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RELIABILITY AND SURFACE DEGRADATION ASPECTS OF SYNTHETIC INSULATOR MATERIALS FOR HV APPLICATION

BY

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A DISSERTATION

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ABSTRACT

This study is a theoretical and experimental investigation on the state of the art of synthetic insulators for outdoor high voltage transmission systems.

The surface of a polymeric material is known to be degraded by, among other things, environmental stresses such as UV, air pollutants, etc. The reliability of an insulator material is governed by the surface and other characteristics that do not drift much as a function of stresses and time.

The surface characteristics of various synthetic materials, when these materials were exposed to UV radiation in the laboratory were studied. The changes in the surface properties of these materials were observed by measuring the electrical noise generated on the surface as a result of applied electric field, the hydrophilicity of the surface (θ_{H_2O}) and the leakage current developed on application of electric stress before and after UV aging. UV aging decreases θ_{H_2O}. The amount of change in the wettability of a particular specimen due to UV aging was related to the amount of change in the leakage current of the specimen and the amount of change in the surface noise generated on the specimen. Increase in hydrophilicity increases the surface noise and the leakage current, thereby degrading its effectiveness as an insulator.

Experiments were done to investigate the effects of exposing a

typical polymer insulator made of R.B.G.F. core covered with silicone elastomer to polluting gases like NO_2, SO_2, H_2S, and CL_2, UV, and polluting gases plus UV. From the data obtained on the accelerated life tests, the life of the material in normal usage was extrapolated as a function of the above stresses using a modified Arrhenius equation. Suggestions are given for further research on the studies of insulator surfaces in new as well as degraded conditions.

APPROVAL OF DISSERTATION

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SATYAPAL S. BHATIA

FOR

DEPARTMENT OF ELECTRICAL ENGINEERING
NEW JERSEY INSTITUTE OF TECHNOLOGY

BY

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October 1977

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Chapter I
INTRODUCTION

1.1 Nature of the Problem

High voltage transmission technology has now reached a point where lines carrying 765 KV are operating presently and lines to carry over one million volts are being contemplated for the near future. To achieve these goals, considerable effort is being made to develop well designed insulators suitable for use in these transmission line systems.

New synthetic materials (fiberglass, polytetrafluoroethylene, epoxy resins, silicone elastomer, etc.) have made possible the development of non-ceramic insulators. Synthetic insulating materials, appropriately designed, have important advantages compared with conventional ceramic insulators. They have a high tensile strength to weight ratio and less susceptibility to mechanical damage compared to porcelain insulators. Therefore, mechanical loading and reliability of transmission lines can be considerably increased by the use of suitable synthetic insulators. Also, synthetic insulators can be manufactured as one piece in the largest dimensions required in practice.

New extra high voltage and ultra high voltage transmission systems are designed to handle larger quantities of electrical energy and these systems require outdoor insulators that will meet severe electrical, mechanical and environmental requirements. The

composite insulator approach in synthetic insulating materials makes it possible to optimize the mechanical and electrical performance of available polymer systems. The mechanical function is provided, for example, by a resin bonded fiberglass core which is covered with weather and high voltage stable sheds of suitable synthetic materials. These materials must be screened and evaluated under conditions simulating the operating conditions of an insulator in all phases of high voltage transmission.

The composite insulators have been evaluated in the field for several years, in the U.S., Europe and Canada, but the experience of these trial evaluations are such that further development of materials and design is necessary to meet all the functional requirements of the future transmission systems.

The outdoor high voltage environment for a synthetic insulator consists of a combination of degradation elements like ultraviolet radiation, corona, erosion, reactive gases, solid contamination, humidity, etc. The changes in the physical, chemical and electrical characteristics of the synthetic polymers under such stresses are not yet fully understood.

The reliability of an insulator material is governed by the excellent surface and other characteristics that do not drift much as a function of stresses and time. Detailed studies on the insulator surfaces are, therefore, required to determine the effect of important environmental stresses on the surface characteristics of

these new synthetic insulating materials and also to determine the superiority of one material over the other. The studies conducted so far in this direction are far from conclusive. Most experimental techniques and tests presently being used to screen and evaluate new synthetic insulators for outdoor high voltage use measure the material's tendency to form carbonized tracks when exposed to severe acring. These tests are probably developed from the experience gained from the usual porcelain insulators which develop uncontrolled surges of leakage current and arcing when moisture and contamination are present. Researchers involved in developing and testing synthetic insulators normally assume that the same surges of leakage current will be formed on synthetic materials also and thus attempt to recreate arcing defined for porcelain insulators by water filming which is produced by covering the insulator with excessive amounts of artificially wetting agents and surfactants. The design of these tests destroys a very valuable property that some of the synthetic materials possess. This property is the ability to prevent water filming from occuring on the surface of these synthetic materials. Porcelain cannot maintain a high non-wetted surface and so these tests are perfectly alright for testing porcelain insulator, since these tests simulate a very common failure mechanism of porcelain insulators. Synthetic insulating materials, however, have high arc suppression under wet conditions and not necessarily maximum arc-track resistance. The order of testing these synthetic insulating materials should, therefore, be reversed. These materials should be screened on their ability to maintain a hydrophobic surface, high surface resistance

and arc-suppression under normal conditions. Extremely good, high power density arc-track resistance is important only if the material severely loses its hydrophobic nature and ability to control surface leakage currents. For this reason, the author feels that investigations characterizing the hydrophilicity of the surface before and after aging due to environmental stresses are more relevant in studies on degradation of synthetic insulating material surfaces. The longer a material can maintain its hydrophobic nature, the longer it will preserve its surface resistivity and thus inhibit the flow of excessive leakage current and severe arcing and so need not have maximum arc-track resistance. Of course, when optimum design achievements are made, the synthetic insulator selected will have both hydrophobicity as well as arc-track resistance properties. New test technique specially suitable for characterizing synthetic insulator surfaces in new, as well as weathered conditions, are, therefore, extremely important to make accurate predictions of reliability and surface degradation of synthetic insulating materials for outdoor high voltage systems.

This thesis research has been primarily directed towards new techniques for the characterization of polymer insulating material surfaces before and after environmental aging. Measurements of water contact angles on the surface have been made to determine the hydrophilicity of the surface. The changes in the surface characteristics of the synthetic insulating material due to important environmental stresses like ultraviolet radiation and exposure to reactive gases (SO_2, NO_2, H_2S, etc.) have been determined by measuring the

water contact angle before and after aging. The changes in the surface characteristics of the synthetic insulating materials has also been studied by measuring the amount of electric noise generated on the surface of these materials on application of electric field, by measuring the leakage current developed on application of electric stress and by observing the scanning electron microscope pictures of the surface before and after aging. The rationale for selection of water contact angle and electric noise measurements in characterizing synthetic insulating material surfaces is treated in Chapter V in detail.

The results obtained on the aging of snythetic insulating material surfaces on exposure to ultra violet radiation characterized by water contact angles, electric noise measurements and the leakage current, show an excellent correlation between the three parameters. An increase in hydrophilicity (decrease in water contact angle) is followed by an increase in electric noise and an increase in leakage current. The results obtained on degradation of different materials are further substantiated by the scanning electron microscope studies on the surface. A detailed discussion of the results obtained is given in Chapters VI and VII. An important aspect of any reliability study is to determine the normal life of a component of system in a relatively short period by accelerated testing techniques and suitable mathematical models. The results obtained on the life of a typical synthetic insulator material made of resin bonded fiberglass core covered with silicone elastomer on exposure to ultraviolet radiation

and reactive gases and ultraviolet radiation in succession have been used to determine the life of this material in usage by using the modified arrhenius equation.

1.2 Scope of This Study

The purpose of this study is to explore both theoretically and experimentally some of the basic questions of reliability and surface degradation aspects of synthetic insulating materials for outdoor high voltage transmission systems.

In completing this study, it was first necessary to look at the different types of synthetic insulating materials which can be considered as suitable for use in extra high voltage line systems of the future. In Chapter II, therefore, an investigation is done first of the state of the art of synthetic insulating materials. Some of the basic properties required of compound insulators for use in extra-high voltage transmission line systems are then discussed and finally some important synthetic insulating materials along with their manufacturing technology and basic characteristics are discussed.

In order to perform a study on reliability and degradation of synthetic insulating materials, it was important to look at the concepts and mechanisms of degradation relevant to synthetic insulating materials for outdoor high voltage application. The basic studies of Chapters III and IV were carried out to develop a clear concept of the aging of electrical insulation. A detailed discussion of the

definitions of aging along with associated terms and procedures and techniques suitable for performing accelerated tests and prediction of aging characteristics are investigated in Chapter III. Before carrying out any aging or degradation studies on polymeric insulating materials involving accelerated testing and suitable mathematical models, it is rather important to know precisely as far as possible, the mechanisms of degradation of these materials due to important stresses. The degradation mechanisms of polymeric insulating materials due to some important stresses are, therefore, covered in Chapter IV.

As stated earlier in another context, most typical studies on the surface of synthetic inculating materials have ignored an important property of these materials. This property is the hydrophilicity of the surface of a synthetic material. The importance of characterizing synthetic material surfaces by measuring the hydrophilicity of the surface determined from water contact angle measurements and the electric noise generated on the surface of an insulating material on application of electric stress has been described in Chapter V.

The techniques of characterizing synthetic insulating material surfaces by measuring the electric noise and leakage current generated on the surface of a material on application of electric stress and by measuring the water contact angle on the surface have been used in an experimental investigation to study the surface degradation of five different synthetic insulating materials on exposure to ultraviolet

radiation. The results obtained on the degradation of synthetic materials indicate a correlation between the contact angle and the electric noise and leakage current measurements. The results of this study along with conclusion and discussion of the results obtained are described in Chapter VI.

The degradation of synthetic materials on exposure to ultraviolet radiation is expected to generate new chemical functional groups, change in hetrogeneity and an increase in the roughness of the surface. To observe these phenomena, the surface of the insulating materials were observed by looking at the scanning electron microscope picture of the surface before and after aging due to ultraviolet radiation. This scanning electron microscope investigation of the surface is given in Appendix (A). The scanning electron microscope study of the surfaces correlates very well with the noise and hydrophilicity study in Chapter VI.

One of the basic ideas in reliability engineering is to predict the normal life of a material or component in a relatively short period by using techniques of accelerated testing and suitable mathematical model. The effects of exposing a typical composite insulator made of resin bonded fiberglass core covered with silicone elastomer to pollutant gases (SO_2, NO_2, H_2S, and CL_2), ultraviolet radiation and pollutant gases and ultraviolet radiation as a function of temperature has been studied as described in Chapter VII. Hydrophilicity (θ_{H_2O}) and noise were used as the criteria for degradation of

insulator characteristics. The results on the life test data were used to determine the parameters of the modified Arrhenius equation. These parameters were then used to predict the estimated life of the material in normal usage.

A summary of the conclusions drawn from this thesis along with important suggestions for further research work in this area is described in Chapter VIII.

Chapter II

SYNTHETIC INSULATORS FOR H.V. TRANSMISSION

2.1 Introduction

About thirty years ago, electrical insulation was provided by simple materials such as oil, paper, porcelain, and ceramics. These materials had been used for insulation purposes ever since electricity was first generated in volume some eighty-five years ago. The performance of these materials over the years has been very good.

In the last twenty-five years, plastic technology has advanced at astonishing rate. Over these years, considerable work has been done to investigate the electrical properties of plastic materials. The results found indicate that plastic materials have great potential to be used as electrical insulators in place of the conventional materials.

Insulators made with epoxide resins were used in medium voltage indoor switching systems in the fifties.[1] The performance obtained from these insulating systems has been very encouraging. The experience gained from this was utilized to produce insulators with cycloaliphatic epoxide resins for use in 110KV outdoor stations.

It must be emphasized that the development of plastic materials for use as electrical insulators was not done merely to replace or

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[1] See Bibliography No. 5-59, 6-59 and 10-60, pp. 135-136.

exchange porcelain insulators for use in transmission lines. Manufacturing of insulators of great length as a single unit and the flexibility of shed designs are two of the important advantages of plastic insulators over the conventional insulators. The experience gained with plastic insulators have led many countries around the world including the Unites States, Germany, Belgium and the U.K., to use plastic insulators in transmission line systems.[1] The experiences have been gained with plastic insulators in H.V. transmission systems of up to 550 K.V. using insulators made of epoxy.

2.2 Development of Compound Insulators

The recent studies on silid core plastic insulators indicate the low probability of finding a single material which will have both the mechanical and electrical properties required of electrical insulators for E.H.V. and U.H.V. transmission lines of the future.[2] This has led researchers to the idea of developing a composite insulator material. The principal of a composite insulator, has been applied, as early as 1925[3], to find solutions to insulation problems of specific nature.

In a compound insulator, two materials are used to make an insulator. One material fulfills the mechanical requirements such as tensile strength and the other fulfills the electrical requirements

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[1]See Bibliography 13-72, p. 150.

[2]See Bibliography 3-73, p. 150.

[3]See Bibliography No. 2-32, p. 133.

such as resistance to electrical discharges and atmospheric influences.

A typical composite insulator for H.V. application consists of a central core made of resin bonded glass fiber (R.B.G.F.) with sheds of suitable organic materials. For the sheds, different types of material are being tried. Polytetrafluoroethylene (PTFE), epoxy resin, and silicone elastomer are among the materials which are hoped to be suitable to withstand the severest environmental stresses required of the shed materials.

2.3 Properties Required of Compound Insulation

An important aspect of the construction of a compound synthetic insulator with a central core and a suitable covering is the choice and coordination of the thickness of the shielded covering and the bonding between the rod and the outer covering. Special care is needed in the processing of these materials to avoid formation of cracks or gas bubbles.

Important manufacturing or design defects occur in the compound insulators mainly due to the bad bonding between the central rod and the outer covering, with the consequent existence of air bubbles between rod and cover, and a weak mechanical strength. The puncture that occurs in these cases are such as to involve the body of the insulator, so that once they have occurred, they reduce the withstanding strength of the insulator and severely prejudice its life, since they make it possible for humidity and pollution to go below the protective covering. The insulation with very minute defects of the

above type might pass the conventional electrical endurance tests of short duration but will fail in the course of long duration tests.

A compound insulator must, therefore, have some basic physical and mechanical characteristics as discussed below.

1. Resistance to Thermal and Chemical Stresses

The rod and the shed material must have excellent adhesion which should not weaken much as a function of thermal and chemical stresses. The gap between the central rod and the cover material is normally filled with an intermediate layer of glue. Over a range of temperature, this junction must not be endangered by chemical corrosion. This is especially important when the gap is not covered from every side by the shed material but is partially exposed to direct corrosion under environmental influence. If the glue contains, for instance, ester or amino groups, the danger of dissolving the connection by hydrolysis exists.

2. Mechanical Characteristics of the Rod and Shed Material

The rod and the shed material must have compatible properties. For example, the bonding between the rod and the shed material must be continuous, so that the action of the load on the rod material and on the cover material produces nearly identical deformations.[5] The deformation of a compound insulator under the influence of a tensile force is shown in Figure 2.1.

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[5]See Bibliography No. 4-74, p. 151.

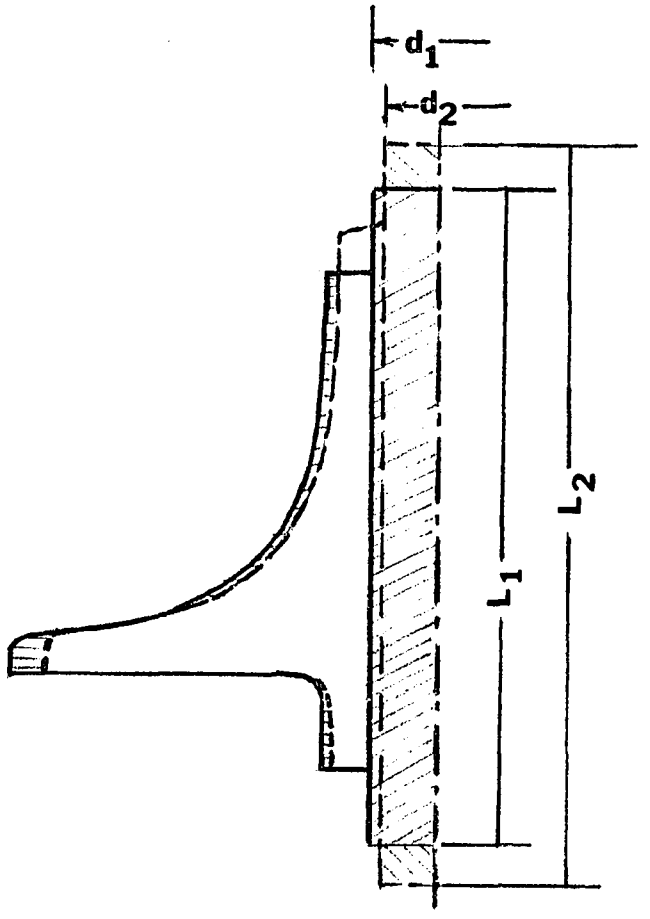

Figure 2.1 Showing deformation of a compound insulator under the influence of a tensile force.

Due to tensile load, the length of the rod material increases from L_1 to L_2. This results in the transversal contraction of the rod. The rod diameter changes from d_1 to d_2. In order to avoid high shearing stresses in the gap, the shed must follow the rod volume without much resistance. The resistance against deformation is determined by the specific work done in deformation per unit volume, of the shed and the length of the junction over which the deformation

loads are conveyed. For a cylindrical rod the specific work done in deformation is given by

$$a = \frac{\sigma^2}{2E} = \frac{F.\varepsilon}{2Q}$$

where

ε = breaking elongation

F = tensile force

Q = sectional area of the rod

σ = tensile stress

E = modulus of elasticity

Shed materials with a low modulus of elasticity and high elongation show the least resistance to deformation. Thus, a good shed material has to have a high value of breaking elongation and a low modulus of elasticity. These properties have to be effective over a wide range of temperature.

3. Retardation Characteristics

An ideal shed material must have good retardation characteristics, i.e., the property of being restored to its original state (shape and volume) after sudden release of mechanical stress. Thus, the shed material must be selected so as to have high elasticity and low retardation time at sudden stress release.

4. Connection Characteristics

The compound insulator materials must provide an excellent connection. The connection problems arise, for instance, between resin bonded glass fiber rod of unsaturated polymer resin and teflon shed material. A chemical bond is not possible in this case.

```
        F   F   F   F
        |   |   |   |
- - - - C - C - C - C - - - -
        |   |   |   |
        F   F   F   F
```

The atomic bonding energy of the covalent C-F bond in the lateral chains of the material is approximately 26% higher than the binding energy of the main chain C-C. Any attempt to break the bond would immediately result in the destruction of the C-C linkage. A connection problem, therefore, exists between these two materials.

2.4 Materials and Manufacturing Technology of Compound Insulators for H. V. Application

Compound insulators which meet the tough requirements discussed above and which have been manufactured and tested by researchers in this field are discussed below. Typical compound insulators for H.V. application is made of:

a. Resin bonded glass fiber (R.B.G.F.) core and polytetrafluoroethylene sheds.

b. R.B.G.F. core and cycloaliphatic epoxide resin (CEP) sheds.

c. R.B.G.F. core and silicone elastomer sheds.

Resin Bonded Glass Fiber Rod[1]

The core material in all the three types of insulators described above is made from the fiber glass rod. The function of the core material is to provide very high mechanical resistance with low weight. The rod material is manufactured by impregnation of fiberglass with resin arranged in one direction along the rod, and the subsequent polymerization of the resin. Good bonding between the glass and the resin is obtained by proper surface treatment of the rod. The glass rod is made of aluminabrorosilicate, free of alkali, completely neutral, and very easily wetted, while the resin for impregnating the rod could be a cycloaliphatic one, with low viscosity and good anti-tracking characteristics.

Two manufacturing techniques are used in common: (a) continuous and (b) discontinuous. In the continuous process, the fiber glass rod is produced by passing impregnated fibers through extruders, in which the polymerization operation takes place. In the second process, which is a discontinuous process, impregnated fibers are put into aluminum alloy moulds, and resin polymerized by a hot process. The manufacturing process in both techniques are carried out with special care to avoid the formation of cracks or air bubbles in the rod. The fiberglass rods have the following mechanical characteristics:

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[1]See Bibliography No. 4-74, p. 151.

Ultimate tensile strength - 600 N/mm^2

Elongation after fracture = 1.6%

Modulus of elasticity - 37,000 N/mm^2

Shed Materials

a) Polytetrafluoroethylene (P.T.F.E.)

The choice of P.T.F.E. as a shed material for H.V. application received tremendous attention in the beginning of the research in this field due to its excellent electrical, chemical and mechanical properties. But, over the years, many researchers have found that P.T.F.E. cover material, although non-tracking, erodes heavily due to leakage currents. Another problem in using P.T.F.E. cover material is the difficulty in obtaining a good adhesion of the rod material with P.T.F.E. surface. Usually the adhesion between the rod material and P.T.F.E. surface can only be obtained by etching the surface. The strength of the connection obtained is not very high. Another problem in R.B.G.F. rod P.T.F.E. cover material compound insulators is the fact that the thermal coefficient of expansion of the P.T.F.E. can be as much as fifty times higher than the coefficient of the R.B.G.F. rod within the range of the operating temperatures of a transmission line insulator. If there is frequent temperature cycling, it is quite possible that the connection becomes loosened and moisture penetrates into the gap.

The breaking elongation, hydrophilicity, homogeneity, and elasticity of P.T.F.E. material, although quite good, are again temperature dependent.

Due to the reasons mentioned above, present research activities are concentrated on other shed materials.

b) Cycloaliphatic Epoxide Resins (C.E.P.)

Cycloaliphatic epoxide resins have been used as shed materials in synthetic insulators because of their excellent insulating properties[1] as well as the natural ability of the epoxide resins to form very good adhesive bonds with R.B.G.F. rod. Similar to P.T.F.E. material, the coefficient of thermal expansion of the cycloaliphatic epoxide resins depends on the ambient temperature. The value of the coefficient of thermal expansion of highly flexible C.E.P. may vary from 3×10^{-6} to 150×10^{-6} depending upon ambient temperature. This amounts to as much as twenty times the coefficient of thermal expansion of the R.B.G.F. rod. In spite of these vast differences in the values of the thermal coefficient, there is no real danger of a puncture of the junction because of the very good natural bond between the R.B.G.F. rod and cycloaliphatic epoxide resin cover material.

Cycloaliphatic epoxide resin cover material, however, has one severe disadvantage in that it becomes very brittle and cracks at low temperatures. One study[2] indicates that a C.E.P. material with value of breaking elongation of more than 120% at room temperature cracked at -20°C. Also, studies of U.V. exposure on cycloaliphatic epoxide resin indicate that U.V. considerably degrades the insulating charac-

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[1]See Bibliography No. 6-59, p. 136.

[2]See Bibliography No. 28-70, p. 146.

teristics. One study[1] estimated the normal life of a cycloaliphatic resin cover material due to U.V. exposure as 5.4 years which is quite low for insulators for E.H.V. and U.H.V. transmission lines.

c) Silicone Elastomers

Compound insulators made of R.B.G.F. rod covered with silicone elastomers seem to have the greatest potential to be used in the future E.H.V. and U.H.V. lines.[2] Silicone elastomer material with its Si-O-Si central chain have a structure similar to glass. It is bonded with R.B.G.F. rod using a special kind of silane. The bond strength achieved is excellent over a wide range of temperatures. This fact makes silicone elastomer cover materials better than P.T.F.E. and cycloaliphatic resin cover materials, the bond strength of which is highly dependent on temperature.

Silicone elastomer has excellent resistance against U.V. and other environmental stresses such as exposure to air pollutants, etc., compared to other organic materials.[3] The modulus of elasticity of silicone elastomer is very low permitting it to withstand high mechanical stresses. The retardation behavior of silicone elastomer is excellent. Even at low operating temperatures, the time of retardation is short, safeguarding the shed material against possible cracks.

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[1]See Bibliography No. 1-76, p. 152.

[2]See Bibliography No. 15-68, p. 143.

[3]See Bibliography No. 1-74, p. 151.

From the properties of the three cover materials discussed above and the experimental investigation conducted during this research, it can be said that properly designed compound insulators made of R.B.G.F. rod covered with silicone elastomer could quite possibly become the insulators in the E.H.V. and U.H.V. transmission lines of the future.

CHAPTER III

AGING OF ELECTRICAL INSULATION

3.1 Introduction

The term aging of a material is referred to the changes in properties of the material which influence its proper functioning. Aging of insulation system, as defined by IEC TC 63 is "irreversible deleterious change to the serviceability of the insulation system. Such changes are characterized by a failure rate which increases with time."[1]

It must be emphasized that all materials age with time; the extent of aging being different in different materials. The rate of aging, that is, the rate of changes in the properties of a material with time depends, among other things, on the environmental stresses it is exposed to. It is often the combination of two or more stresses which results in the most severe deterioration with time. The knowledge of the aging characteristics of an insulating material can be used to determine its reliability and expected life of the system in which it is employed.

3.2 Importance of Aging Studies of Electrical Insulating Materials

The aging of synthetic insulating materials when exposed to outdoor environmental stresses is a complex process. The knowledge of the aging characteristics of a particular insulating material and its

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[1]See Bibliography No. 5-75, p. 152.

diagnosis are important in designing proper insulating systems to meet high demands and environmental considerations of present time.

Different materials degrade to different levels due to different types of stresses. For example, synthetic insulating materials are mainly derived from hydrocarbons. These organic materials are known to react with oxygen under various conditions to decompose to a variety of more or less volatile compounds.[1] Depending on temperature, the electric field, supply of oxygen, humidity, pressure, presence or absence of catalysts, etc., any one of these reactions could be dominant. Since many of these lead to formation of volatile materials, and therefore to an apparent weight loss of the system, it is impossible to find out which reaction was responsible for the observed change in weight. This shows that the aging of such materials involves many reactions, all having a finite but different probability of occurring depending on the existing environmental conditions.

To gain a detailed insight into the complex problem of aging of synthetic insulating materials due to different types of stresses and more importantly to a combination of stresses, a knowledge of the aging process is badly needed. Unfortunately the studies conducted so far in this direction are far from complete. To develop synthetic insulating materials for economic and efficient engineering use, considerable effort on the part of the industries and researchers is required to develop standards for testing and selection of materials.

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[1]See Bibliography No. 3-76, p. 152.

The importance of aging is, therefore, quite evident since to achieve the above goals, reliable and efficient means for predicting aging characteristics of both electrical insulating materials and systems must be developed. Moreover, a knowledge of the aging characteristics of an insulating material will permit the prediction of the useful life of new insulating materials required for E.H.V. and U.H.V. transmission lines.

3.3 Review of Fundamental Concepts About Aging

A brief discussion of the terms aging, stresses and prediction of aging characteristics of insulating materials is given below:

Aging: The term aging of an insulating material simply means the change in the characteristics of the material, both electrical and physical when the material is exposed to a variety of stresses and/or environments. The degradation of the material may be due to a single stress or a combination of stresses like electric field, temperature, air pollutants, humidity, dust, etc.

Stresses: Any physical or chemical parameter which results in the changes in the characteristics of the insulating material can be included in the term stress. Some of the important stresses which affect the performance of a synthetic insulator for outdoor high voltage transmission lines are electric field; UV radiation; air pollutants like SO_2, NO_2 H_2S, and CL_2; solid contaminants like coal dust, salt, sand, cement dust, and soot; temperature; mechanical stresses like vibration, shock, deformation, etc.

Prediction of Aging Characteristics: The studies of aging characteristics of the insulating material due to normal stresses encountered in service are not practical because of the time and expanses involved. The usual way to do this is to suitably accelerate the degradation parameter in order to obtain the end of life data relatively quicker. Understanding the physics and chemistry of the degradation, the data can then be used to predict the life of the material under normal stresses. Accelerated testing, however, needs extreme care to arrive at meaningful results. The author and his advisor feel that better prediction can be made using a small accelerating factor as far as possible and increased sensitivity of the measuring equipment because a large accelerated factor may induce new failure modes.

Another factor in the prediction of the aging characteristics of a material is the important concept of aging due to combined stresses. Most research studies on aging in the past used only one stress at a time and the superposition of the outcomes due to different single stresses was used to predict the life of the material in normal use. This was done for simplicity and time limitations. However, it is now increasingly being realized that the results obtained by single stress at a time may not give a true picture of the degradation of a material because sometimes on some materials complex stresses produce interactive effects which can not be derived by simple superposition of the outcomes of simple single factor tests.[1] Studies uncovering

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[1]See Bibliography No. 3-76, p. 152.

this aspect of aging are receiving lots of attention. For example, it has been observed[1] that the simultaneous aging at high temperatures in x-ray radiation of a polymide, a polyvinylformal, and a polysiloxane produced considerably increased life-times compared to just thermal aging at the same temperature. On the other hand, polytetrafluoroethylene deteriorated much more rapidly under the simultaneous action of heat and radiation. Studies like this, hopefully, will change the trend in future research activities.

3.4 Accelerated Life Testing and Data Analysis

Accelerated life testing of a material or product is a technique to get information on the life distribution of the material or product economically or quickly. The material or product is stressed at a level more than what it is supposed to withstand in normal use. This results in short life of the material. The results obtained are used to extrapolate the life of the material or product in normal use using statistical techniques and suitable reliability models. Accelerated testing techniques are specially suitable for materials or products such as synthetic insulating materials for H.V. applications, the normal life of which is so great that testing at nominal conditions is very time consuming and, therefore, expensive. The accelerated testing not only is an economical and efficient method for life testing such materials but is the only practical way to find out the superiority of one material over the other in a short time.

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[1]See Bibliogrpahy No. 11-64, p. 138.

Accelerated testing is also useful for testing materials or products for a number of different stresses that they are supposed to encounter in normal life and thus predict the failure mode of the material or product due to each one of these stresses and then use the results obtained to incorporate design and manufacturing improvements to increase the life of the material or product.

An important consideration in the accelerated testing of materials or products is the choice of the failure criterion. In the view of the author the failure criterion should be chosen so that it is meaningful in terms of the use of the product and is simple enough to detect without using complex experimental set up. This is because of the very high acceleration. Also, if possible, the failure time criterion should be selected so that it occurs just before the catastrophic failure so that the service of the equipment or product does not have to be interrupted for a prolonged time and at the same time making use of the useful life of the material or product. Also, as far as practical, the parameter selected to determine failure should be verified by using another parameter to determine the degradation and before making a decision on the failure criterion.

1. Testing Methods:

Although most people associate accelerated testing with testing at higher than ordinary stresses and using the results obtained to extrapolate the life at normal stresses, the term accelerated testing, in general, includes testing at nominal stresses but early termination

of the testing. This second type of accelerated testing has not received significant response by researchers involved in accelerated testing of materials or products.

There are three different techniques[1] used in accelerated testing of materials or products involving higher than normal stresses. These are briefly described below:

a. Constant Stress

In constant stress testing, the material or product is tested at a constant elevated stress until failure. A number of different elevated stress values are used and life test data obtained for each one of these elevated stress values. Constant stress testing is the most common method to obtain accelerated life test data.

b. Step Stress Testing

Another method to obtain data for accelerated testing is the technique of step-stressing. In this method, the stress on the material or product is not kept constant. The units are stressed for a specified time at a particular value of stress. If the unit does not fail, the stress is increased in regular steps until the material or product fails.

c. Progressive Stress Testing

In the progressive stress testing, the stress on a material or product is continuously increased, usually at a linear rate until the material or product fails. Different rates of increase of stress are

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[1]See Bibliography No. 13-67, p. 141.

used to obtain a large amount of life test data and the data then analyzed to predict normal life. This test method is used only in special circumstances such as in studies of metal fatigue to determine the endurance limit of a metal.

A detailed description of the accelerated life testing methods is given by W. Yurkowsky, et. al.[1]

2. Use of a Suitable Model to Extrapolate the Normal Life from Accelerated Life Test Data

The selection of a suitable model to obtain the normal life of a material or product depends upon the distribution of the failure data obtained and also on the mode of failure of the material or product. From the knowledge of the physical and chemical characteristics of the aging of the material or product, a suitable model is chosen to fit the data obtained. If the data fits the model selected, the various parameters involved in the model are determined using graphical and analytical techniques. Once the different parameters which satisfy the aging data of a particular material or product have been determined, for the values of the elevated stresses used in experimental tests, the life of the material can be easily predicted at nominal stress values.

Arrhenius Model

The degradation of a synthetic insulator material due to environ-

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[1]See Bibliography No. 13-67, p. 141.

mental stresses such as U.V. radiation, and air pollutants such as SO_2, NO_2, H_2S, and CL_2, etc., is a chemical process. The most common model which is based on the relationship between chemical reaction rates and temperature is the Arrhenius model. It is commonly used for materials or products that degrade and fail as a result of a chemical degradation.

In the Arrhenius model given by Arrhenius in 1889, in a process involving chemical degradation, the reaction rate is given by:

$$r = A\ e^{-E/KT} \tag{3.1}$$

where E = Energy of activation

A = Frequency factor

K = Boltzman's constant

T = Temperature in degrees kelvin

From the Arrhenius equation given by (3.1), the life of the material can be given by the equation:

$$\text{life } (l) \ \alpha\ 1/r = A'\ e^{E/KT} \tag{3.2}$$

and

$$\text{Ln } (l) = \text{Ln } A' + E/KT \tag{3.3}$$

The Arrhenius model is specially suitable for accelerated life test data where temperature is the only accelerating variable. For accelerated testing involving degradation by chemical process but having temperature as well as some other accelerating variable, the

modified Arrhenius equation has been used.[1] In the modified Arrhenius equation:

Specific reaction rate $r = A' e - (E-BI)/KT$ (3.4)

where A' = Frequency factor

E = Activation energy

I = Intensity of the stress

B = Constant for the material

K = Boltzman's constant

T = Temperature in degrees kelvin

Using the modified Arrhenius equation, the life of a synthetic material due to a combination of two stresses can be given by the equation

$$\text{Life } (1) = \frac{1}{A'} e^{(E-BI)/KT} \quad (3.5)$$

and

$$\text{Ln } (1) = - \text{Ln } A' + (E-BI)/KT \quad (3.6)$$

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[1]See Bibliography No. 1-76, p. 152.

Chapter IV

DEGRADATION MECHANISMS OF POLYMERIC INSULATING MATERIALS FOR OUTDOOR HV TRANSMISSION

4.1 Introduction

New extra high voltage transmission (E.H.V. and U.H.V.) systems are presently being developed to handle large quantities of electrical energy. These systems require insulators that will not degrade much as a result of the severe electrical, mechanical and environmental stresses under which these materials are supposed to function.

The predominant stresses that degrade a typical polymeric material insulator for HV applications are:

1. Electric field. This field is more on the surface than in the bulk of the material and depends on the dielectric constant of the material.
2. Ultraviolet radiation.
3. Temperature.
4. Pollutant gases, such as ozone, oxides of sulphur, oxides of nitrogen, hydrogen sulphide, chlorine, etc.
5. Humidity.
6. Pollution on the surface.

The above stresses degrade the insulator characteristics of a synthetic insulator by mechanisms like:

a. Tracking.
b. Surface erosion.
c. Treeing.

d. Increase in hydrophilicity.

e. Increase in leakage current through wet and contaminated surfaces.

f. Change in chemical composition and structure of the material of the insulator.

g. Change in dielectric constant and dielectric strength of the material.

A brief review of some of the degradation mechanisms is given below:

4.2 Degradation due to Electric Field

The failure mechanisms such as tracking, surface erosion, and treeing on synthetic insulators are caused by electric field.

4.2a Tracking:[1]

Electric stress distributed along the surface of certain synthetic materials results in the breakdown of the material from local heating and ionic bombardment associated with the flow of leakage current. Failure of surface begins by a tiny arc, i.e., scintillation at the point where energy density is greatest. A short line remains at that point as a track and is lengthened by successive failures. It grows to a longer line and sometimes bridges the gap between electrodes. Such insulation degradation may leave conducting corbonaceous residue,

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[1]See Bibliography No. 14-65, pp. 139-140.

which promotes the continuation of the process.

Studies of degradation mechanisms of organic insulators have shown that tracking is a predominant cause of failure of synthetic insulators specially on contaminated surfaces in the presence of humidity. The contaminated surface with ionic pollution and humidity develops a conducting path on the surface of the insulator. This results in increased leakage current, substantially larger than that experienced with a clean insulator. Due to flow of this leakage current, temperature of the surface conducting track will rise and will tend to dry out the selective portion of the surface of the insulator forming a dry spot or dry band. Once the local stress exceeds the breakdown of the air-solid interface, the dry spot will be shorted by small electrical discharges -- bright spots called scintillations. These scintillations will tend to raise the temperature of the surface track further developing hot spots on the surface. This continuously increasing heat energy will reach a level when there is sufficient energy to break the bonds in the organic compound. The bonds with least strength breaking first and so on. The values of bond strengths in organic insulators is given in Table 6.1.

Depending upon the relative strength of bonds in the particular organic material, some materials leave these free carbon molecules on the surface resulting in tracking failure. However, in some materials like polytetrafluoroethylene (P.T.F.E.) free carbon formed is removed at a rate faster than the rate of formation thus, preventing tracking failure.

In general, if the rate of formation of carbon is faster than the rate of removal, tracking occurs and if the rate of removal of carbon is faster than its formation, the tracking does not occur. The process of removal of carbon is a chemical reaction involving carbon, oxygen and water at a temperature above 1300°K, as shown below.

$$C + O_2 = CO_2$$

$$C + \tfrac{1}{2} O_2 = CO$$

$$C + H_2O = CO + H_2$$

$$C + 2H_2O = CO_2 + 2H_2$$

$$C + CO_2 = 2CO$$

The above reactions suggest that to remove carbon or to prevent tracking failure, compounds rich in oxygen should be used as fillers in resins. Hydrates like $Al_2O_3\ 3H_2O$ are excellent in removing carbon by the formation of CO and H_2. The hydrates also physically scrub the reaction area by the formation of steam due to decomposition at temperatures above 200°C. The fillers being inert inhibit track formation. The formation of steam from $Al_2O_3\ 3H_2O$ could create the cooling effect by absorbing heat energy, thus preventing or slowing down track formation, silica fillers act similarly.

Review of Test Methods for Tracking Failure

In the early research on synthetic insulators, tracking was considered to be a very serious failure mode because of the complexity

to reproduce its features in the laboratory for testing purposes.

Saito et al,[1] studied the tracking phenomena by employing tiny arcs started by a capacitor to simulate the features of tracking phenomena. Ikejiri[2] and Billings et al[3] have contributed a lot in clearing concepts about tracking failure and its prevention by the use of fillers. As a result of this research, insulators of moulded epoxy resin round a glass fiber core have been produced. Two types of resins have been used in this development: the earlier type using bisphenol -- a resin made track-resistant by the use of hydrated alumina, and the latter type using track resistant cycloaliphatic resin. Tonnesen[4] has developed a new approach for the study of surface tracking. He focussed infrared energy on the surface of an insulating material and measured the change in resistance with time. Voltage was also varied to measure resistance at which thermal instability develops as a function of voltage. Formaldehyde (F) resins melamine F, melamine/phenol F, urea F, and epoxy resins based on diglycidylethes of bisphenol A with metaphenylele diamene all formed semiconductive residues which resulted in thermal instability. A

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[1]See Bibliography No. 14-65, pp. 139-140.

[2]See Bibliography No. 16-68, p. 143.

[3]See Bibliography No. 2-67, p. 140.

[4]See Bibliography No. 8-73, p. 151.

cycloaliphatic epoxy cured with hexahydrophathalic acid, a polyester, a polyethylene, polyvinyl chloride did not form semiconductive residues but eroded. It is claimed that discharges are apparently necessary to cause failure of these materials and are required to form semiconductive residues. However, the resistance of some of these materials degraded to values of resistivity between 5×10^6 and 10^7 ohm-cm and thermal stability could have occurred at higher voltages than those reported.

Niemi et al[1] have used a variety of test methods to study the dry band arcing phenomena of surface failure. Scintillation currents measured using a modification of the inclined plane test, liquid contaminant arc test (ASTM D2302), showed the suppression of current spikes caused by complete surface wetting as produced by a silica filler in an epoxy together with the generation of current spikes caused by improved wetting of low surface energy materials such as fluorocarbons, polyolefins and silicones. They also used salt fog test to determine difference between low and high surface energy materials. Low energy materials were stable longer than high energy materials.

4.2b Surface Erosion

Erosion is a surface failure mechanism similar to tracking but the failure here results in a physical removal of the insulating

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[1]See Bibliography No. 3-73, p. 150.

material instead of a progressive carbonish paths across the surface as in tracking phenomena. Polytetrafluoroethylene (P.T.F.E.) is an example of an insulating material which develops strong surface erosion on application of electric stress due to arc discharge or scintillations on the surface. The degradation of P.T.F.E. due to this kind of failure has prevented its widespread use in high voltage outdoor application, a field where in most other respects, they are an attractive alternative to porcelain.

Wilkins et al[1] have studied the surface erosion mechanism. They have shown that this breakdown mechanism can be explained in terms of a thermal phenomena. They measured the temperature of the surface of some polymeric insulating materials immediately under discharges between electrodes and showed that a breakdown temperature can be defined which is constant for each material. They also found that this breakdown temperature is related to the temperature of thermal decomposition of the insulating material. The thermal decomposition temperature was defined as the temperature at which there was a loss of 10% in the weight of the material.

The breakdown temperature and the 90% thermal decomposition for some organic materials is shown in the table below.

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[1] See Bibliography No. 7-69, p. 144.

Material	Breakdown Temperature (T °C)	90% Thermal Decomposition Temperature
Polyvinylchloride	186	248
Polymethylmethacrylate	223	285
Epoxy Resin - CY175/HT907	301	342
Polypropylene	308	366
Epoxy Resin - MY 750/HY906	333	360
Glass Filled P.T.F.E.	446	510

** Temperature raised at the rate of 6 deg. C/min

It has been shown[1] that for each material there exists a threshold current depending upon the geometry of the material below which no breakdown can be produced. This threshold current can be predicted from a knowledge of the breakdown temperature and the heat conduction field in the material.

4.2c Treeing

Treeing breakdown in synthetic insulators occurs due to minute discharges in air voids near the surface or in the interior of the material due to strong electric field. When a so called "branch" which is localized discharge path reaches the opposite electrode, insulation breaks down.

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[1]See Bibliography No. 7-69, p. 144.

The treeing dreakdown differs from that of breakdown due to insulator corona in the fact that the breakdown due to insulator corona is considered to proceed via atmospheric oxygen whereas treeing does not require the presence of oxygen. Gas evoluation in treeing is caused by the actual decomposition in the large electric field at the tip of the branches as well as by heat and radiation accompanying the discharge. A combination of these decomposition processes is responsible for the gas evolution. The treeing path is created by gaseous decomposition produced by the breaking of polymer chains. The energy required for tree growth is supplied by electrical discharge. The tree branches are extremely slender and long. Although the rate of branch elongation is long, the rate of branch diameter is not so large as discussed by Matsuba et al.[1]

Treeing generation and its growth

The reasons for the generation and growth of trees have long been a subject for conjecture. Kitchen and Pratt[2] observed that treeing occurs from surface contamination and impurities in the insulating materials and that treeing is the final step of most insulator breakdowns. They also found that the application of AC and DC voltages as well as pulsed voltages is effective to form the tree.

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[1]See Bibliography No. 17-68, p. 143.

[2]See Bibliography No. 3-58, p. 135.

Dittmer[1] applied pulsed voltages to materials like acrylic resin, epoxy, polyethylene, polystyrene, etc., and made a study of the effect of applied voltage waveform and polarity on the tree growth rate. The study revealed that the growth rate of treeing were dependent on the material and on polarity. They have thus concluded that the phenomena is not due to mechanical deterioration caused by electric field.

Olyphant et al[2] did a comparative study of tree resistance of different materials. They embedded a needle into epoxy resin and measured the resistance of the tree branch and observed that a tree is a non-conductive tube and the electrical conduction between the tree and the needle occurs due to the discharge in the tube. It has also been shown that internal pressure in the tube increases as a result of gas generation. McMohan and Perkins in their study[3] concluded that treeing occurs due to discharge in the air gap between the needle tip and the insulating material. They used polarized light photographs to confirm the formation of voids at the needle tip. Mitsui et al[4] studied the effect of gas generated on the shape and growth of treeing. Yasui has studied the relation between the

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[1]See Bibliography No. 8-63, p. 138.

[2]See Bibliography No. 6-63, p. 137.

[3]See Bibliography No. 7-63, pp. 137-138.

[4]See Bibliography No. 14-67, p. 141.

amount of charge and the length of trees generated at the needle shaped void. He concluded that treeing is a result of the localized discharge at the tip of the void.

Matsuba et al[1] have attempted to clarify the phenomena of generation and growth of treeing. Their observations were as follows:

a. The initiation of treeing results from an electrical discharge at a sharp edge near the needle tip.

b. Tree growth is affected by the applied voltage, but also by the rate of escape of the gas involved during tree growth. When gas cannot escape readily, tree growth is slowed down. This is due to the fact that as the internal pressure in the tree branch increases, the gas discharge within the branch is weakened and sometimes stopped altogether.

c. The gases generated as treeing progresses are decomposition products of the plastic material and consist mainly of hydrogen and water but other substances such as unsaturated hydrocarbons are also present. Treeing, therefore, differs from oxidative decomposition of the surface, i.e., corona deterioration.

d. The principal mechanism of treeing is probably the insulation breakdown of the material by the strong electric field at the tip and not due to the decomposition of the material by collision with electrons and ions produced by the electrical discharge within the tree branch.

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[1]See Bibliography No. 17-68, p. 143.

Lately, Noto and Yoshimura in an impressive study[1] correlated the mechanical strain produced by electric field stress and tree initiation as a function of time and temperature. They plotted the percentage of specimens with trees as a function of voltage, time and temperature (-50 to 80°C). Time to tree initiation is very sensitive to temperature. Once a tree is initiated, it jumps to a critical length. This length is predicted from the mechanical properties such as viscosity coefficient and Young's modulus. At low temperatures below -10°C (Tg for PE), the measured tree initiation voltages are higher than predicted by this analysis. However, it is noted that the electric field stress correlates very well with the tensile strength.

4.3 Degradation due to Increase in Hydrophilicity

The hydrophobic nature of a synthetic insulating material is the most efficient property a high voltage insulator can possess.[2] Many synthetic insulating materials fail due to tracking or generation of a progressive carbonaceous deposit on the insulator surface which provides a conducting path and leads to failure of insulator. For this reason, considerable work has been done to develop higher track resistance plastics for high voltage insulators. Since tracking phenomena on synthetic insulators is fairly well understood now and it is known that surface arcing in tracking is preceded by the gene-

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[1]See Bibliography No. 13-73, p. 151.

[2]See Bibliography No. 15-72, p. 150.

ration of water film formation and leakage current, the most suitable materials for high voltage applications will be the ones which are hydrophobic and the hydrophobicity of which does not change much as a function of environmental stresses.

4.3a Hydrophilicity and environmental exposure

In general, the low surface energy materials like polytetrafluoroethylene, epoxy resins and silicone elastomers are hydrophobic in nature. Investigations have shown that these low surface energy materials can maintain high surface resistance and control surface leakage currents.[1] However, on long time exposure to environmental stresses like UV, temperature, and air pollutant gases such as NO_2, SO_2, H_2S, CL_2, etc., these materials lose their hydrophobic nature and become hydrophilic.[2,3] This results in low electrical surface resistance and increased surface leakage currents which will result in the ultimate failure of the insulator function of the material.

4.3b Hydrophilicity of organic materials with inorganic fillers

The inorganic insulating materials like porcelain glass, silica, and hydrated alumina have a property that is common with all these materials. All these materials have high surface energy which results in easy spread of water over their surface as a continuous film rather than forming separate isolated droplets. It has been observed

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[1]See Bibliography No. 28-71, p. 148.
[2]See Bibliography No. 1-76, p. 152.
[3]See Bibliography No. 2-76, p. 152.

that surface conductance of these materials increases drastically with increased moisture exposure or humidity. This results in increased surface leakage currents. That is why conventional porcelain insulators are inevitably coated with low surface energy silicone grease which forms a hydrophobic surface on these insulators and results in high surface resistance and low leakage currents.

To avoid failures due to tracking in synthetic insulator materials, inorganic compounds rich in oxygen are used as fillers as discussed above. However, it is very important to realize the trade offs for introducing high levels of inorganic fillers into plastic dielectrics. These fillers may, although prevent tracking failure, change low surface energy materials into a high surface energy material which results in an increase in hydrophilicity of the surface and increased leakage currents and surface discharges under high voltages. These trade offs for introducing inorganic fillers in plastic materials are discussed by D. J. Parr[1], M. J. Billings et al[2], and A. W. Stannet et al[3]. Also in another study[4], it has been rightly suggested that in the selection of suitable synthetic materials for high voltage insulation, the property of low surface energy and hydrophilicity of the surface of the material should be

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[1]See Bibliography No. 7-65, p. 139.

[2]See Bibliography No. 18-68, p. 143.

[3]See Bibliography No. 9-69, p. 144.

[4]See Bibliography No. 15-72, p. 150.

considered as the first line of defense, and the property of arc-track resistance which is required only when the first property is lost as the second line of defense.

4.3c Hydrophilicity and Corona Exposure

It is quite well known that corona and surface discharges degrade the surface properties of a synthetic insulating material. The degradation results from accumulation of surface charges and chemical modification of the surface structure to form new chemical groups. The degree and rate of change of hydrophilicity of the surface varies considerably among different types of materials. In a study by R. G. Niemi[1] moulded specimens of silicone elastomers having organic substituent groups of hydrogen, methyl, and phenyl were exposed to corona. The results indicated that in all three materials an increase in hydrophilicity was noticed. More importantly, the study indicated that the differences in hydrophilicity between these groups after corona exposure was much greater than the differences in hydrophilicity before exposure. Specifically, the phenyl containing elastomer surface showed a wider area of degradation and more intensive degradation than the other elastomers.

4.4 Degradation due to Gaseous Pollution

Reactive gases such as ozone, oxides of sulphur, oxides of

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[1]See Bibliography No. 28-71, p. 148.

nitrogen, chlorine, etc., are known to degrade polymeric material surfaces directly and/or by accelerating the degradation process in the presence of other environmental stresses like UV, moisture, temperature, electric field, etc. Wider applications of synthetic materials for outdoor high voltage insulation pruposes make this degradation very important. A brief explanation of degradation of polymers due to some important air pollutant gases is given below.

OZONE[1]. Ozone being very active chemically attacks any unsaturation present in a polymer, causing chain scission and carbonyl formation. The mechanism(s) of degradation are complex and uncertain. Razumovski et al[2] in their findings indicate that ozone reacts with polymers mainly on the surface, since the reaction rate and the concentration of intermediate peroxy-radicals (RO_2) are proportional to the surface area and not the weight of the polymer.

Unsaturation may sometimes be present in polymer molecules by design, e.g., many elastomers contain large amounts of unsaturation to enable them to be vulcanized. Unsaturation may also be formed in service as a result of UV degradation. The reaction of ozone with an unsaturated site is

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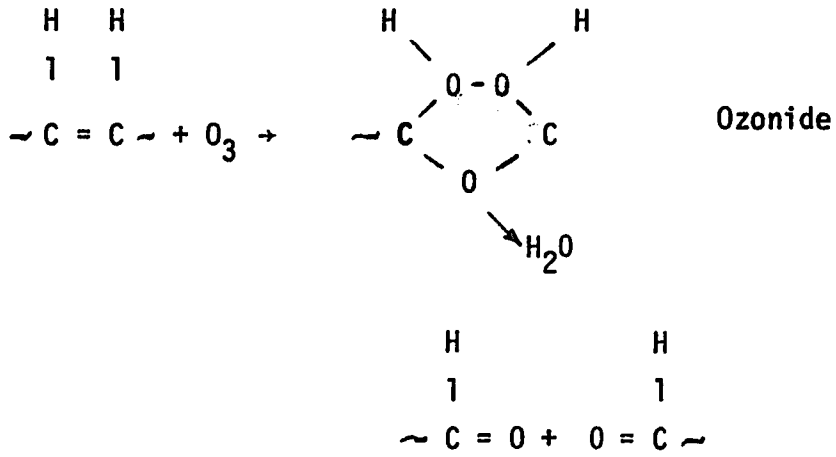
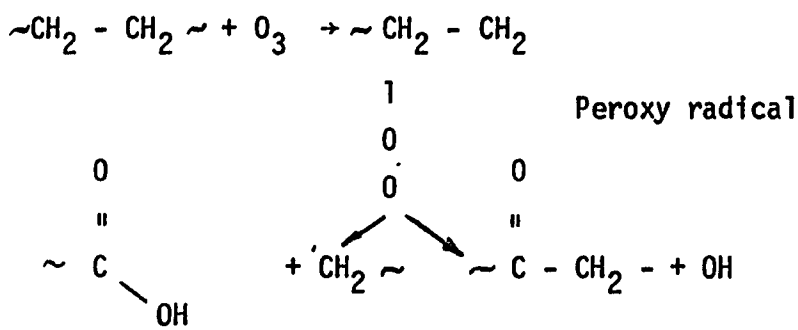
[1]See Bibliography No. 12-72, p. 150.

[2]See Bibliography No. 29-71, p. 149.



Degraded Products

The reaction of ozone with a saturated polymer has been investigated by Razumovski et al[1]. According to them, polymers with saturated hydrocarbon chains such as polyethylene, polypropylene, polyisobutylene, etc., react with ozone by a free radical mechanism. The initial stages of the reaction of ozone with polyethylene proceed as follows



Degraded Products

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[1]See Bibliography No. 29-71, p. 149.

The degradation of polymer chain occurs as a result of decomposition of peroxy radicals.

In another investigation by Priest[1], it has been suggested that the reaction of ozone with polyethylene can proceed very rapdily at 60 ^{o}C with gross chain scission and the formation of large amounts of carbonyl groups.

Oxides of Sulphur. Sulphur dioxide is one of the important air pollutants. It has been observed[2] that sulphur dioxide in the presence of UV light reacts with a hydrocarbon material to yield sulphinic acid.

$$SO_2 \xrightarrow{h\nu} SO_2^*$$

$$SO_2^* + RH \longrightarrow RSO_2H$$

This reaction has been further studied by Jellinek et al[3] who showed that polyethylene, a hydrocarbon polymer, is almost completely cross-linked in the presence of sulphur dioxide and UV light, whereas there is no reaction in the presence of SO_2 alone. Polypropylene is affected in a similar way.

It must be emphasized that polymeric sulphinic acids may be very deleterious in the present context since wetting will occur more readily and thus electrical properties will be impaired.

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[1]See Bibliography No. 30-71, p. 149.

[2]See Bibliography No. 2-50, p. 134.

[3]See Bibliography No. 11-69, p. 144.

Other reactions occurring with sulphur dioxide in the presence of UV light are:

$$SO_2^* + 2O_2 \xrightarrow{h\nu} SO_3 + O_3$$

$$SO_3 \xrightarrow{H_2O} H_2SO_4$$

$$SO_2 + 2O_2 \xrightarrow{h\nu} SO_3 + O_3$$

It is likely that sulphuric acid would damage highly filled polymer systems by reacting with the inorganic filler as well as causing high leakage currents in humid conditions. The elastomers (unsaturated polymers) are more susceptible to SO_2 than saturated polymers.[1]

<u>Oxides of Nitrogen</u>. Nitrogen dioxide reacts with hydrocarbons to produce either a nitro or nitride side group along the polymer backbone, or to scission and cross-linkings.

$$RH + NO_2 \rightarrow R + HNO_2$$

$$R + NO_2 \rightarrow RNO_2, \text{ etc.}$$

According to Jellinek et al[2] exposure to nitrogen dioxide results

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[1,2]See Bibliography No. 11-69, p. 144.

in incorporation of nitro groups as shown by absorption in the infrared spectra at 6.4 μ. Some slight viscosity increase was also apparent. In the case of polyethylene, cross-linking occurred in the presence of UV light. Also, as in the case of degradation due to SO_2, the elastomers (unsaturated polymers) are more susceptible to degradation due to NO_2 than the saturated polymers.

It is apparent from the above discussion that air pollutants and UV radiation form an important degradation exposure for many synthetic materials.

Chapter V

CHARACTERIZATION OF SYNTHETIC INSULATOR SURFACES BY ELECTRICAL NOISE AND HYDROPHILICITY

5.1 Introduction

Electrical noise measurements have been used as a research tool in reliability and failure mechanisms studies in the past. Noise measurements have been employed to detect defects in semiconductor components and resistors.[1] Noise screening of such components have helped reduce in service failure of these components by an order of magnitude.

Depending on the structure and characteristics of a component, the noise generated can be predicted by theoretical and empirical formulas. A defective component will, however generate noise considerably more than that generated on a defect free component. Amount of noise generated, therefore, can be used as a diagnostic tool for studies on reliability and failure mechanisms. Such studies have been successfully performed in connection with life tests on resistors. The drift in the value of resistors correlates very well with the noise produced by them. The resistors with higher noise have larger drift in resistance. Excellent improvements in the failure rates of resistors were achieved by screening them using noise as a failure parameter.[2]

[1,2]See Bibliography No. 6-64, p. 138.

Measurements of electrical noise generated on application of electric stress have been used to separate surface and volume failure mechanisms in synthetic insulators[1] and to study the extent of surface degradation of these insulating materials.[2]

5.2 Electrical Noise Generated on the Surface of an Insulator

The noise generated on application of electric stress on an insulator results from the unevenness on the surface of an insulator. These defects are inherent part of the surface.

The voltage gradient or stress on a dielectric or insulator transmitting dielectric flux is directly proportional to the flux and inversely proportional to the ease with which the insulating material transmits flux. The electric stress in a solid and gas dielectric can, therefore, be written as

$$E_{solid} = \phi/K_s \tag{5.1}$$

$$E_{gas} = \phi/K_g \tag{5.2}$$

From (5.1) and (5.2)

$$\phi = E_s K_s = E_g K_g \qquad \therefore E_g = E_s\ (K_s/K_g) \tag{5.3}$$

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[1]See Bibliography No. 11-73, p. 151.

[2]See Bibliography No. 2-76, p. 152.

where

E_{solid} = Electric field stress in solid dielectric

E_{gas} = Electric field stress in gas dielectric

ϕ = Flux

K_s = Permittivity of solid

K_g = Permittivity of gas

When two dielectric materials such as a gas and a solid are in series transmitting the same dielectric flux, the gas dielectric having lower permittivity will be stressed more than the solid dielectric in series with it as given by equation (5.3) above. This higher stress will produce excited and ionized molecules which will generate radio noise. Electrical noise will also be produced by the partial discharges occurring at the sharp edges.

The amount of noise generated on the surface of the insulator depends, among other things, upon:

a. The applied electrical stress

b. Surface condition (hydrophilic or hydrophobic)

c. Surface area

d. Ambient atmospheric conditions, like temperature, humidity, pollution, etc.

e. Permittivity of the material of the insulator.

Since the insulator corona also depends on all of these factors, it can be said that the electrical noise is directly related to the

intensity and quantity of corona.

5.3 Noise as a Diagnostic Tool to Determine the Surface Degradation of an Insulator

For the same amount of electric stress, the noise generated on a particular insulating material gives an indication of the surface condition of the insulating material. The change in the surface characteristics of an insulating material due to environmental aging can be observed by measuring the noise generated on the surface before and after aging. Noise measurements can, therefore, be used as a parameter to determine the extent of surface degradation of an insulating material due to various environmental stresses.

5.4 Characterization of Polymeric Insulating Material Surfaces by Measurement of Hydrophilicity

Most experimental techniques and tests presently being used to screen and evaluate new synthetic insulators for outdoor high voltage use measure the material's tendency to form carbonized tracks when exposed to severe arcing. These tests are perhaps developed from the experience gained from the usual porcelain insulators. Porcelain insulators develop uncontrolled surges of leakage current and arcing when moisture and contaminations are present on the surface. Researchers involved in developing and testing synthetic insulators normally assume that the same surges of leakage current will be formed on synthetic materials also and, thus, attempt to recreate arcing

defined for porcelain insulators by water filming which is produced by covering the insulator with excessive amounts of artificial wetting agents and surfactants. The design of these tests destroys a very valuable property that some of the synthetic materials possess. This property is the ability to prevent water filming from occurring under actual outdoor environmental exposure. Porcelain cannot maintain a high non-wetted surface and so these tests are perfectly alright for testing porcelain insulators since these tests simulate a very common failure mechanism of porcelain insulators.

The conventional test methods which measure the material's tendency to form carbonized tracks when exposed to severe arcing may sometimes give grossly wrong results when used to test synthetic insulating materials. For example, years of outdoor use in actual service have proved that silicone compounds can perform the electrical functions of an insulator under the most severe of polluted conditions. Yet, these fail rapidly when evaluated by the conventional accelerated laboratory screening tests discussed above. The fact is that these compounds were designed to give maximum arc suppression under wet conditions and not necessarily to have maximum arc-track resistance. The order of testing these synthetic insulating materials should, therefore, be reversed. These materials should be screened on their ability to maintain a hydrophobic surface, high surface resistance, and arc suppression under normal outdoor conditions. Extremely good, high power density arc-track resistance is important only if the material severely loses its hydrophobicity and ability to control sur-

face leakage currents. For this reason, the author feels that investigations characterizing the hydrophilicity of the surface before and after aging due to environmental stresses are more relevant in studies on synthetic insulating materials. The longer a material can maintain its hydrophobic nature, the longer it will preserve its surface resistivity and thus inhibit the flow of excessive leakage current and severe arcing and so need not have maximum arc-track resistance. Of course, when optimum design achievements are made, the synthetic insulator selected will have both hydrophobicity as well as arc-track resistance properties.

5.5 Measurement of Hydrophilicity of a Surface by Measuring the Contact Angle

The ability of a surface to absorb water filming on the surface or to resist water filming can be measured in terms of the water contact angle on the surface.

Contact Angle. Liquids rest on solid surfaces at a definite angle, θ , (measured in the liquid), depending on the surface property and the liquid as shown in Fig. 5.1 below.

Let

γ_{SL} = Surface tension of the solid-liquid film

γ_{SV} = Surface tension of the solid-vapor film

γ_{LV} = Surface tension of the liquid-vapor film

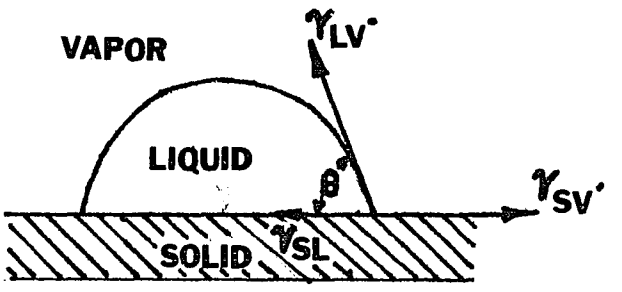

Fig. 5.1 Schematic diagram of the contact angle (θ) formed by a drop resting on a solid surface

By treating the surface tensions as mathematical tensions pulling parallel to the surfaces, Thomas Young derived for the equilibrium of these surface tensions acting at any point of such a surface, the following relation

$$\gamma_{SV} - \gamma_{SL} = \gamma_{LV} \cos \theta \tag{5.4}$$

Also, Dupre's equation for the work of adhesion of a solid to a liquid

$$W_{SL} = \gamma_{SV} + \gamma_{LV} - \gamma_{SL} \tag{5.5}$$

The work of adhesion W_{SL} is the work necessary to separate the liquid from the solid by separating them perpendicularly from each other, against the adhesive force between them.

Combining (5.4) and (5.5) above, the work of adhesion

$$W_{SL} = \gamma_{LV} (1 + \cos \theta) \tag{5.6}$$

Equation (5.6) shows that the contact angle is determined by the relative strengths of the adhesion of the liquid to the solid, and to itself, for the latter is $2\gamma_{LV}$. If the contact angle is zero, $W_{SL} = 2\gamma_{LV}$, so that the liquid attracts the solid as much as it attracts itself. A contact angle of 90° indicates that the attraction of the liquid for the solid is half that for itself, and a contact angle of 180° would indicate no adhesion between the liquid and the solid. As there is always some adhesion, angles of 180° are unrealizable.

Young's equation given by (5.4) above is simple in form only, because both conceptual and experimental difficulties exist concerning it which have been the source of many arguments. In the definition of γ_{SL} and γ_{SV}, one is faced with the dilemma that there is no reliable way to measure either of these quantities. Also, there is the difficulty that any tensile stress existing in the surface of a real solid would seldom be a system in static equilibrium, for solids are rare whose surfaces are free of internal stresses acting in or just below the outermost layer comprising the surface layer.[1]

A modern approach for the treatment of equation (5.4) is as a result of the thermodynamic equilibrium of a surface system. As Sumner[2] and many others since then have shown, the Young equation

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[1]See Bibliography No. 14-72, p. 150.

[2]See Bibliography No. 1-37, p. 133.

can be derived for the ideal three-phase interface of Fig. 5.1, provided that the system is in thermodynamic equilibrium; also, the quantities γ_{SL}, γ_{SV}, and γ_{LV}, must be defined as follows:

$$\gamma_{SL} = \left(\frac{\gamma F}{\partial A_{SL}}\right) T, \mu i \tag{5.7}$$

$$\gamma_{SV} = \left(\frac{\partial F}{\partial A_{SVo}}\right) T, \mu i \tag{5.8}$$

$$\gamma_{LV} \equiv \left(\frac{\partial F}{\partial A_{LVo}}\right) T, \mu i \tag{5.9}$$

In equations (5.7), (5.8), and (5.9) above, F is the work function of the system, A_{SVo} is the area of the solid/saturated vapor interface, A_{SL} is the area of the solid/liquid interface, and A_{LVo} is the area of the liquid/saturated vapor interface. T is the absolute temperature and μi is the chemical potential of the i'th component in the indicated phase. It is assumed throughout these relationships that contact angle θ is independent of the volume of the drop and that it depends only on the temperature and the material of three phases in contact.

5.5a Measurement of Contact Angle

Contact angle measurements have long been an important research tool for researchers involved in surface energetics of wetting, spreading and adhesion. However, the old techniques of measuring the contact angles have been replaced by more sophisticated methods.

Adam and Jessop made the water contact angle measurements on a solid in the form of a plate by what is called the "plate" method. In this method, the solid is held in an adjustable holder capable of being tilted to any angle; provisions are made for raising or lowering it slowly with respect to the water surface, so as to measure the angle under advancing and receding conditions. The plate is set at various angles until a position is found at which the water surface remains undistorted right up to the line of contact with the solid. The angle θ between the plate and the liquid surface gives the contact angle.

A more elaborate method, called the cylinder method depending essentially on the principle of Adam and Jessop was used by Ablett to make contact angle measurements. An accurately turned cylinder of the solid, mounted with its axis horizontal and capable of being rotated about this axis, is partially immersed in the liquid. The level of the liquid is adjusted until the liquid surface remains horizontal right up to the line of contact with the solid, under prescribed conditions of rotation of the cylinder, i.e., with prescribed speeds of advancing and receding motion. The contact angle is calculated from the relative heights of the axis of the cylinder and the level of the water.

Presently, contact angle measurements are being made with an instrument called contact angle goniometer system. This precisely constructed system features ease of operation and accuracy for measuring contact angles as shown in Fig. (5.2). The basic system consists

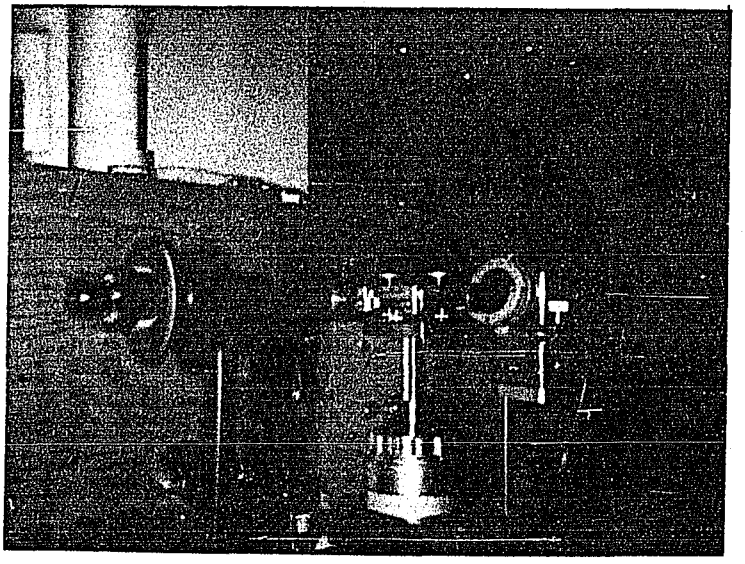

FIG 5.2 CONTACT ANGLE GONIOMETER

of an optical bench on which are mounted the microscope assembly, a specimen stage and a variable intensity illuminator. Under study, the specimen appears as a silhouette against a soft, green background. The liquid/solid interface is alligned with the horizontal crosshair, and the contact angle is determined by rotating the read-out cross-hair to tangency with the drop profile. Contact angle value is read directly on the graduated goniometer scale.

5.5b Factors Modifying Contact Angles[1]

Contact angle measurements have been a topic of controversy over the past century's literature of physics, chemistry, and engineering. This could probably be attributed to the lack of knowledge in the area of factors modifying contact angles. Now that the contact angle measurements and the factors modifying it are better understood, contact angle is being measured routinely in many laboratories for research, product development and quality control.

Important factors modifying contact angles are:

a. Greasy layers. Layers of grease as small as one molecule thick can increase the contact angle very considerably. It may not even be necessary for the layers to have their molecules closely packed on the surface. Langmuir showed that a glass plate brought up through a water surface covered by a monomolecular film of some fatty substance had its contact angle very much increased.

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[1] See Bibliography No. 20-68, p. 143.

b. Moisture on or just below the surface. Prolonged soaking of organic materials in water, produces a greater or smaller decrease in the contact angle without, however, abolishing the hysterises. The hysterises of the contact angle is the difference between the advancing and the receding contact angles and is sometimes used to characterize surfaces. If many substances are allowed to crystallize in contact with water, the angles against water are often lower than when they crystallize in air. This has been attributed to an orientation of the water attracting groups outwards, but is more probably due to water molecules becoming entrapped in the surface layers, and increasing the adhesion of the surfaces for water.

c. Roughness of surface. The effect of roughness is to decrease the contact angle if the true angle is less than 90° but to increase the angle if the original angle is greater than 90°. This is because the liquid penetrates into the hollows if the true angle is less than 90°. Part of the supposedly plane surface consists not of solid but of the liquid qhich has a zero contact angle with itself. If the original angle is greater than 90°, no liquid penetrates into the hollows. The apparently plane surface of solid consists, therefore, partly of solid and partly of air, for which the liquid has no adhesion.

Chapter VI

SURFACE DEGRADATION OF POLYMERIC HV INSULATING MATERIALS DUE TO U.V. EXPOSURE

6.1 Introduction

Insulator specimen when subjected to electric stress will generate radio noise. The origin of this noise is attributed to the very minute air bubbles in the bulk of the material and to the unevenness of the surface. These defects are almost invariably left in the manufacturing process. On application of electric stress, these tiny air gaps will be stressed more than the solid since the dielectric constant of the solid is greater than unity. This will produce excited and ionized molecules which will result in the generation of radio noise.

Using the same amount of electric stress, the noise generated from a given insulating material can be used as a parameter to determine the insulator condition. The change in surface properties of insulating materials due to aging effects during outdoor use of these insulators will result in change in noise level generated on the surface of these materials. Thus, noise generated due to electric stress in insulators and the change in noise level due to aging caused by various environmental stresses should be very useful parameters to predict the insulator behavior.

Large number of studies starting as early as 1930[1,2] have been carried out to study radio noise on high voltage porcelain insulators. Since then, many authors[3,4,5] have investigated the radio noise due to insulator corona and the effect of ambient conditions such as humidity on the level of radio noise on these porcelain insulators. Liao et al[6] have described a relationship between corona and radio noise. However, no work has been done to relate surface conditions of insulators (porcelain or synthetic) and electrical noise generated on the surface of insulator specimen due to electrical stress. The absence of such a study prompted the experimental research presented in this chapter. In the study presented here, measurements of surface noise were made to follow changes in surface properties in five different polymeric insulating materials when subjected to ultraviolet radiation. Exposure to ultraviolet radiation is one of the important environmental considerations.

The stability of polymeric insulators for outdoor high voltage application depends on their ability to control leakage currents. Studies carried on the development of leakage current indicate that significant differences in electrical surface stability exist between

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[1]See Bibliography No. 1-30, p. 133.

[2]See Bibliography No. 1-32, p. 133.

[3]See Bibliography No. 13-65, p. 139.

[4]See Bibliography No. 2-64, p. 138.

[5]See Bibliography No. 14-73, p. 151.

[6]See Bibliography No. 2-59, p. 135.

different insulating materials.[1] These differences are attributed to the initial surface energy of these materials and how it is maintained under actual outdoor environmental stresses. For the same amount of electric stress, low surface energy materials develop less leakage current compared to high surface energy materials.

The surface energy of polymeric insulators changes on exposure to environmental stresses. The extent of change in the surface energy of polymeric insulator materials can be determined by measuring the amount of leakage current developed on the materials on application of electric stress and the changes in the leakage current values on exposure to environmental stresses. In the study presented in this chapter, the amount of leakage current developed on five different polymeric insulator materials at different electric stress levels were observed before and after aging due to ultraviolet radiation exposure to follow changes in the surface energy and hence the insulating properties of these materials. The changes in the surface properties of different specimens due to expsoure to ultraviolet radiation was also studied by measuring the water contact angle on the surface of the specimen before and after aging due to ultraviolet radiation. An excellent review of the application of contact angle in characterizing polymeric surfaces is given by Zisman.[2]

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[1]See Bibliography No. 15-72, p. 150.

[2]See Bibliography No. 14-72, p. 150.

6.2 Theory of Degradation of Polymer Surface due to U.V. Exposure

Ultraviolet radiation degrades polymer surfaces since the energy of the individual photons in U.V. light wavelength is usually greater than the lowest bond energy found in the polymer molecule.

The energy of a photon 'e' is related to its associated wavelength λ by the equation

$$e = hc/\lambda \tag{6.1}$$

where

h = Planck's constant
$= 6.63 \times 10^{-34}$ Joules

c = velocity of light
$= 2.98 \times 10^{8}$ m/sec

λ = Wavelength in meters

The excitation energy E per mole is given by

$$E = N\ hc/\lambda \tag{6.2}$$

where

N = Avogadro's number
$= 6.023 \times 10^{23}$

Substituting the values of N, h, and c in equation (6.2), we have

$$E = 1.197 \times 10^{-1}/\lambda \quad \text{Joules/mole}$$

or

$$E = 0.0284/\lambda \quad \text{cal/mole} \tag{6.3}$$

(1 Joule = .237 cal)

Substituting the value of λ- the wavelength, the excitation energy for different values of wavelength can be obtained.

A straight line showing the plot of equation (6.3) for different wavelengths is shown in Fig. 6.1

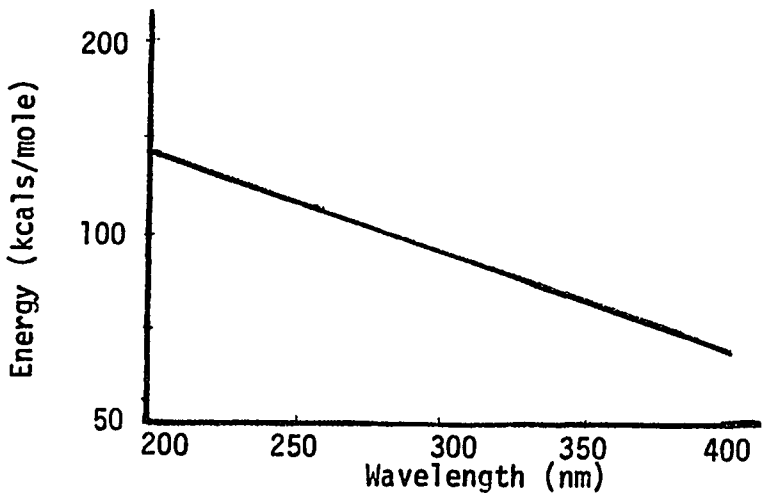

Fig. 6.1 Plot of Excitation Energy Against Wavelength

The values of bond strength of interest in polymeric insulating materials are given in Table 6.1 below[1]:

[1]See Bibliography No. 12-72, p. 150.

Table 6.1

Bond	Bond Strength (kcals/mole)	Bond Strength (Electron Volt)
C-C	82.6	3.60
C=C	147	6.37
C-H	98.7	4.29
C-N	70	3.03
C=N	213	9.24
C-O	84	3.64
C=O	171	7.22
C-F	116	4.55
C-Si	69.3	2.99
Si-O	88	3.82
C-Cl	81	3.51
N-H	93	4.03
O-H	110	4.77

From Fig. 6.1 and Table 6.1 shown above, it can be said that U.V. radiation (220-400 nm wavelengths) has sufficient energy to break several different types of chemical bonds such as C-H, C-C, C-Cl, C-Si, C-N, etc., some of which are present in most polymers.

Approximately 5% of the total sunlight reaching the earth's surface falls within the U.V. wavelength. If a polymer contains a photoactive group or groups, these groups can absorb U.V. light and thus become energy rich or excited in the absorption process. Such excita-

tion causes weakening or breaking of the chemical bonds depending upon the extent of the excitation energy absorbed. The breaking of the chemical bonds called scission, results in a reduction in molecular weight and degradation of the mechanical and electrical properties such as strength, elongation, dielectric constant, dielectric strength, track resistance, chalking, hydrophilicity, etc., of the polymer.

Many synthetic materials in pure state are transparent to U.V. radiation. However, due to oxidation during processing or in service, photo-active groups may be present which can absorb U.V. radiation and hence degradation. Ketones or aldehydes are usually the photo-active species present in most polymer systems. U.V. exposures of ketonic structures usually follows the following reaction[1]

$$CH_2 - CH_2 - CH_2 - \overset{\overset{\displaystyle O}{\|}}{C} - CH_2 \longrightarrow \begin{cases} CH_2 - CH_2 - CH_2 + \overset{\overset{\displaystyle O}{\|}}{C} - CH_2 \\ CH = CH_2 + CH_3 - \overset{\overset{\displaystyle O}{\|}}{C} - CH_2 \end{cases}$$

Polymer — Degraded products showing chain scission

The exact breakdown mechanism(s) depend on the original chemical structure present in the polymer. Aliphatic are the most likely structures in insulation materials for high voltage application, since the base polymer of such a component will have been fabricated

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[1]See Bibliogrpahy No. 12-72, p. 150.

from a non-aromatic system. Polymers containing aromatic groupings have inferior track resistance.

6.3 Experimental Investigation

Measurement of Noise

The specimens used for measuring noise generated on the surface were in the form of rods of 3.8 cm diameter. For a description of the polymer samples used see Table 6.2. An electric field directed along the surface of the specimen was produced by connecting two annular (hose clamp) electrodes 2.54 cm apart fitted on these specimens. To suppress any corona activity produced due to the electrodes themselves, special care was taken to assure that there was no air gap between the electrodes and insulator surface. Such air gaps were eliminated by inserting a thin metal strip equal to the width of the electrode around the insulator rod under the electrode. Any residual air gap between the material and the electrode was minimized by tightening the electrode with the help of adjusting screws. Arrangement of insulator specimen, electrodes and antenna assembly is shown in Fig. 6.4.

The electrodes were connected to an adjustable voltage source (0-15KV) through a regulator and an isolation transformer. The specimen rods and the electrodes were placed in a glass tube about 10 cm. diameter on which was wound a 50 turn antenna. The antenna was connected to a very sensitive Hammurlund (HQ100A) receiver which was used to measure the noise level. The magnitude of the noise genera-

Table 6.2

Specimen No.	Specimen	Before Degradation					After Degradation				
		Contact Angle θ (H_2O) Degrees	Surface Noise Microvolts	Leakage Current (Microamps) Stress KV/cm 2.36	3.04	4.72	Contact Angle θ (H_2O) Degrees	Surface Noise Microvolts	Leakage Current (Microamps) Stress KV/cm 2.36	3.04	4.72
1	Polyethylene	81.0	57	25.7	39.5	65.0	-*	-	-*	-*	-*
2	Polytetra-fluoroethylene	84.2	72.7	11.5	17.5	35.0	82.7	139.8	12.5	19.0	39.5
3	Fiber-Glass Core with Silicone Cover	75.3	35.14	13.5	34.5	57.5	31.7	181.5	20.5	48.5	82.5
4	Fiber-Glass with Polyester Resin Cover	80.0	62.49	12.6	24.6	46.3	72.2	93.6	13.5	27.5	51.3
5	Epoxy Rod (From A B Chance Co.)	78.7	93.6	15.7	31.2	51.5	18.6	204.9	26.5	51.0	95.0

*Noise leakage current and contact angle could not be measured on this surface after U.V. aging, because the material cracked.

NOTE: Each of the readings in the above table is a mean of ten measured values.

ted was obtained from the S-meter readings on the receiver. The S-meter was calibrated such that 50 microvolts signal at the input of the receiver corresponds to 9S units and an increase in each S unit corresponds to 6 db increase. The noise readings were converted into microvolts. The noise readings reported here are at a frequency of 1.6 MHz and at a stress level of 4.72 KV per cm. Refer to Fig. 6.5 for circuit arrangement for measurement of noise.

Noise measurements were repeated for all specimens before and after U.V. degradation. A set of ten readings was taken on each specimen before and after U.V. aging and the mean and $\pm 3\sigma_x$ limits, where σ_x is the standard deviation of the mean, were computed from these readings.

Measurement of Contact Angle

To measure the water contact angle on the surface of various specimens, a thin slice about 1.27 cm wide and 0.25 cm thick was removed from each specimen. The surface of these specimens were then smoothened on a polishing wheel.

Measured quantity of pure water (resistivity better than 15 megaohms) was then placed on these samples and contact angle measured using Ramehart model A-100 contact Angle Goniometer, Ramehart, Inc., Mountainlake, New Jersey. Contact angle measurements were made on new specimens as well as on specimens aged under ultraviolet light, ($12 mW/cm^2$ for 90 hours). A set of ten readings were taken on each specimen before and after degradation and the mean of these readings

computed.

Measurement of Leakage Current

The specimen used for measuring leakage current produced in the insulator specimen on application of electric stress were in the form of rods of 3.8 cm diameter. Two annular electrodes 2.54 cm apart were fitted on these specimen rods. The electrodes were connected to an adjustable high voltage source (0-15 kv) through a regulator and an isolation transformer. A fuse and a 10 k Ω resistor were connected in series with the electrodes. To measure the leakage current developed in the insulator specimens, voltage readings were observed by connecting an oscilloscope and a H.P. 37402 A digital meter across the 10 k Ω resistor. Circuit arrangement for measurement of leakage currents in insulator specimens is shown in Fig. 6.5. Leakage current readings were repeated for all specimens before and after U.V. degradation at three different stress levels of 2.36 kv per cm, 3.54 kv per cm and 4.72 kv per cm.

Aging of Specimens Under Ultraviolet Radiation (in Air)

Various specimens tested here were degraded in a special environmental chamber made by Tenny Engineering Company, Union, New Jersey. The high intensity ultraviolet light was obtained from a 360 watt High Pressure Mercury Vapor Lamp (U.A. 360) made by General Electric Company. The U.V. intensity was measured using a Photometer Model IL 254 with PT 100 Sensor made by International Light, Inc., Newburyport, Massachusetts.

6.4 Results and Discussion

The results obtained show that the amount of noise generated on the surface of different specimens increases significantly in all specimens after they were exposed to U.V. radiation. However, the level of increase in noise is different for different specimens as expected. The change in the amount of noise depends on the change in the surface properties of different materials due to U.V. aging.

Contact angle measurements were used to follow changes in surface properties of polymers after U.V. exposure. The contact angle measurements made on various polymeric specimens indicated a significant change in the value of contact angle between new and degraded samples in most cases. After exposing the specimens to U.V. light, the contact angles of specimens 1, 3, and 5 have appreciably deceased, thus indicating that the materials have become more hydrophilic. This change in the surface property of these specimens could be attributed to the breaking of bonds in these materials since the energy of the photons associated with the U.V. intensity was larger than the critical bond strengths between atoms or radicals in these polymers. This break up of bonds also seems to be the cause of the increase in noise generated on the surface of these polymers. For example, in specimen number 3, the noise increased from 35.14 microvolts to 181.5 microvolts corresponding to a change in contact angle from 75.13^{o} to 31.7^{o} when the material was aged under U.V.

The results obtained on the change in leakage current values

after degradation show an increase in leakage current in all specimens after degradation. However, the level of increase in leakage current in different specimens is different. A larger change in the values of leakage current in specimens 1, 3, and 5 could be attributed to an increase in the surface energy of these materials on exposure to U.V. radiation. Low surface energy materials can withstand an increased amount of stress than high surface energy materials before significant leakage current develops[1]. A relative value of surface energy of different polymers can be obtained from their water contact angle readings. In this respect, the results obtained show a correlation between the change in leakage current and the change in surface energy of the different specimens.

It has been established that eroding .63 cm spacing of an insulator specimen increased its surface noise at 4.72 KV per cm stress to about three times its original value[2]. In the example illustrated above, the noise level increased about five times its original value when the specimen was subjected to a U.V. radiation of 12mW/cm^2 for 90 hours. This provides some comparison of the surface damage due to U.V. aging and the surface damage due to erosion.

The effect of various gas plasmas on the wettability and other surface characteristics of polymers has been studied by many investi-

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[1]See Bibliography No. 1-74, p. 151.

[2]See Bibliography No. 11-73, p. 151.

gators as reviewed by DeLollis[1]. The mechanism(s) by which corona or plasma treatment changes surfaces of polymers is quite complicated and sometimes contradictory findings have been reported. Sowell et al[2] observed changes in contact angle of water on polymer surfaces when the latter were irradiated with vacuum U.V. irradiation. More recently, Owens[3,4] in his studies of polyethylene and polyethylene-terephthalate (PET) films, found similarities between the effects and products of corona treatment and U.V. exposure. He used self-adhesion of these polymers as a measure of changes in the surface chemistry introduced as a result of above treatments. The formation of enolic hydrogen and carbonyl groups has been demonstrated in the case of PE, while in the case of PET, there is a generation of phenolic hydrogens and carbonyl carboxyl groups. Furthermore, both corona and U.V. treatment culminate into an increase in the polar component of surface free energy of these polymers. Sahu and Misra[5] have used change in hydrophilicity of a polymer sample as a failure parameter to predict the life of a polymer insulator. Hudis[6] has studied the change in contact angle of water on RTV silicone subjected to vacuum U.V. irradiation.

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[1]See Bibliography No. 12-73, p. 151.

[2]See Bibliography No. 16-72, p. 150.

[3]See Bibliography No. 1-75, p. 152.

[4]See Bibliography No. 2-75, p. 152.

[5]See Bibliography No. 1-76, p. 152.

[6]See Bibliography No. 4-75, p. 152.

Our results on the change in contact angle of water on various polymers as a result of exposure to U.V. radiation agree qualitatively with the findings of others. Furthermore, different polymers behave differently with respect to decrease in contact angle, which is quite understandable.

In summary, the results presented here show a relationship between the hydrophilicity of polymer insulators and the amount of surface noise generated. For a more thorough investigation, one should (i) determine the nature of functional groups generated as a function of U.V. exposure using the procedure of Owens[1]. This should lead to a better understanding of the role of surface groups in determining the extent of noise generated, (ii) study the contact angle hysteresis to determine the heterogeneity introduced, and (iii) determine the roughness of surfaces as a result of U.V. exposure with a scanning electron microscope and (iv) determine r_c -- the critical surface tension of wetting of polymer insulator specimens to look at the change in surface energy of these materials before and after aging.

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[1]See Bibliography No. 1-75, p. 152.

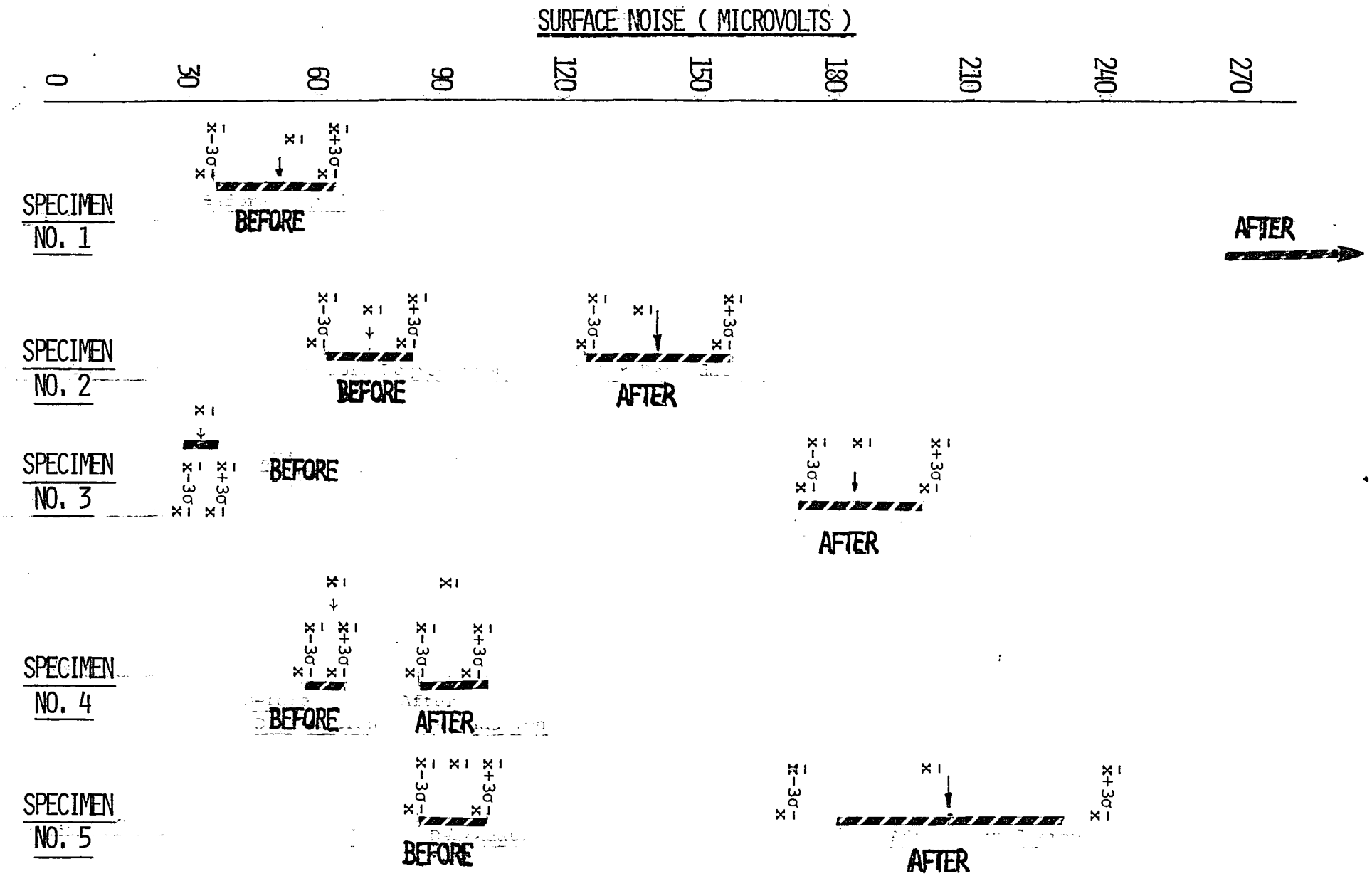


FIG. 6.2 SURFACE NOISE GENERATED ON DIFFERENT SPECIMENS BEFORE AND AFTER DEGRADATION

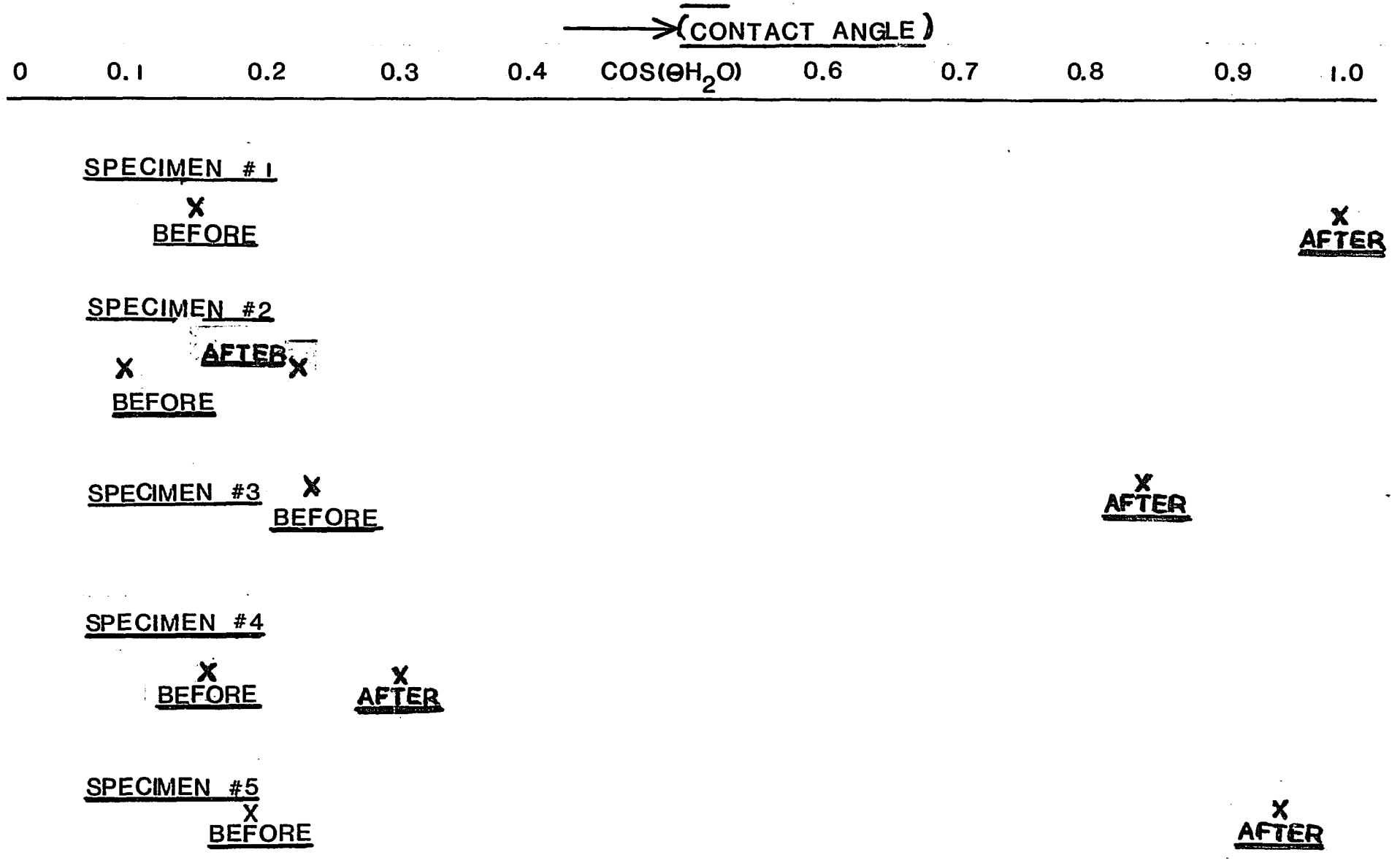
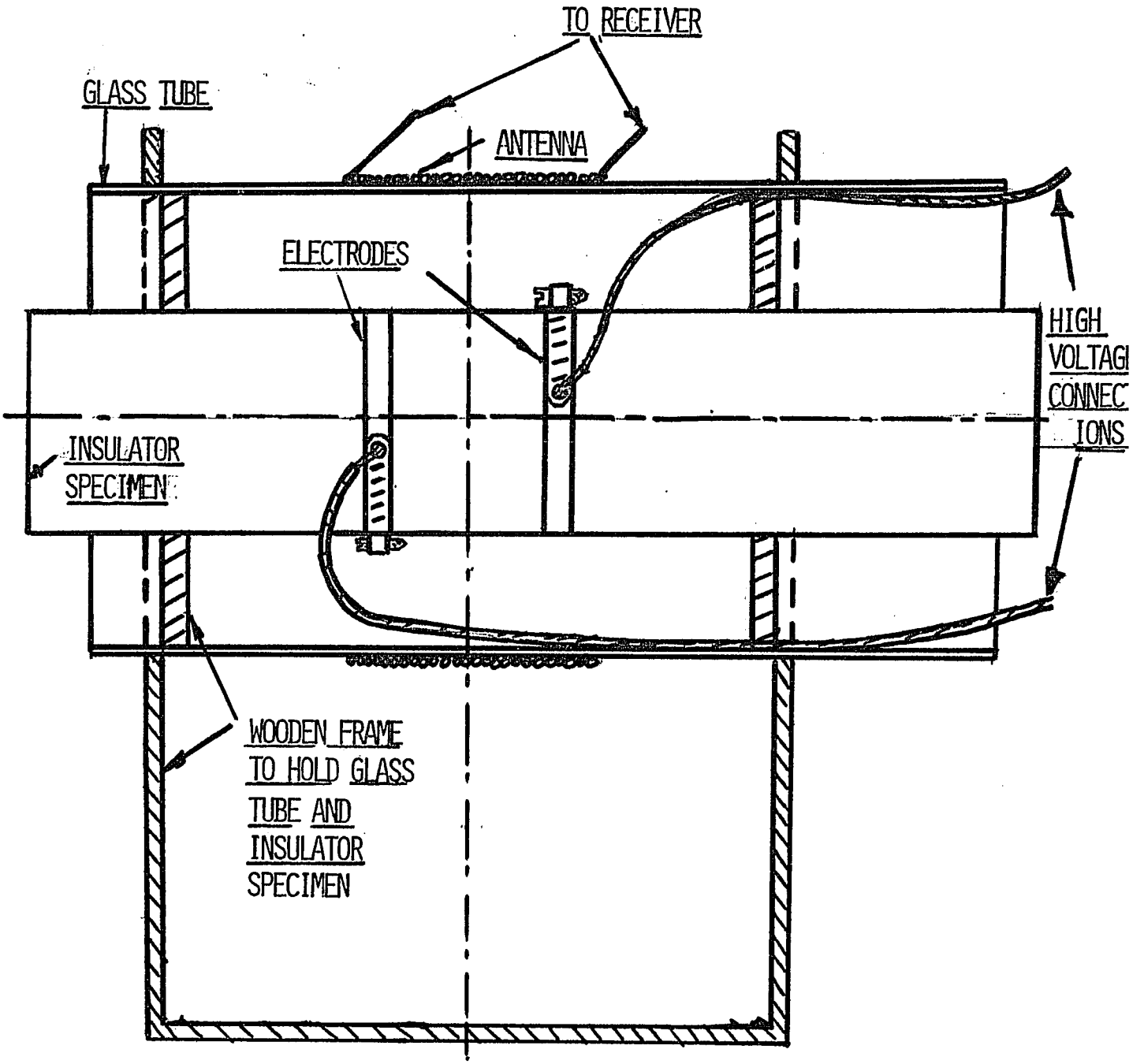


FIG. 6.3 COS (Θ H_2O) ON THE SURFACE OF DIFFERENT SPECIMENS BEFORE AND AFTER DEGRADATION



STRESS - 4.72 KV/CM

FREQUENCY - 1.6 MHz

FIG. 6.4 ARRANGEMENT OF INSULATOR-SPECIMEN, ELECTRODES AND ANTENNA ASSEMBLY FOR THE MEASUREMENT OF ELECTRICAL NOISE ON SPECIMEN SURFACE.

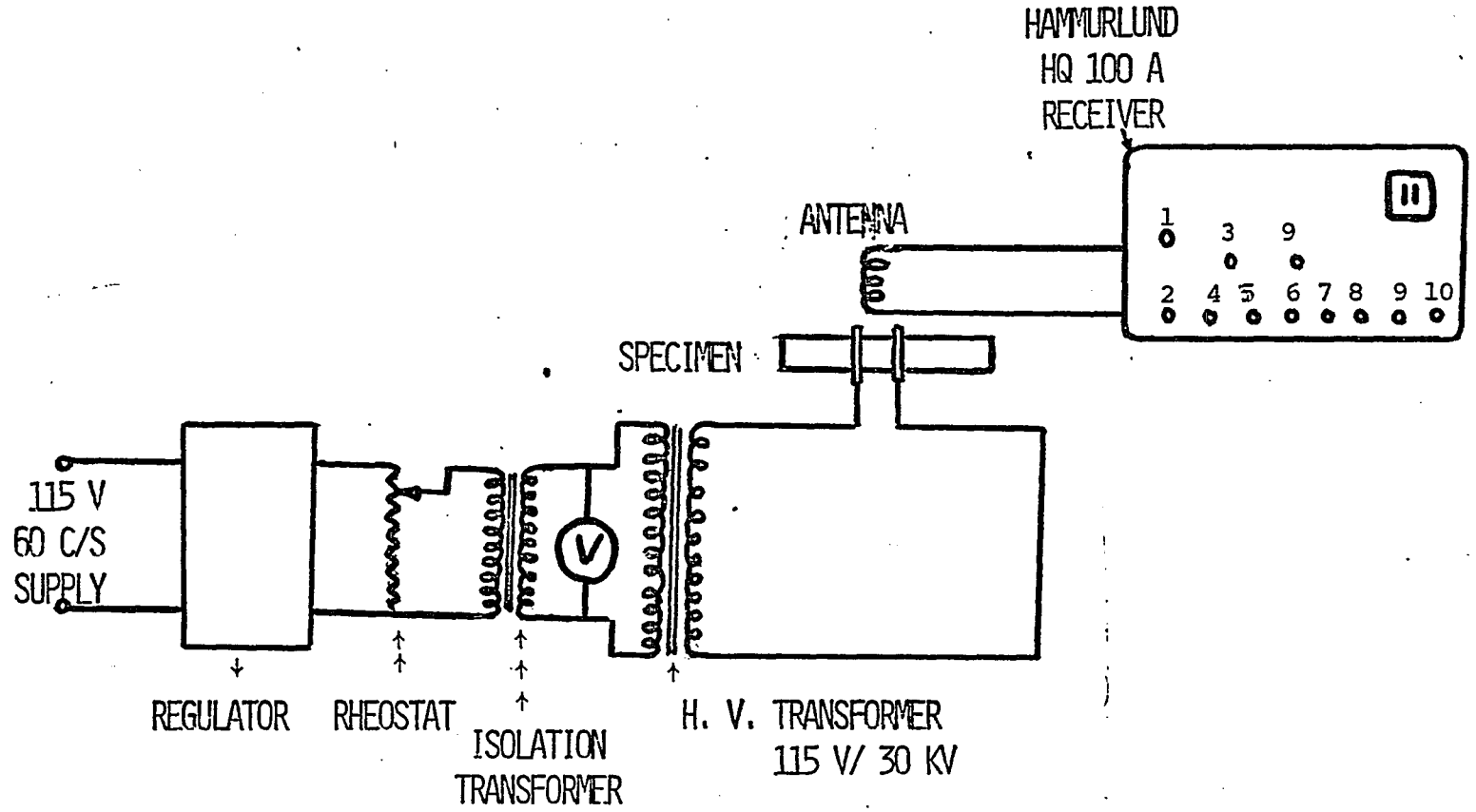


FIG. 6.5 GENERAL CIRCUIT ARRANGEMENT FOR MEASUREMENT OF SURFACE NOISE.

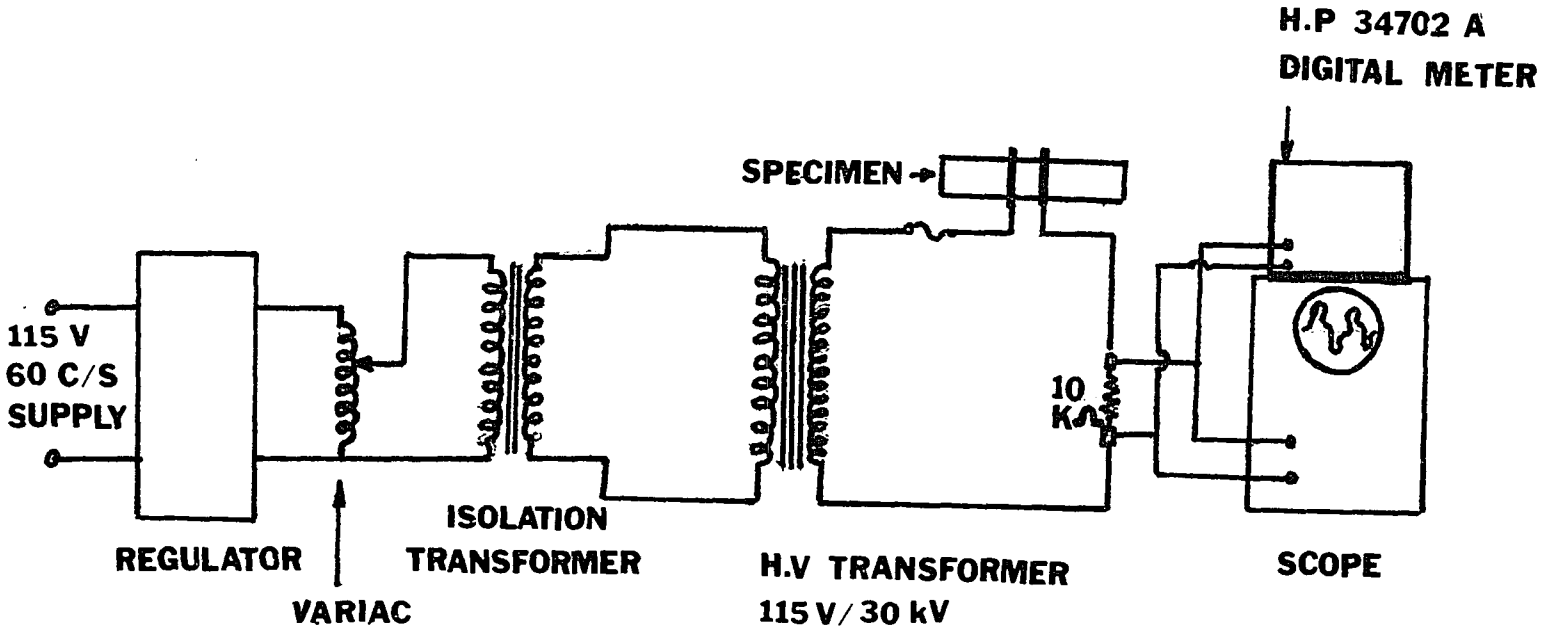


FIG. 6.6 **CIRCUIT ARRANGEMENT FOR MEASUREMENT OF LEAKAGE CURRENT**

(b) before aging

(a) after aging

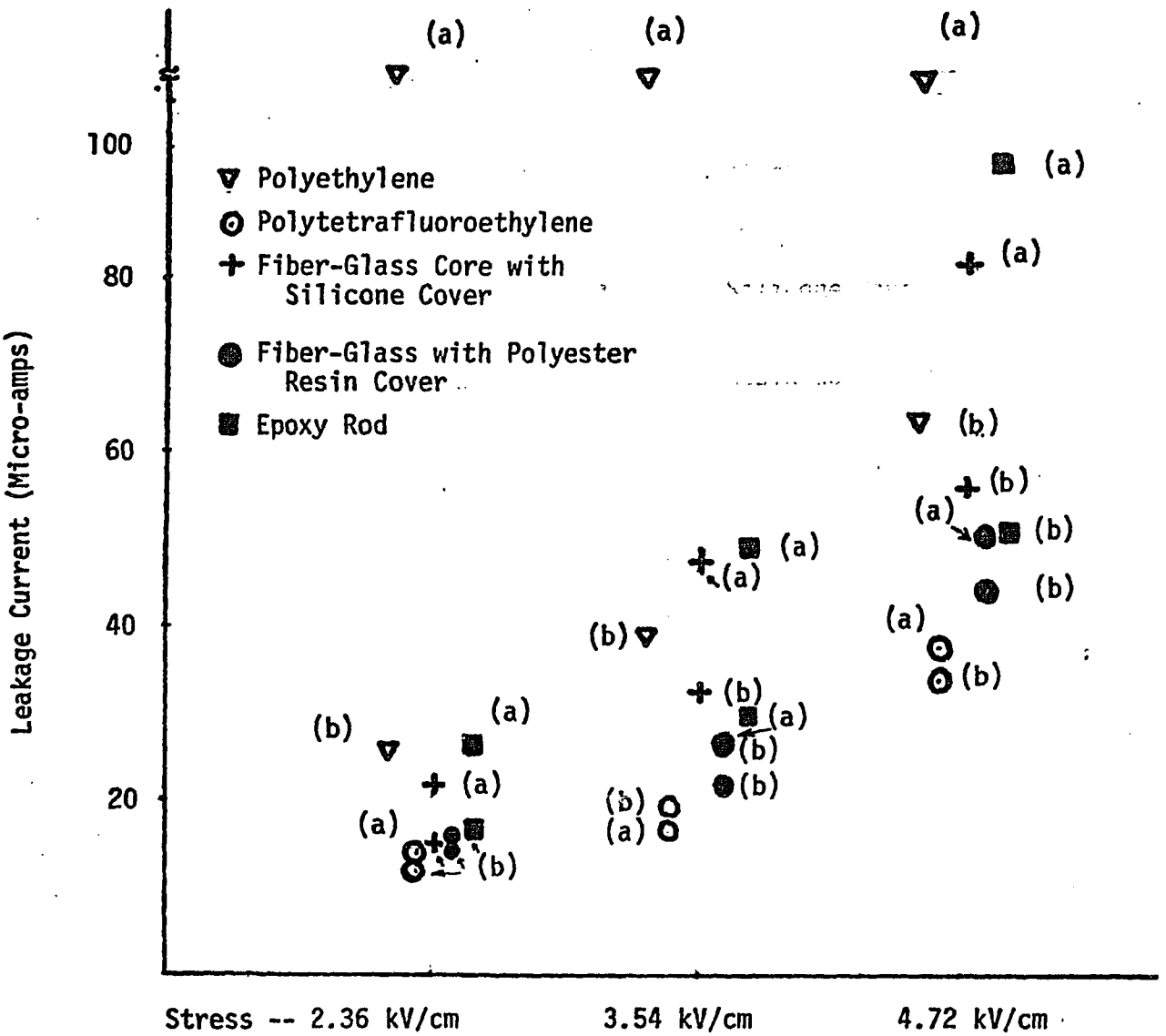


FIG. 6.7 Leakage Current developed on different specimens before and after degradation.

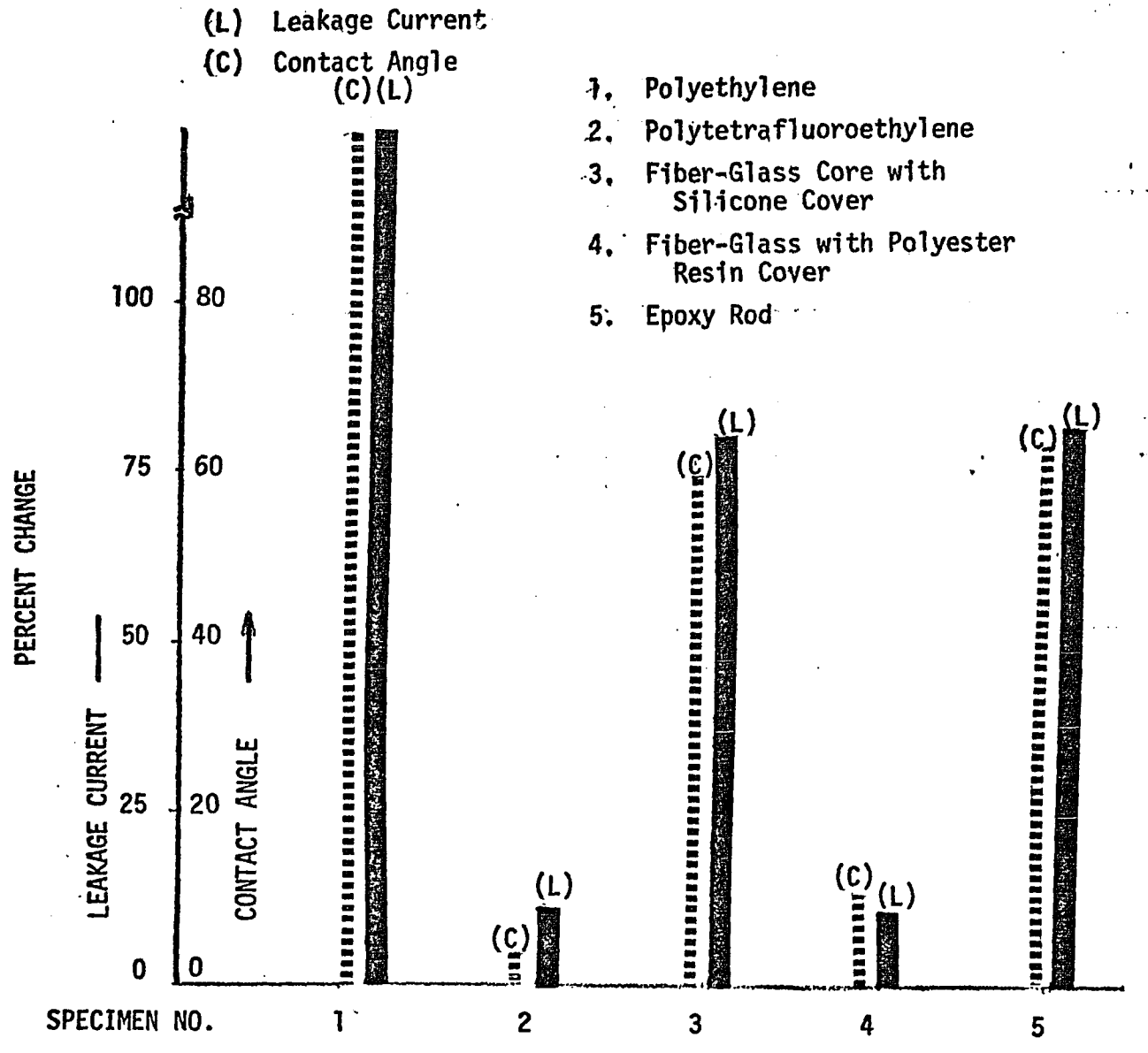


FIG. 6.8 Effect of UV Exposure on the Percentage Change in Contact Angle and Leakage Current in Different Specimens.

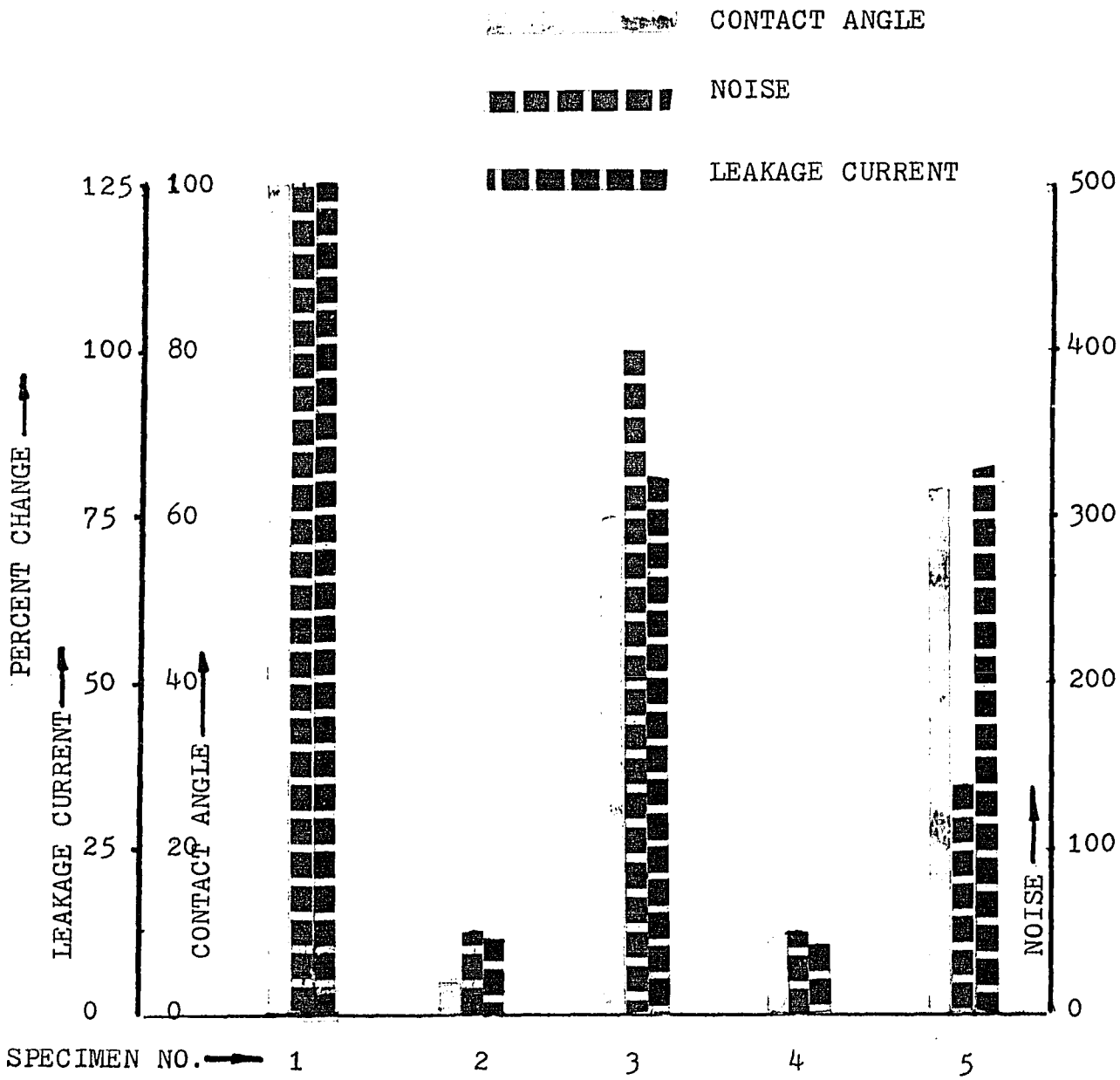


FIG. 6.9 SHOWING EFFECT OF UV EXPOSURE ON THE PERCENTAGE CHANGE IN CONTACT ANGLE, NOISE AND LEAKAGE CURRENT IN DIFFERENT SPECIMENS.

Chapter VII

LIFE TESTING OF A COMPOSITE INSULATOR DUE TO ENVIRONMENTAL STRESSES

7.1 Introduction

During recent years, considerable work has been done to find suitable synthetic insulating materials with excellent mechanical and electrical properties required in outdoor high voltage transmission. The concept of a composite insulator made of resin bonded glass fiber (R.B.G.F.) core covered with epoxy resin, silicone elastomer, polytetrafluoroethylene, etc., is gaining considerable attention. In the principle of a composite insulator which has been used as early as 1925[1], two materials are combined, one to fulfill the mechanical functions like tensile strength and the other to satisfy the insulating requirements like resistance to electrical discharges and environmental influences.

Although composite insulators made of R.B.G.F. core with sheds of silicone elastomer seem to be quite encouraging for use in extra high voltage transmission lines, further detailed studies are required to look at the long life and reliability necessary of such materials under severest environmental conditions.[2]

Synthetic materials for high voltage outdoor applications are known to be degraded by, among other things, combinations of environ-

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[1]See Bibliography No. 2-32, p. 133.

[2]See Bibliography No. 3-76, p. 151.

mental stresses. Air pollutant gases such as oxides of sulphur, oxides of nitrogen, hydrogen sulphide, chlorine, etc., ultraviolet radiation are two of the important environmental considerations.

This chapter describes the results of experimental work investigating the effects of exposing a typical polymer insulator made of resin bonded glass fiber core covered with silicone elastomer to pollutant gases, U.V., and pollutant gases plus U.V. as a function of temperature. Increase in hydrophilicity[1,2], and the amount of electrical noise generated on the surface of the insulator on application of electric stress[2,3] were used as the criteria to determine the life of the insulator specimen. The importance of using the properties of hydrophilicity of the surface and the amount of noise generated on the surface of the insulator in characterizing polymer insulator surfaces is described in Chapter V.

7.2 Experiment

Aging in pollutant gases

Insulator specimens in the form of rods of 3.8 cm diameter and about 20 cm long were placed in a doubled walled environmental testing chamber as shown in Fig. 7.1, in which a mixture of gases NO_2, SO_2, H_2S, and Cl_2 along with pure compressed air were introduced

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[1]See Bibliography No. 1-76, p. 152.

[2]See Bibliography No. 2-76, p. 152.

[3]See Bibliography No. 11-73, p. 151.

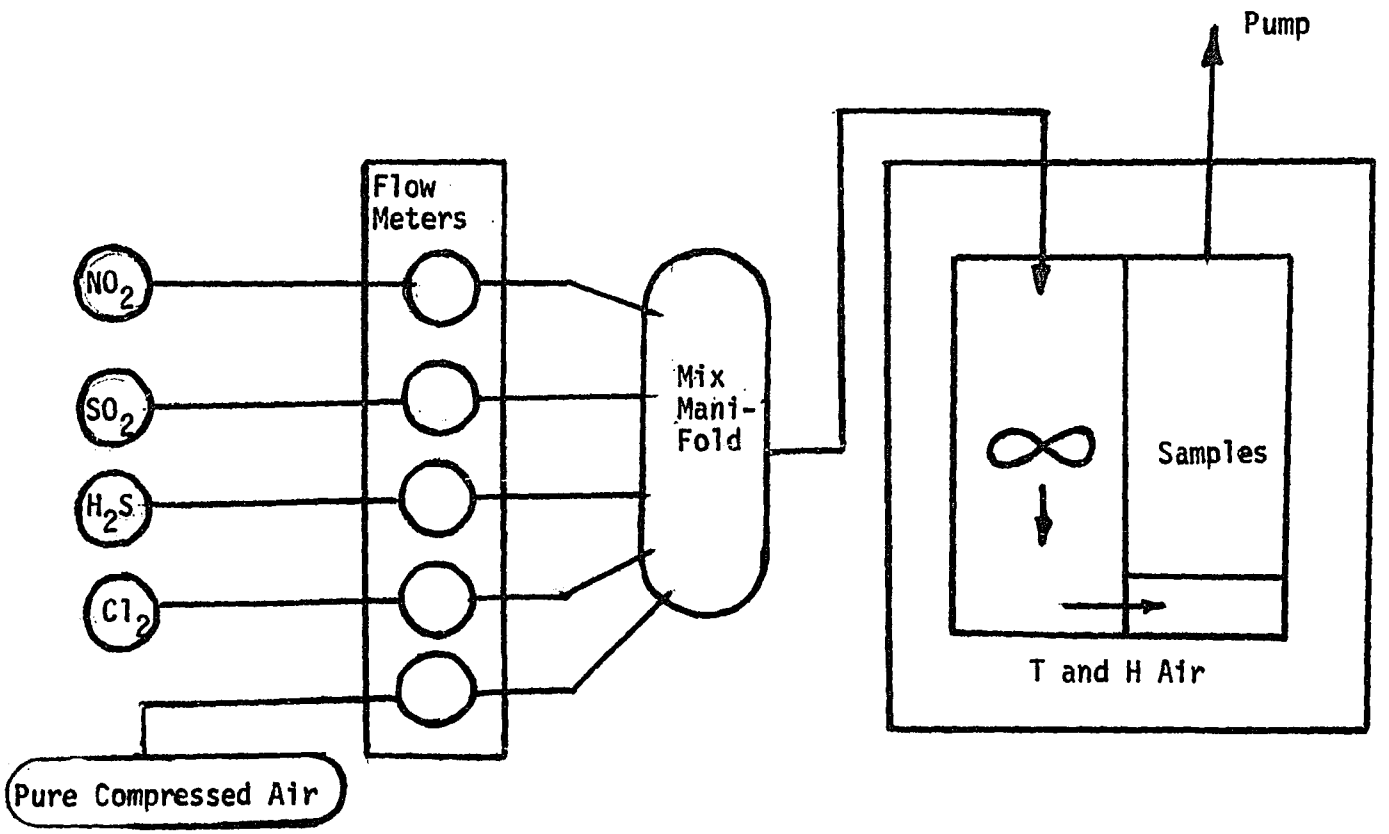

Fig. 7.1 Showing Arrangement for Degrading Insulator Specimens under Reactive Gases.

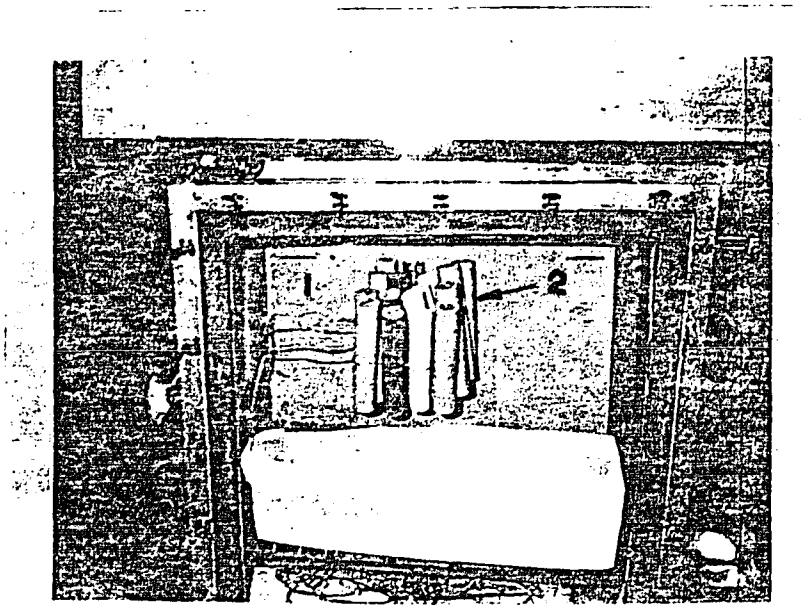

Fig. 7.2 Chamber for Degradation of Insulator Material in Reactive Gases.

(1) Chamber (2) Insulator Specimens

through a mix manifold. The samples were placed in the inner chamber. The desired temperature and humidity (T and H) controls were achieved by introducing T and H air in the outer chamber. The inner chamber was kept at a negative pressure with respect to the outer chamber to cause the air with proper T and H to be pulled into the inner chamber containing test specimens. The T and H air is then pulled out with a pump. The samples were pulled out after regular intervals. A photograph of the samples arranged in the test chamber is shown in Fig. 7.2. Test conditions for testing of specimens in reactive gases is given below:

H_2S - - - - - 350 ppb

SO_2 - - - - - 496 ppb

NO_2 - - - - - 700 ppb

CL_2 - - - - - 52 ppb

Temperature - - - - - 70^oC

Relative Humidity - - - - - 80%

Aging under U.V. radiation (in air)

The specimens were exposed to U.V. radiation in an environmental chamber made by Tenny Engineering Company, Union, New Jersey. The high intensity U.V. radiation was obtained from a 360 watt high pressure mercury vapor lamp (UA 360) made by General Electric Company. The U.V. intensity at different temperatures was measured using IL 254 model photometer with PT 100 sensor made by International Light, Inc., Newburyport, Massachusetts.

Measurement of Contact Angle (θ_{H_2O})

Water contact angles were measured on surface of test specimens about 1.27 cm wide and .25 cm thick at different levels of degradation due to exposure to reactive gases, U.V., and reactive gases plus U.V. Pure water drops (resistivity better than 15 mega-ohms) were placed on these samples and contact angle measured using Ramehart model A-100 contact angle goniometer, Ramehart, Inc., Mountainlake, New Jersey.

Measurement of Electric Noise

The amount of noise generated on the surface of the insulator specimen on application of electric stress was measured using Hammurlund model HQ-100A receiver. The test specimens were in the form of rods about 3.8 cm in diameter. The noise was measured at a stress level of 4.72KV per cm and a frequency of 1.6 Mhz. The details of measurement of surface noise including arrangement of insulator specimen, electrodes, antenna assembly, circuit arrangement, etc., is described in Chapter VI.

7.3 Results and Analysis of Data

A typical graph showing Cos (θ_{H_2O}) versus time when a specimen was degraded in pollutant gases plus U.V. radiation at different temperatures is shown in Fig. 7.3. Similar plots have been obtained for degradation of insulator specimen on exposure to different intensities of U.V. and on exposure to pollutant gases plus U.V. ex-

posure of different intensities as a function of temperature.

Fig. 7.4 shows a plot of the amount of noise generated on insulator specimen on application of electric stress at different levels of degradation.

From a typical plot of the contact angle versus time, it was observed that the contact angle decreases exponentially with time to about 40 degrees without any visual surface damage. If the material is degraded further, micro-size cracks appear on the surface of the material. Therefore, time to failure of the surface or life of the specimen was selected as the time when the contact angle reaches 40 degrees or Cos (θ_{H_2O}) = .766.

The time of failure of the insulator specimen when the specimen is degraded on exposure to U.V. and on exposure to pollutant gases plus U.V. is shown in Table 7.1. Fig. 7.5 shows a plot of Ln (life) versus 1/T at different levels of degradation of the insulator specimen.

Analysis of data

From the results obtained, the life of the insulator specimen made of resin bonded glass fiber core covered with silicone elastomer on exposure to U.V. radiation and on exposure to reactive gases plus U.V. radiation has been calculated by using modified Arrhenius equation as discussed in Chapter III.

Table 7.1

Experimental Life of Silicone Elastomer

for Different Levels of Degradation

		Type of Aging			
		U.V.		Reactive Gases Plus U.V.	
Temp. °C	U.V. Intensity mW/cm^2	Life (L) Hrs.	Ln (L)	Life (L) Hrs.	Ln (L)
	6	1408	7.25	992	6.9
60	9	1152	7.05	854	6.75
	12	871	6.77	658	6.19
	6	1096	7.0	804	6.69
70	9	934	6.84	658	6.49
	12	765	6.64	512	6.24
	6	897	6.8	595	6.39
80	9	772	6.65	512	6.24
	12	584	6.37	411	6.02

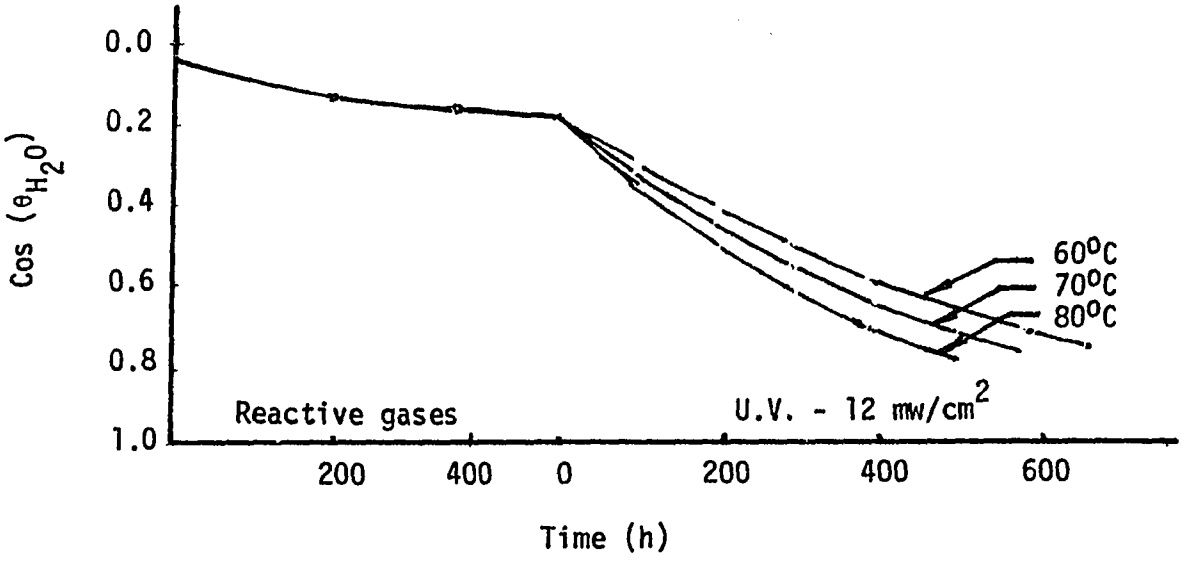

Fig. 7.3 Cos (θ_{H_2O}) vs. Aging of Insulator Due to Reactive Gases and U.V. as a Function of Temperature.

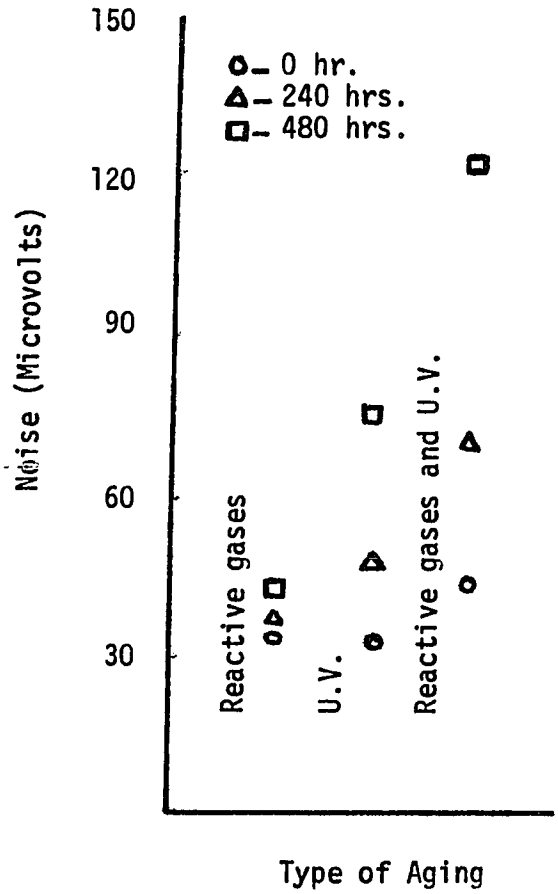

Fig. 7.4 Electrical Noise on Insulator at Diff. Levels of Degradation.

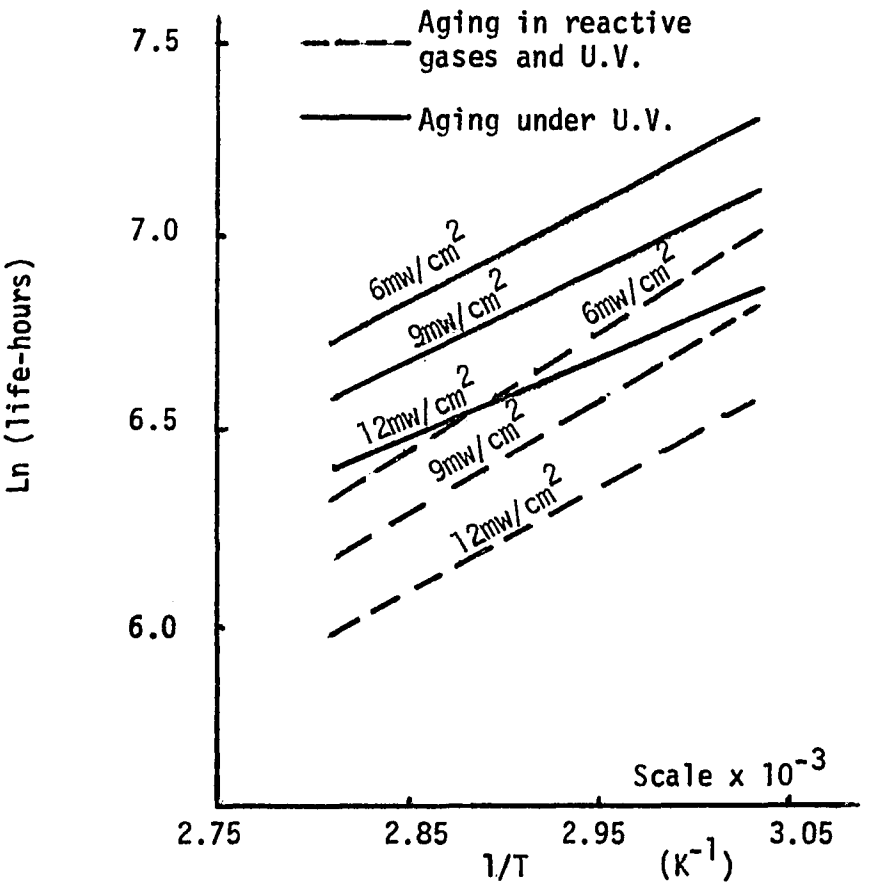

Fig. 7.5 Ln (Life) vs. 1/T at Diff. U.V. Intensities.

$$\text{Ln (Life)} = K + (E - BI)/RT \qquad (7.1)$$

where

E = Activation energy

I = U.V. intensity

R = Gas law constant

T = Temperature in ^{o}kelvin

K and B are constants of the material

The values of the constants K and B and the activation energy E for a typical polymer insulator made of resin bonded glass fiber core covered with silicone elastomer cover have been calculated from experimental data and are shown in Table 7.2. Once the constants in the model hypothesized have been obtained, the normal life of the material can be obtained for any particular set of conditions.

Assuming an average U.V. intensity of 0.93 mW/cm^2 on a normal sunny day and an average 2392 hours of sunshine per year[1], the values of the normal life of resin bonded glass fiber core, covered with silicone elastomer material have been obtained as shown in Table 7.2 below.

Table 7.2

Type of Aging	K	E	B	Normal Life (years)
UV	0.692	6079	209	19.33
Reactive Gases plus UV	-1.747	7222	200	11.94

[1]See Bibliography No. 1-76, p. 152.

Calculations

Determination of constant 'B'

From the modified Arrhenius equation

$$Ln\ (L) = K + (E - BI)/RT \tag{7.2}$$

from which

$$K = Ln\ (L) - S\ (1/T) \tag{7.3}$$

where

$$S = (E - BI)/R \tag{7.4}$$

If S_1, S_2, and S_3 refer to the values of the slopes corresponding to U.V. intensities I_1, I_2, and I_3 respectively then

$$S_1 = (E - BI_1)/R \tag{7.5}$$

$$S_2 = (E - BI_2)/R \tag{7.6}$$

Subtracting equation (7.6) from equation (7.5)

$$S_1 - S_2 = (B/R\ (I_2 - I_1) \tag{7.7}$$

or

$$B_1 = (S_1 - S_2)\ R\ /\ (I_2 - I_1) \tag{7.8}$$

Another value of B can be calculated by suing slopes S_2 and S_3 corresponding to U.V. intensities I_2 and I_3 respectively, giving

$$B_2 = (S_2 - S_3)\ T\ /\ (I_3 - I_2) \tag{7.9}$$

The value of B used to determine the life of the insulator specimen for a particular type of aging is the average of the values obtained from equations (7.8) and (7.9)

$$B = (B_1 + B_2)/2^* \tag{7.10}$$

Determination of constant 'K'

From equation (7.1)

$$Ln\ (L) = K + (E - BI)/RT$$

or

$$K = Ln\ (L) - S\ (1/T)$$

where

$$S = (E - BI)/R$$

the values of K can be obtained for each of the slopes of Fig. 7.5, giving

$$K_1 = Ln\ (L_1) - S_1\ (1/T) \tag{7.11}$$

$$K_2 = Ln\ (L_2) - S_2\ (1/T) \tag{7.12}$$

$$K_3 = Ln\ (L_3) - S_3\ (1/T) \tag{7.13}$$

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*The values of B_1 and B_2 obtained for both degradation due to U.V. and reactive gases plus U.V. are approximately equal suggesting the validity of the model used.

The value of the constant K selected is the average of the values obtained from equations (7.11), (7.12), and (7.13)

$$K = (K_1 + K_2 + K_3)/3 \tag{7.14}$$

Determination of 'E'

From equation (7.4)

$$E = S.R + B.I \tag{7.15}$$

for slope S_1 corresponding to intensity I_1

$$E_1 = S_1\ R + B\ I_1 \tag{7.16}$$

similarly

$$E_2 = S_2\ R + B\ I_2 \tag{7.17}$$

and

$$E_3 = S_3\ R + B\ I_3 \tag{7.18}$$

The value of 'E' selected is the average of the values obtained from equations (7.16), (7.17), and (7.18)

$$E = (E_1 + E_2 + E_3)/3 \tag{7.19}$$

Sample Calculations*

Type of Aging

U.V.	Reactive Gases Plus U.V.
From Fig. 7.4	
$S_1 = 2409$	$S_1' = 3012$
$S_2 = 2109$	$S_2' = 2711$
$S_3 = 1780$	$S_3' = 2411$
$B_1 = (S_1 - S_2)\ R/(I_2 - I_1)$	$B_1' = (S_1' - S_2')/(I_2 - I_1)$
$= (2409 - 2109)2/3$	$= (3012 - 2711)2/3$
$= 200$	$= 200.67$
Similarly	
$B_2 = 218$	$B_2' = 200$
$B = 209$	$B' = 200$

---

*Subscript 1 refers to degradation at 6 mW/cm^2

Subscript 2 refers to degradation at 9 mW/cm^2

Subscript 3 refers to degradation at 12 mW/cm^2

The constants with prime symbols attached are for degradation due to reactive gases plus U.V. aging.

$K_1 = Ln\ (L_1) - S_1\ (1/T)$

$= 7 - 2409 \times .00295$

$= - 0.022$

$K_1' = Ln\ (L_1') - S_1'\ (1/T)$

$= 6.7 - 3012 \times .00295$

$= - 2.07$

Similarly

$K_2 = 0.705$

$K_3 = 1.4113$

$\underline{K = 0.698}$

$K_2' = - 1.40$

$K_3' = - 1.77$

$\underline{K' = - 1.747}$

$E_1 = S_1\ R + B\ I_1$

$= 2409 \times 2 + 209 \times 6$

$= 6072$

$E_1' = S_1'\ R + B\ I_1$

$= 3012 \times 2 + 200 \times 6$

$= 7224$

Similarly

$E_2 = 6097$

$E_3 = 6068$

$\underline{E = 6079}$

$E_2' = 7220$

$E_3' = 7218$

$\underline{E' = 7222}$

7.4 Discussion

The results obtained indicate the level of surface degradation of a typical polymer insulator material made of resin bonded glass fiber core covered with silicone elastomer cover when it is exposed to reactive gases, U.V. radiation, and reactive gases plus U.V. exposure.

The data indicates that U.V. degrades more than reactive gases and the degradation is enhanced due to the combined effect of the two.

Clabburn et al[1] have studied some parameters affecting the outdoor performance of plastic materials. Their findings show that the degradation of plastic materials due to SO_2 and NO_2 is enhanced in the presence of U.V. The degradation of polymer surfaces in reactive gases has also been studied by Razumovski et al[2]. They found that reactive gases such as SO_2, CL_2, NO_2, and O_3, etc., accelerate degradation of polymer materials.

Jellinek et al[3] have studied the effect of exposing various polymers to SO_2 and NO_2 under various conditions. The degradation was observed by observing chain scission, cross-linking reactions and changes in infrared spectra. Different levels of degradation

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[1]See Bibliography No. 12-70, p. 145.

[2]See Bibliography No. 29-71, p. 149.

[3]See Bibliography No. 11-69, p. 144.

were observed in all polymers when exposed over long periods of time. However, their findings indicate that elastomers are more susceptible to these gases than saturated polymers.

The life of a resin bonded fiber glass core epoxy resin covered material due to U.V. exposure using modified Arrhenius equation has been established[1]. Our results on the life of the silicone elastomer cover material using a similar procedure indicate the superiority of silicone elastomer cover material over epoxy resin as far as degradation due to U.V. exposure is concerned.

Noise generated on the insulator surface on application of electric stress is an indication of the insulator surface condition[2,3]. Our results on the amount of noise verify the fact that reactive gases accelerate the level of degradation.

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[1]See Bibliography No. 1-76, p. 152.

[2]See Bibliography No. 2-76, p. 152.

[3]See Bibliography No. 11-73, p. 151.

Chapter VIII

CONCLUSION AND RECOMMENDATIONS FOR FURTHER RESEARCH

8.1 Conclusion

Some of the important observations made during this research work are summarized below:

1. Significant electric noise is generated on a polymer insulator on application of electric stress. The cause of this noise is attributed to the tiny air bubbles in the bulk and unevenness of the surface of the insulator material. On application of electric stress, these defects are stressed more than the solid. This produces excited and ionized molecules which generate radio noise. For the same amount of electric stress, the noise generated on different materials gives an indication of the surface condition of these materials.

2. The aging of a polymeric insulator can be studied by measuring the electric noise generated on the surface of the material before and after aging. The difference in the noise level before and after aging gives an indication of the extent of degradation.

3. The conventional test methods for testing insulator materials which measure the material's tendency to form carbonized tracks when exposed to severe arcing are not very suitable for testing modern synthetic insulating materials which are designed to give maximum arc-suppression under wet conditions and not necessarily to have maximum arc-track resistance. These materials should be screened on their ability to maintain a hydrophobic surface, high surface resistance and arc suppression under normal outdoor conditions. Therefore,

the characterization of synthetic insulator surfaces can best be studied by measuring the hydrophilicity of the surface. A hydrophobic surface will prevent the formation of a resistive surface due to pollution and moisture on the surface and thus prevent excessive leakage currents and severe arcing which are causes of tracking and/or erosion.

4. The hydrophobic surface of most polymers changes its hydrophilicity and becomes hydrophilic on exposure to environmental stresses such as U.V. radiation, reactive gases like oxides of sulphur, oxides of nitrogen, ozone, hydrogen sulphide, etc. For the same amount of environmental stress, the change in hydrophilicity in different polymer insulator materials is different.

5. The surface degradation of different polymer insulating materials for high voltage application on exposure to U.V. radiation has been experimentally investigated. The amount of electric noise generated on application of electric stress was measured before and after aging. The polymer surfaces were also characterized by measuring the water contact angles on the surface of the materials before and after aging. The change in the amount of noise is related to the change in contact angle. Increase in electric noise is followed by a decrease in contact angle or an increase in the hydrophilicity of the surface.

6. The surface degradation of different polymeric insulating materials due to U.V. aging was also studied by measuring the leakage current on application of electric stress and by observing the scanning electron microscope pictures of the surface before and after

aging. The results obtained show that different materials degrade to different extents on exposure to U.V. radiation. Also, the results of surface degradation obtained from measurement of leakage current and from scanning electron microscope study have a strong correlation with the results obtained from the characterization of the surface of the materials by electric noise and water contact angles.

7. Synthetic insulators for outdoor high voltage transmission systems are known to be degraded by, among other things, combination of environmental stresses. The changes in the characteristics of the synthetic insulators under such stresses is not fully understood[1]. In an experimental study investigating the effects of exposing a typical composite insulator made of resin bonded glass fiber (R.B.G.F.) core covered with silicone elastomer to reactive gases such as NO_2, SO_2, H_2S, and CL_2; U.V. radiation; and reactive gases plus U.V. radiation. the results obtained show that U.V. degrades more than reactive gases and the degradation is enhanced by the combined effect of the two,

8. The surface degradation of a polymer insulator on exposure to environmental stresses such as reactive gases, U.V. radiation, temperature, etc., is a chemical process. The life test data of exposing a typical composite insulating material made of R.B.G.F. core covered with silicone elastomer on exposure to such stresses has been found to follow the modified Arrhenius equation[2].

The life of a composite insulator material made of R.B.G.F. core

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[1]See Bibliography No. 3-76, p. 152.

[2]See Bibliography No. 1-77, pp. 152-153.

covered with epoxy resin cover material, using change in surface hydrophilicity as the failure criterion and using modified Arrhenius equation has been established[1]. Results obtained in the present investigation on the silicone elastomer cover material using a similar procedure indicate the superiority of the silicone elastomer material over epoxy resin as far as the degradation due to U.V. exposure is concerned.

8.2 Recommendations for Further Research

The aging of synthetic insulating materials for high voltage applications when exposed to outdoor environmental stresses is a complex process. The knowledge of reliability and failure mechanism (s) studies on synthetic insulating materials and their diagnosis are important in designing proper insulating systems to meet high demands and environmental considerations of present times. Unfortunately, the studies conducted so far in this direction are far from complete. Considerable effort on the part of the industries is required to develop efficient and meaningful standards for testing and developing synthetic insulating materials for extra high voltage transmission systems. From the experience gained during this research on theoretical and experimental studies on synthetic insulating materials, a few suggestions for further research work on the subject are described below.

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[1]See Bibliography No. 1-76, p. 152.

8.3 A Quantitative Study on Aging of Synthetic Insulating Materials

Most test methods on the aging and reliability of a synthetic material for insulation purposes are qualitatitive in nature. Not many studies have been carried out to measure precisely the extent of degradation of synthetic insulating materials due to various stresses. The studies conducted so far are what are known as rank order tests in which the emphasis is on determining the superiority of one material over the other. With the availability of large numbers of materials, the properties of which do not differ much, the results of the rank order tests with qualititative observations cannot determine the superiority of one material over the other with a significant confidence level. This calls for very precise quantitative measurements to observe properties of these insulating materials and specifically the extent of change in the properties caused by aging due to different types of stresses. The need to use precise quantitative measurements to study performance and aging characteristics of synthetic insulating materials has also been stressed lately in a report prepared by the task force on aging of electrical insulation of the conference on Electrical Insulation and Dielectric Phenomena[1]. One such method which could be used to measure the precise quantitative changes in the surface properties of a polymeric insulator is discussed below.

Fig. 8.1 shows a flat surface of an insulating material. Two

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[1]See Bibliography No. 3-76, p. 152.

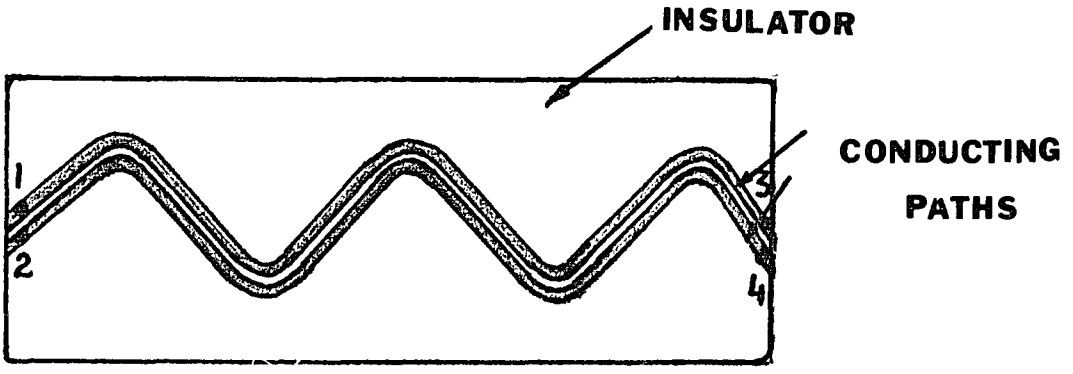

FIG.8.1 SHOWING TWO CONDUCTING PATHS ON THE INSULATING MATERIAL SURFACE

zig-zag paths shown on the face of the surface indicate two conducting paths created by vacuum deposition of a good conductor like gold about 2000 A^0 thick. The two conducting paths are separated by a small distance about one mm between them. Points 1, 2, 3, and 4 indicate the four connections formed to make electrical measurements.

The values of the capacitance 'C', the quality of factor 'Q', and the leakage current measured before and after aging will show the extent of degradation produced due to particular aging conditions.

A mathematical model describing the change in electrical parameters on the model shown in Fig. 8.1 resulting in the change in the values of capacitance and quality factor values before and after degradation is given below.

Change in Dielectric Constant

Before Aging

$$C_1 = k_1 \varepsilon_0 A/d$$

where

C = Capacitance

K_1 = Dielectric Constant

= Permittivity of air

A = Area, and

d = Distance between the conducting paths

After Aging

$$C_2 = k_2 \varepsilon_0 A/d$$

where

K_2 is the dielectric constant after aging.

$(C_2 < C_1 \;\; ; \text{ if } \; k_2 < k_1)$

Change in Quality Factor 'Q'

Before Aging | **After Aging**

Equivalent electrical circuits for the model shown in Fig. 8.1 before and after aging can be shown as in Fig. 8.2 and Fig. 8.3 respectively.

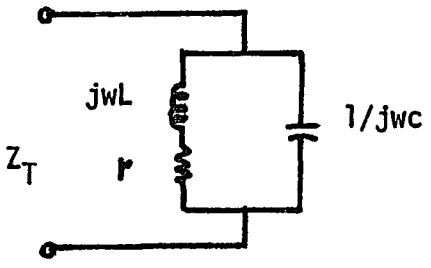

Fig. 8.2

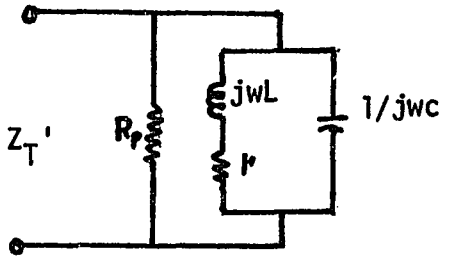

Fig. 8.3

From Fig. 8.2

$$1/Z_T = jwc + 1/(r + jwL)$$

$$= \frac{1 - w^2Lc + jwrc}{r + jwL}$$

$$Z_T = \frac{r + jwL}{1 - w^2Lc + jwrc}$$

$$= \frac{r + jwL}{jwrc}$$

$$= \frac{L}{rc} - \frac{j}{wc}$$

substituting

$$c = \frac{1}{w^2L}$$

$$Z_T = \frac{w^2L^2}{r} - jwL$$

After aging, there will be an increase in leakage current. This can be represented by the circuit as in Fig. 8.3, in which an additional resistance R_p is introduced. The effect of this R_p will be to change the value of 'Q' from wL/r to $wL/(r + \Delta r_p)$ where Δr_p has been introduced because of the resistance R_p. The new value of Q that is Q' in terms of L, r and R_p is derived below.

Before Aging

$$= \frac{wL}{r}(wL) - jwL$$

$$= QwL - jwL$$

$= wLQ$ (Since $wL < QwL$) assuming Q is of the order of 100 or so.

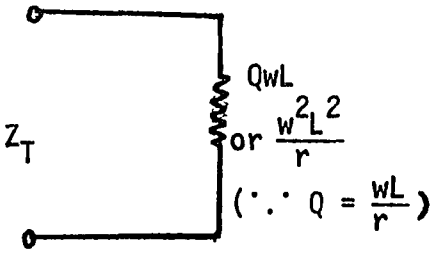

Fig. 8.4

So the model in Fig. 8.2 can be approximated as in Fig. 8.4 above

After Aging

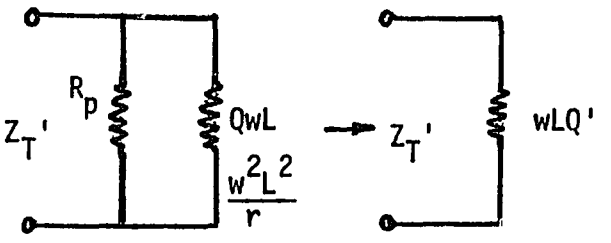

Fig. 8.5

$$Z_T = \frac{\frac{w^2L^2}{r}(R_p)}{\frac{w^2L^2}{r} + R_p} = \frac{\frac{w^2L^2}{r}(R_p)}{R_p + QwL} \tag{8.1}$$

where

$Q = wL/r$

After aging

$$Q' = \frac{wL}{r + \Delta r_p} \tag{8.2}$$

$$wLQ' = \frac{w^2L^2}{r + \Delta r_p} \tag{8.3}$$

Before Aging

After Aging

Also, from equation (8.1) for the approximate equivalent circuit

$$wLQ' = \frac{\frac{w^2L^2}{r}\ (R_p)}{R_p + QwL} \qquad (8.4)$$

Equating (8.3) and (8.4), we ha have

$$\frac{w^2L^2}{r + \Delta r_p} = \frac{w^2L^2/r\ (R_p)}{R_p + QwL} \qquad (8.5)$$

from equation (8.5)

$$r + \Delta r_p = \frac{(R_p + QwL)\ r}{R_p}$$

or

$$\frac{R_p}{r}\ (r + r_p) = R_p + QwL$$

or

$$R_p + \frac{R_p\ r_p}{r} = R_p + QwL$$

$$r_p = \frac{QwLr}{R_p}$$

with $Q = \frac{wL}{r}$

Before Aging

After Aging

$$r_p = \frac{w^2L^2}{R_p} \qquad (8.6)$$

Substituting the values of r_p from (8.6) in 8.2, we obtain the new value of Q, i.e., Q'

$$Q' = \frac{wL}{r + r_p} = \frac{wL}{r + \frac{w^2L^2}{R_p}} \qquad (8.7)$$

Equation (8.7) shows how with R_p in the circuit due to increased leakage because of aging, the value of Q' will be less than original Q.

8.4 Problem of Binding Central Rod and Outer Covering of Composite Insulators

An important aspect of the construction of a synthetic insulator with a central rod and a suitable covering is the choise and coordination of the thickness of the shedded covering and the bonding between the rod and the outer covering. Special care is needed in the processing of these materials to avoid the formation of cracks or gas bubbles.

Insulators with important manufacturing or design defects consist mainly in bad bonding between central rod and outer covering, with the consequent existence of air bubbles in the space between rod and cover. The puncture that occurs in these cases are such as to involve the body of the insulator, so that once they have occurred, they reduce the strength of the insulator and severely prejudice its life, since they make it possible for humidity and pollution to go below the protective covering.

The insulators with very minute defects of the above type might pass the conventional electrical endurance tests of short duration but will fail in the course of a long duration test. The existence of air bubbles between the central rod and outer covering of the composite insulating materials is, therefore, a problem which needs very careful consideration.

The use of the measurement of noise generated on application of electric field has been used to investigate surface irregularities and surface aging due to environmental stresses. The electric noise could also be used as a parameter to determine the effectiveness of the rod covering interface. For this purpose, electric noise can be measured by inserting two electrodes -- one in the outer covering and one in the central rod as shown in Fig. 8.6. The idea here is to confine the noise measurements to the interface of the fiberglass rod and the outer cover material of the composite insulator. The amount of noise generated on application of electric stress will indicate the degree of imperfection of this bonding and the presence of air

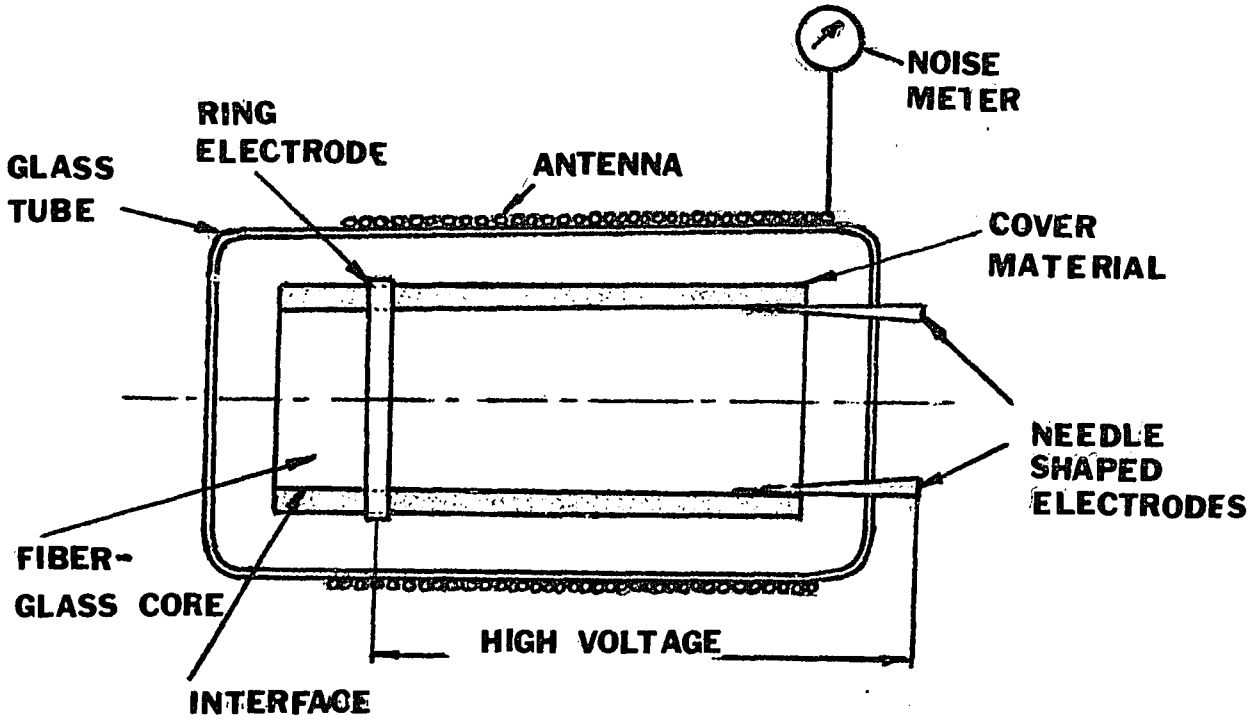

FIG. 8.6 ARRANGEMENT FOR TESTING EFFECTIVENESS OF BONDING BETWEEN THE COVER AND CORE MATERIAL OF A COMPOSITE INSULATOR

voids, etc.

Another possible way of looking into the imprefections between the central rod and the outer covering could be to see the rod-covering interface under a scanning electron microscope.

8.5 Study of Surface Aging of Synthetic Polymer Insulator Materials by Measuring the Critical Surface Tension of Wetting (r_c)

Low surface energy polymeric materials are known to withstand higher voltage stress than high surface energy materials before significant leakage current develops[1] and are thus better suitable for use as cover materials for composite insulators in high voltage transmissions systems. The studies on surface aging of synthetic polymer insulators must, therefore, emphasize the importance of studying the surface energy of insulating materials before and after exposure to stresses of outdoor service conditions. These studies may prove to be vitally important in selecting efficient insulating materials for high voltage application.

Studies related to the measurement of surface energy of solid materials have sometimes reported contradictory findings.

Most modern studies on measurement of surface energy of solid materials measure the critical surface tension of wetting (r_c) to determine the value of surface energy of the material. In determining the value of r_c -- the critical surface tension of wetting,

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[1]See Bibliography No. 1-74, p. 151.

contact angle measurements are made on the solid material using a number of liquids of different surface tensions. The values of surface tension of a liquid and the cosine of the corresponding contact angle θ is then plotted on a cos θ versus surface tension plot as shown in Fig. 8.7. A straight line is then fitted through these points. The intersection of this straight line with the cos θ = 1 line gives the value of r_c -- the critical surface tension of wetting as shown in Fig. 8.7. The choice of liquids to be used to make contact angle measurements depends on the specific polymer under study and other considerations.

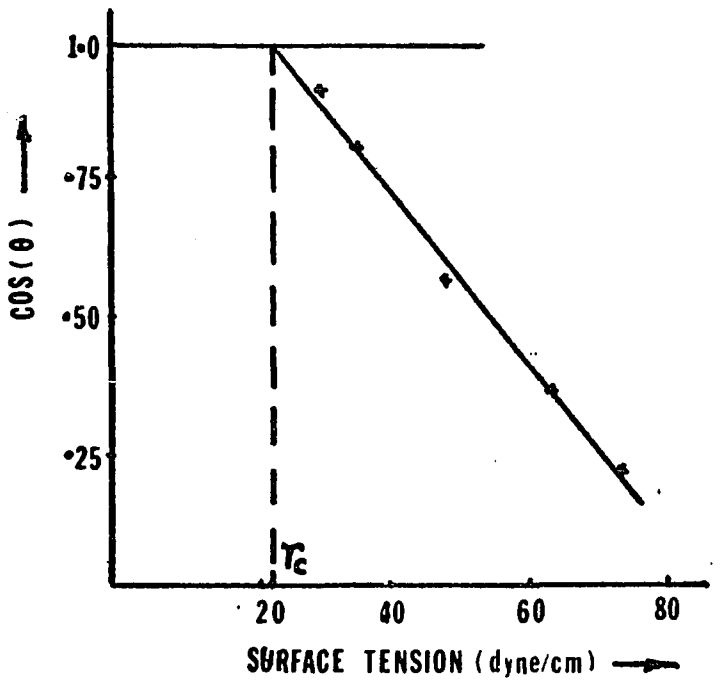

FIG. 8·7 PLOT OF γ_c vs. COS(θ) FOR DETERMINING CRITICAL SURFACE TENSION OF WETTING (γ_c)

APPENDIX A

SURFACE STUDY OF POLYMERIC INSULATING MATERIALS BY USE OF SCANNING ELECTRON MICROSCOPE

The degradation of synthetic insulating materials on exposure to ultraviolet radiation is expected to result in, besides other things, new functional chemical groups, change in heterogeneity and an increase in roughness of the surface. To observe these phenomena, the surface of some synthetic insulating materials were observed by looking at the scanning electron microscope pictures of the surface before and after aging due to ultraviolet radiation. The results obtained are shown in Fig. A.1 through Fig. A.8. The pictures clearly show that for the same time and intensity of ultraviolet radiation, the surface degradation of polyethylene and epoxy rod (from A. B. Chance Company) is more severe as compared to polytetrafluoroethylene. The results substantiate the results obtained in Chapter VI. The technique for preparation of polymer insulator specimens for examination in the scanning electron microscope along with specifications of the equipment used is given in Appendix B.

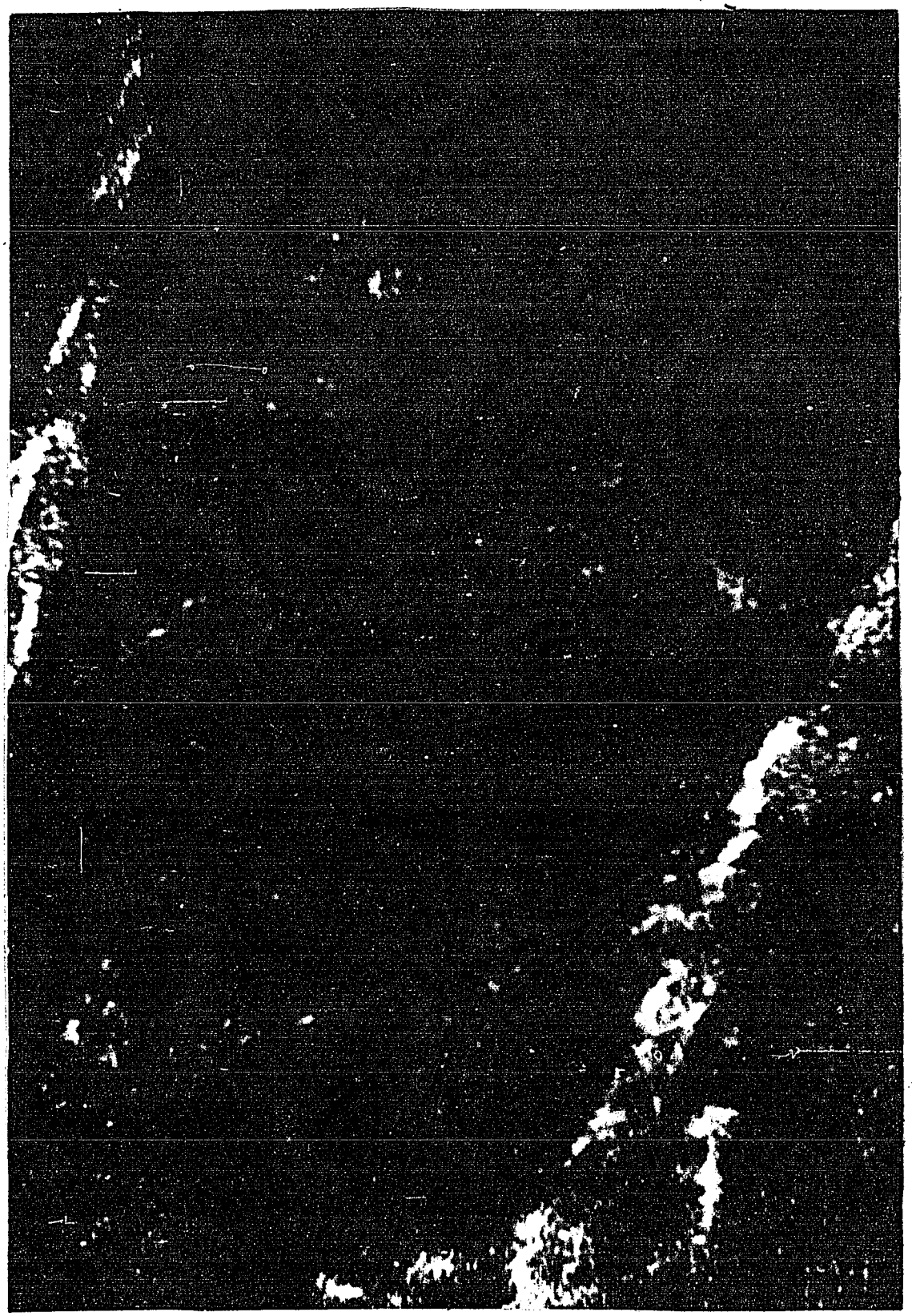

Fig. (A.1) Polytetrafluoroethylene (New) Magnification 4000X

Fig. (A.2) Polytetrafluoroethylene (Degraded) Magnification 4000X

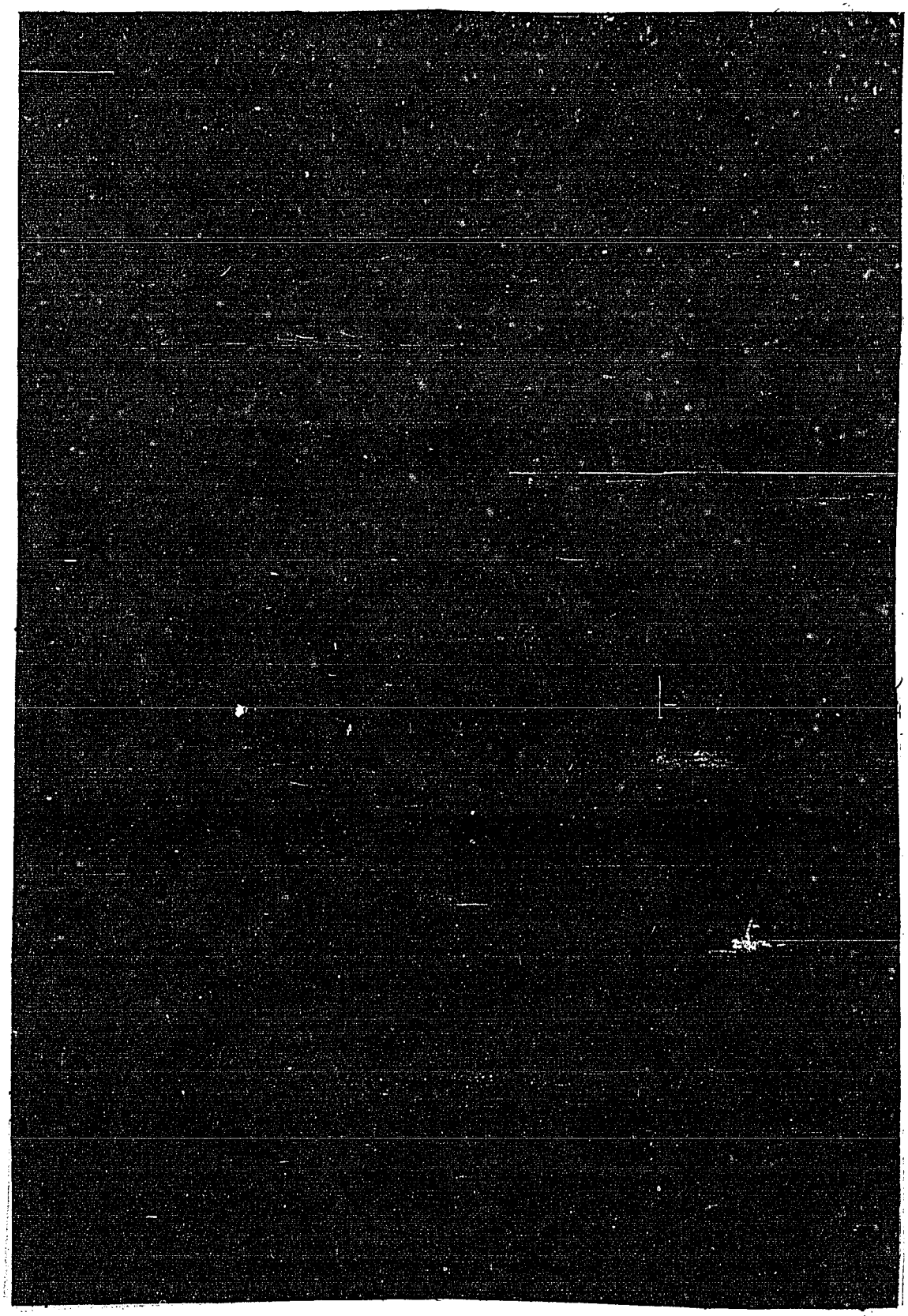

Fig. (A.3) Epoxy Rod (New) Magnification 4000X

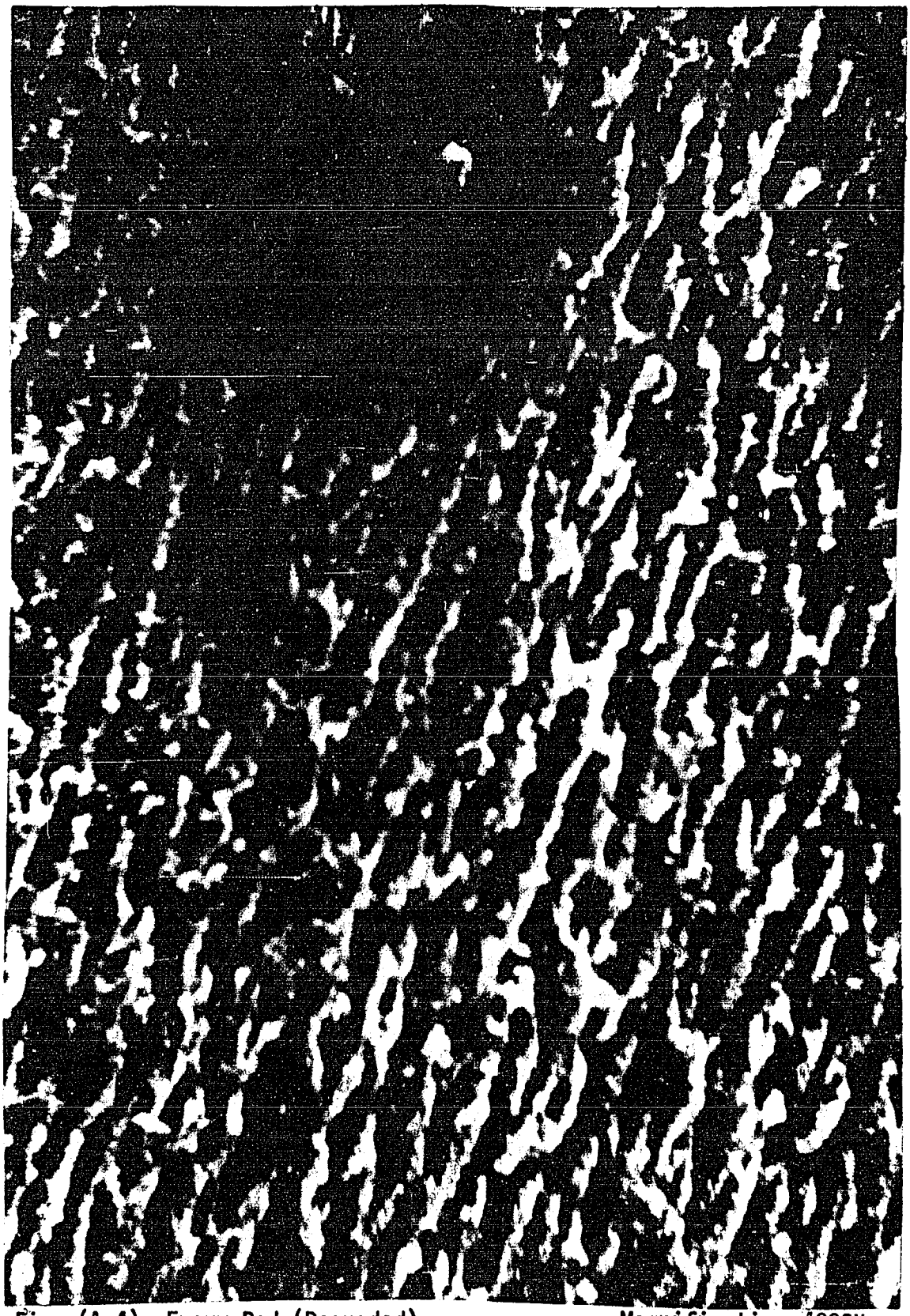

Fig. (A.4) Epoxy Rod (Degraded) Magnification 4000X

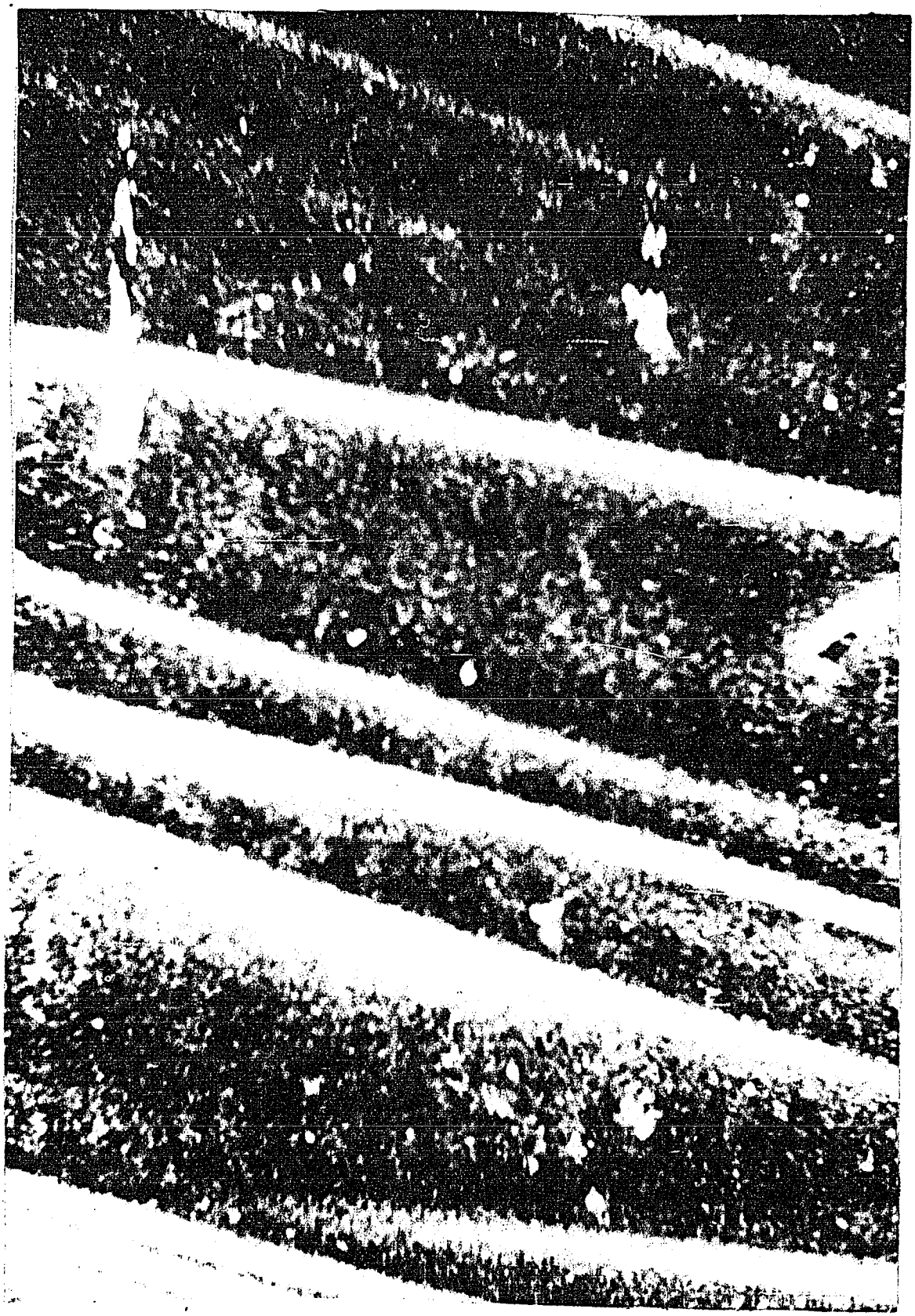

Fig. (A.5) Fiber-Glass Rod (New) Magnification 4000X

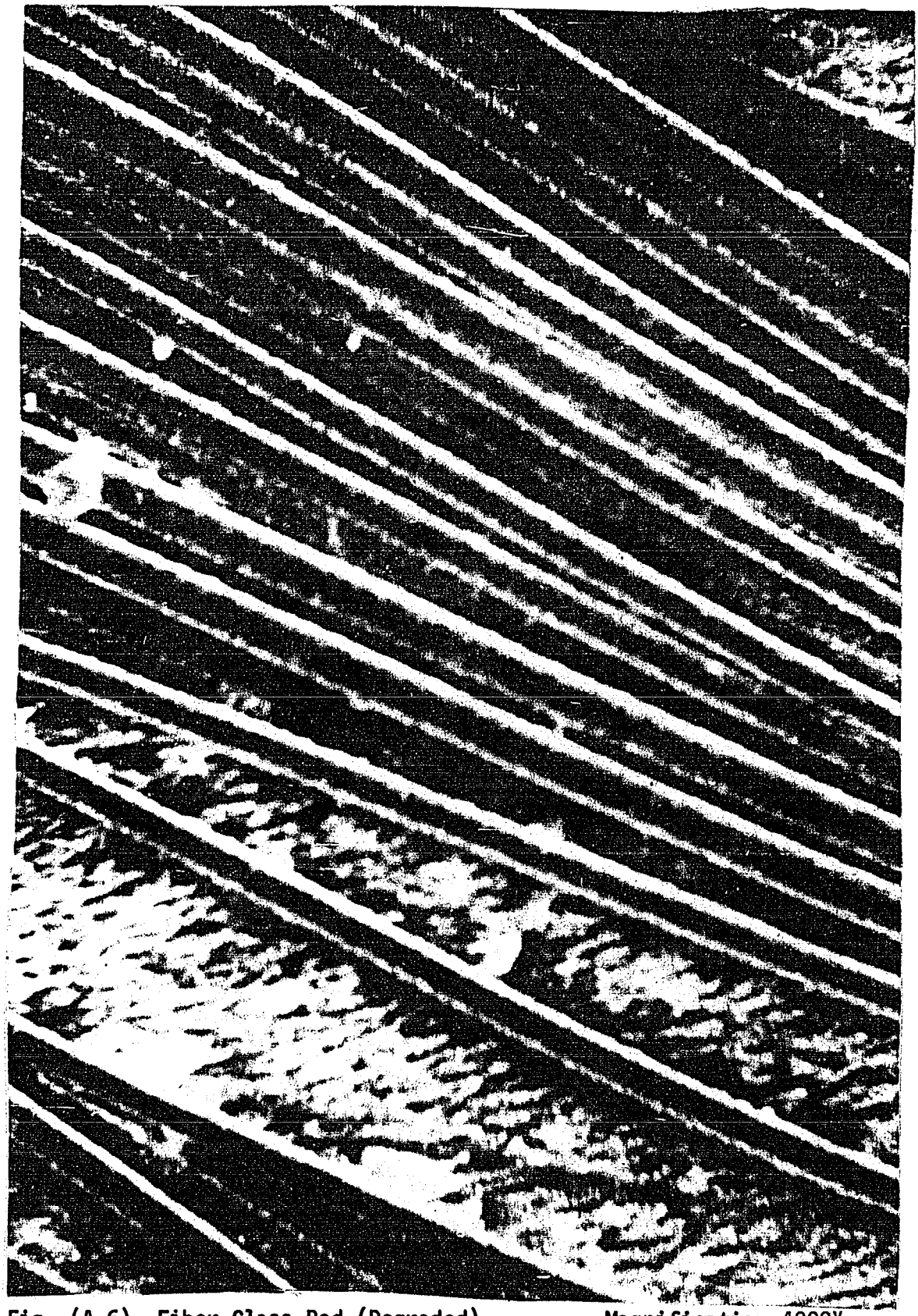

Fig. (A.6) Fiber-Glass Rod (Degraded) Magnification 4000X

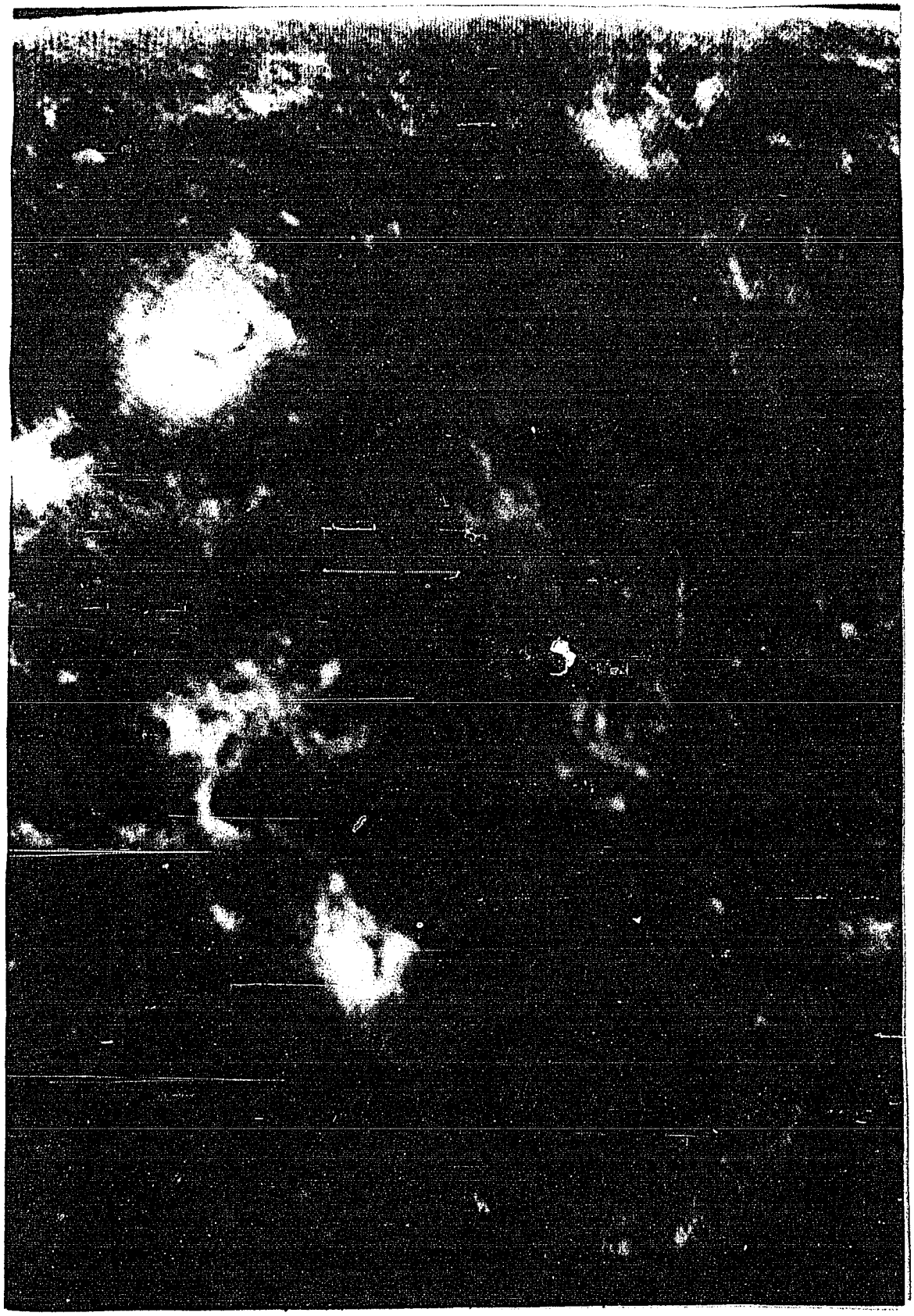

Fig. (A.7) Polyethylene (New) Magnification 4000X

Fig. (A.8) Polyethylene (Degraded) Magnification 4000X

APPENDIX B

SAMPLE PREPARATION FOR EXAMINATION OF SYNTHETIC INSULATORS IN THE SCANNING ELECTRON MICROSCOPE

Electrically non-conducting specimens such as synthetic insulators cannot be examined in a scanning electron microscope because even with the lowest value of beam current (10^{-11}A), excessive charging takes place. This results in a general loss of resolution and the appearance of structureless bright patches in the image. Such specimens can, however, be examined in a scanning electron microscope with a reasonable degree of success, either by prior evaporation of a thin metal film or by decreasing the accelerating potential of the incident electron beam.

To examine the insulator specimens in the scanning electron microscope specimens of the insulator surfaces about 1.27 cm wide and 0.25 cm thick were used. A layer of gold about 500 A^{o} size thick was evaporated on these specimens. These specimens were then mounted on cylindrical shaped specimen holders made of aluminum (2.5 cm diameter, 1.5 cm high). The contact between the specimen and the specimen holder was made using conducting silver paint.

The specifications of the metal evaporating equipment and the scanning electron microscope used are given below:

Scanning Electron Microscope

Model JSM

Resolution: Better than 500 A^{o} (in 25KV)

Magnification: 100 ∿ 30,000 continuously variable

Scanning Area: Maximum 1 mm^2 (in 25 KV) variable

Japan Electron Optic Lab., Co., Ltd.

Metal Evaporation System

MRC Series V-4 VE-10 Vacuum Evaporator

Materials Research Corp., Orangeburg, New York

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