint No.4817 has been found suitable.
5. Apparatus

5.1 A simple schematic diagram of the apparatus is given in Fig. B3 and consists of the following.

5.1.1 A 60 Hz power supply with an output voltage stabilized to ± 1 percent which can be varied from 1 to at least 7.5kV with a rated current of no less than 0.1 A for every test station to be used (that is 0.5 A for five stations).

5.1.2 A means for applying a specified contaminant solution at a controlled rate to the specimen surface.

5.1.3 Stainless steel top and bottom electrodes as shown in Fig. B4.

5.1.4 A pad of filter paper cut as shown in Fig. B5 to fit under the top electrode and used to smooth out the flow of the contaminant solution.

5.1.5 A set of ballast resistances (50, 10, and 1-k ohm rated at 200W each) to be connected as specified in series with each test specimen on the high voltage side of the power supply.

5.1.6 A 330 ohm, 1/2 W, carbon resistor mounted with a simple tension spring and connected in series with the specimen and ground to act as an overload, high-voltage fuse.

5.1.7 Structural parts and a grounded safety enclosure.

6. Procedure

6.1 Mount and fuse the specimen with the flat test surface on the underside at an angle of 45 deg. from the horizontal as shown in Fig. B3. Insert the contaminant delivery hose midway between eight thicknesses of the filter paper "ear" to prevent contaminant from squirting out the sides.

6.2 At the start of each test date, replace all residual liquid in the
contaminant supply beaker with fresh contaminant. Cover all beakers to minimize dust and dirt as well as evaporation. Unless otherwise specified, use 0.1 percent (by weight) ammonium chloride (reagent grade) and 0.02 percent nonionic wetting agent\(^5\) in distilled water. This contaminant solution must have a resistivity between 370 and 400 ohm-cm when measured at 23 \(\pm 1^\circ\)C.

6.3 Adjust the contaminant flow and calibrate to give the flow rate for the voltage to be specified in Table 1.

6.4 After calibration, the start-up procedure differs, depending on whether the test specimen is a carry-over from a previous test, or an entirely new specimen.

6.4.1 For a specimen that has never been subjected to voltages and contaminant (that is, new specimen), start the contaminant injection into the filter paper, allowing the fresh contaminant to wet the filter paper thoroughly and replace the old liquid in the tubes and syringes and to flow as a steady stream (note 1) (not intermittent bursts) across the test specimen face between electrodes. The contaminant must flow from the quill hole in the bottom of the top electrode and should not squirt out of the sides or top of the filter paper during the pressure stroke of the pipet. Close the safety gate and apply the appropriate test voltage tabulated in Table 1.

6.4.2 For a specimen that is a continuation from a previous test (that is, off test overnight), wash down the test specimen face and filter paper with distilled water in order to remove any contaminant residue from the previous test. Do not change the filter paper. Start the contaminant flow, allowing the fresh contaminant to wet the filter paper thoroughly, and replace the old liquid in the tubes and syringes until a steady contaminant flow (Note 1).

\(^5\) Triton X-100 made by Rohm and Haas Co. Philadelphia, has been found satisfactory.
is established across the specimen face. Momentarily arrest the contaminant injection into the filter paper with a manual syringe. Quickly rewash the specimen face only with distilled water, close the safety gate, start up the contaminant flow, and apply the required voltage. Time is of the essence here, for any prolonged delay will result in a too vigorous and faulty start-up.

Note 1—This steady flow condition should be observed for 5 min. at the normal test contaminant feed rate and not at a manually operated accelerated calibration rate.

6.5 Effective scintillation, small yellow to white (perhaps with some parts blue) arcs, should appear predominantly just above the teeth of the lower electrode within at most a very few minutes after application of the voltage. These discharges should occur in essentially continuous fashion, although they may "dance" from one tooth to another before finally settling down to cause a small, bright "hot spot" which will start "chewing" on the specimen surface and which will ultimately lead to tracking failure. The condition of effective scintillation can also be observed with a cathode-ray oscilloscope. The signal may be picked off the ungrounded side of the fuse resistor. Proper scintillation is observed as a continual but nonuniform break-up of the 60 Hz current wave over the whole duration of each half cycle. Effective scintillation is critical and if not obtained, the electrical circuit, the contaminant flow characteristics, and the contaminant conductivity must be carefully checked and adjusted if necessary.

6.6 Regardless of whether the start-up is for new or old specimens, watch the scintillations for the first 15 min., and periodically at least once every hour thereafter. Thus, the tracking time can be noted, in addition to
watching for:

6.6.1 Steady scintillation between successive injections,

6.6.2 Loss of any contaminant, such as by squirting out of side of filter paper,

6.6.3 Whether the contaminant stream down the test specimen face is steady instead of in spurts,

6.6.4 Air bubble leaks into the syringes which would change the contaminant feed rate, and

6.6.5 Stuck syringe pistons.

6.7 Note the time, but do not stop the test to disconnect, any test specimen that has tracked to the 1-in. mark. Stopping the test and removing the voltage, even momentarily, will permit the contaminant to saturate excessively the partially tracked area of other unfailed specimens, with resultant vigorous scintillation after restart. Excessive current in any specimen that continues to track will be taken care of by the fuse resistor.

6.8 If the test is not completed within the working day, the test can be continued the following day if the following precautions are taken:

6.8.1 Remove voltage, and stop the contaminant feed.

6.8.2 Thoroughly wash down the filter paper with distilled water. Do not replace the filter paper.

6.8.3 Thoroughly wash down the specimen face with distilled water.

6.8.4 Throw out the contaminant left in the supply beaker and replace with distilled water so that the feed hose sinker will not become encrusted with dried contaminant residue. Do not pump this distilled water into the hose, filter paper, or syringe.
6.9 The method of voltage applications and the evaluation of tracking or erosion characteristics depend upon the different test techniques used as described in Sections 7, 8, 9.

7. Initial Tracking Voltage Test

7.1 For the determination of the initial tracking voltage, apply the voltage between the electrodes in 250-V steps. Hold each voltage for 1 h (unless failure is indicated) before increasing by 250 V to the next step. A starting test voltage must be determined so that tracking failure does not occur sooner than the third step (between 2 and 3 h). Adjust the rate of contaminant application so as to maintain effective scintillation at the different voltages (see Table 1). Time can be saved in the determination of the appropriate starting test voltage for a specific material if an intermediate to high voltage is first selected (that is 3.25 kV). If the specimen fails quickly on the first voltage step, the starting voltage for the next test should be decreased, usually at least 1 kV. On the other hand, if four steps or more are needed to cause failure, then the initial voltage may be increased accordingly. Experience soon provides a quick clue to the rapid determination of the appropriate starting voltage.

7.2 The end point of the test is reached at the voltage step where progressive tracking starts. Careful observation is needed to note when isolated markings on the surface first join together and start progressing upward from the bottom electrode. It is important to let this track proceed at least 1/2 in. (13 mm) up the specimen surface before discontinuing the test to make certain that progressive tracking is actually under way. (Some test specimens appear to start tracking and then "clean up"). Record the voltage at which continuous
tracking is established as the "initial tracking voltage." The elapsed
time in the voltage step at which progressive tracking starts should be
recorded but is not considered to be as significant as the value of the
voltage.

7.3 Observe and record the character of the track and the appearance of
the test specimen at the end of the test. Tracking may be, for example,
broad, narrow, filamentary, or dendritic (tree-like), with or without deep
erosion. The track may be black, brown, or sometimes even white, and may
perhaps occur along fiber bundles in the material. The residue in the
track may be hard, tough, brittle, powdery, fluffy, etc. The specimen
itself in the presence of the contaminant and scintillation may change
colour, the weave in fabric reinforcement many become more pronounced,
delamination may be apparent, etc.

7.4 Maintain the contaminant feed rate constant throughout the test.
Calibrate the rate at the beginning and end of each test day, or more often
if the rate appears to be variable.

8. Time-to-Track Test Method

8.1 For the time-to-track technique, a constant, specified test voltage
(note 2) is used and the tracking time is recorded. If the test voltage
is not specified, a voltage 750 V lower than the initial tracking voltage
as determined in Section 7 may be used. All materials in a tracking class must,
of course, be tested at the same voltage. The requirements of Table 1 must
be met for the test voltage used.

Note 2- A test voltage of 2.5 kV has been found generally useful.

8.2 Since relatively long tracking time may result (as much as 10 + h),
It is important that the contaminant feed rate is constant over the total test period. The rate should be calibrated both before the start and at the end of each test or at least at the beginning and end of each day.

8.3 The time to track a distance of 1 in. (25.4 mm) above the lower electrode (to the reference mark of Fig. 82) is taken as the failure criterion and should be reported in hours and minutes. A taut horizontal string within the test enclosure can be used as a sighting reference to judge whether tracking has progressed to the reference marks. If the time to track is less than 10 minutes or more than about 15 h, it may be assumed that the material is out of the voltage class, and a lower or higher test voltage should be selected if evaluation is required in this case.

8.4 Failure time for the total 2-in. (50mm) distance between electrodes (instead of the 25.4 mm test distance) is not representative of the track resistance of the material, since the last 1/4 to 1/2 in. (65 to 125 mm) of the gap (depending on the material) is failed by burning and arcing more so than by tracking.

8.5 The character of the track and the description of the test specimen should be observed and reported as described in 7.3.

9 Report

9.1 The report shall include the following:

9.1.1 Type and designation of material tested,

9.1.2 Details of specimen fabrication including size, thickness, cleaning procedure and solvent used, surface finishing, if any, preconditioning, etc.,

9.1.2 Orientation of the specimen in respect to electrodes (that is, machine direction, cross-machine direction, warp direction, fill direction, etc.).
9.1.4 Contaminant composition, concentration, conductivity, and temperature of liquid during conductivity measurement, and

9.1.5 Test voltage or voltages and the associated rate of contaminant application.

9.2 In addition, the following must be reported for the specific test:

**For Initial Tracking Voltage Test:**

9.2.1 Initial tracking voltage for each specimen as well as the number of voltage steps used including the final step at which continuous tracking occurred,

9.2.2 Time to progressive tracking (7.2) during the last voltage step, and

9.2.3 Appearance of the test specimen and the track, including a notation as to the qualitative degree of erosion.

**For Time-to-Track Test:**

9.2.4 Value of the test voltage,

9.2.5 Time-to-track, in hours and minutes,

9.2.6 Appearance of the test specimen and the track, including a notation as to the qualitative degree of erosion, and

9.2.7 Rate of contaminant application at the beginning as well as the end of each test date.
FIGURE A1 TEST SPECIMEN

FIGURE B2. TEST SPECIMEN SHOWING LOCATION OF CONDUCTING SILVER PAINT AND TRACKING REFERENCE MARKS
Figure B3 SCHEMATIC DIAGRAM OF APPARATUS
Top Electrode

1. 3/8" (1 cm.)
2. 30°
3. 1/8" (.3 cm)

Top and bottom electrode material = 14 mil thick stainless steel

Both straight cut quill tip edges of top electrode should contact specimen face evenly.

Filter paper must be behind electrode and not protrude to prevent contact of electrode to specimen.

Assembly

Clip to fasten contaminant delivery hose to filter paper. Full scale: 7 mil stainless steel

* so hard as to cause hose to plastically collapse.

FIGURE B5 FILTER PAPER, SHOWING CLIP AND METHOD FASTENING
TABLE I

RATES OF CONTAMINANT APPLICATION

Note—The rates of contaminant application shown are suitable only for contaminatns with a resistivity of approximately 370 to 400 ohm-cm at 23°C on nonporous samples. With porous samples it may be necessary to increase the contaminant flow somewhat to maintain effective, continual scintillation. Lower contaminant resistivities also will require a higher rate and higher resistivities, a lower rate of contaminant application; this must be determined experimentally. At too high a contaminant rate scintillation will be greatly reduced because the current will flow in the contaminant film without disrupting it. At too low a rate the solution boils away or at the higher voltages is electrostatically removed so that scintillation occurs only at intervals in scattered bursts. The tendency for tracking and erosion is increased with a decrease in contaminant resistivity or with the incorporation of a carbonaceous material such as sugar, even though in the latter case the resistivity is not decreased. The chemical nature of the ionizable contaminant is usually of minor importance in respect to tracking but may be of major importance in respect to erosion.

<table>
<thead>
<tr>
<th>Rate of Application of 0.1% NH₄Cl-0.02% Wetting Agent, ml/min</th>
<th>Voltage Range, kV</th>
<th>Series Resistor, Ohms</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.075</td>
<td>1.0</td>
<td>1000</td>
</tr>
<tr>
<td>0.15</td>
<td>2.0 to 2.75</td>
<td>10 000</td>
</tr>
<tr>
<td>0.30</td>
<td>3.0 to 3.75</td>
<td>50 000</td>
</tr>
<tr>
<td>0.60</td>
<td>4.0 to 4.75</td>
<td>50 000</td>
</tr>
<tr>
<td>0.90</td>
<td>5.0 to 6.0</td>
<td>50 000</td>
</tr>
</tbody>
</table>

b. Scintillation at 1kV is very critical, and it may be desirable to remove the series resistor and to decrease further the contaminant rate, that is, so that 0.075 ml is applied only once every 2 min. With such slow rates it is possible also to obtain scintillation at voltages even lower than 1kV to permit test of relatively poor materials.
APPENDIX "C"

[Reprinted from Reference 1]

MEASUREMENT OF SALT DEPOSIT DENSITY

The salt deposit density is the measure of the amount of salt present on the surface of the sample insulator after testing. It is an important factor in describing the performance of polluted insulators under fog conditions. The contaminants on the surface of the sample insulators after the fog test were washed into a clean beaker using a syringe filled with distilled water. The water was then transferred to a conductivity cell\(^{(33)}\). The cell has a removable top to permit thorough washing after each test and also has a fixed electrode geometry. The amount of water used for the wash was also fixed at 300cc. Using an alternating supply of 1 kHz from a General Radio Impedance Bridge (type 1650A, serial number 381, accuracy of ±1% over range of interest) to avoid polarization defects, the electrical volume resistance was measured. The order of 20Kohms was the maximum resistance measured by the cell (for the lowest salt deposit density) and therefore capacitive effects were not predominant. The measured resistance was then referred to previously determined calibration curves\(^{(33)}\) of weight of sodium chloride versus resistance. The calibration curve for a temperature of 25°C is shown in Figure C 1. For temperatures other than 25°C, the resistance can be obtained by using a temperature correction factor according to the formula\(^{(33)}\),

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

\[\alpha = \text{temperature coefficient of resistance (0.02)}\]

126.
FIGURE C1 CALIBRATION CURVE FOR NaCl at 25°C
\[ R_t = \text{corrected resistance} \]
\[ R_{25^\circ C} = \text{resistance at } 25^\circ C \]
\[ t = \text{temperature of wash water in } ^\circ C \]


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