"A STUDY OF THE ELECTRICAL INSULATION CHARACTERISTICS OF WOODS LOCALLY AVAILABLE IN KENYA"

BY

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This thesis is my original work and has not been presented for a degree in any other University.

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This thesis has been submitted [illegible] with my approval as University supervisor.

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LIST OF ABBREVIATIONNS

BLUEGUM (A)----Bluegum along its grains

BLUEGUM (C)----Bluagum across its grains

MERU OAK (A)---Meru Oak along its grains

MERU OAK (C)---Meru Oak across its grains

MAHOGANY (A)---Mahogany along its grains

MAHOGANY (C)---Mahogany across its grains

and so on.

SUMMARY

In this study, the electrical insulation characteristics of woods locally available in Kenya were investigated, with the aim of finding out whether any of the woods could be used for high voltage low frequency insulation purposes.

The thirteen woods studied were Bluegum, Meru Oak, Mahogany, Elgon Teak, Muhugu, Pine, Cypress, Cedar, Mvuli, Rosewood, Mukui, Podo and Camphor. In order to choose the most appropriate wood, dielectric strength and loss tangent measurements were first carried out for dry wood and wood impregnated with transformer oil (for 30 minutes, 1 hour, 3 hours and 5 hours). The first four woods, in terms of high dielectric strength and low dielectric loss tangent, were picked for further study using results from this initial study. In the further study the effect of a varnish coating on the dielectric strength and loss tangents were investigated. The treated wood that maintained a high dielectric strength was considered to be the most appropriate for application as an insulator. The shape of the wood for application at 11kV was optimized by calculating field values numerically, making plots of surface electric fields, and by practical measurement of the

flashover voltages and leakage currents of the insulator shapes. The effects of impregnating the wood with transformer oil and varnishing dry wood, on the flashover voltage and leakage current of the untreated dry wood insulator, were also investigated. Lastly, the effectiveness of the varnish coating in keeping moisture away from the insulator, under constant high humidity (96%) and temperature ($40^{o}C$), was investigated.

After a consideration of the dielectric strengths and loss tangents of the dry and impregnated woods, the first four woods starting with the best, in terms of the highest dielectric strength attained, were Muhugu, Elgon Teak, Podo and Cypress. After varnishing, Muhugu had the highest dielectric strength (235kV/cm across its grains). Muhugu is more expensive and difficult to machine. It chips off more easily and is less abundant than Elgon Teak which had the second highest dielectric strength (200kV/cm across its grains). So, Elgon Teak was considered to be more advantageous to use for insulating purposes. When a varnish coating was applied to the dry wood insulator, the leakage current decreased from 54μA to 51μA (dimensions of the insulator as in Table 7.6, shape (b)), while the flashover voltage decreased from 51kV to 49kV. Impregnating the insulator with transformer oil lowered the flashover voltage from 51kV to 49kV and increased the leakage current from 54μA to 60μA. The oil varnish coating of the insulator cracked after 2 months of exposure to high humidity and temperature, and moisture got into the wood.

In conclusion, it was observed that: All dry woods studied have a higher dielectric strength across the grains than along the grains. Effective impregnation of wood with transformer oil is only possible with thin specimens (a cross-section cut across the thick specimens showed that oil seeped to only a small depth from the surface of the insulator) and has the effect of increasing the dielectric strength of wood, and lowering its dielectric loss tangent. Correlation of surface electric field values and flashover voltages of different insulator profiles, shows that the higher the electric field along the surface of an insulator (for a given set of electrodes and applied voltage), the lower the flashover voltage of the insulator. With circular electrodes, the concave insulator was found to have the best shape in terms of highest flashover voltage, least volume leakage current and economy of insulator material. Oil varnishes are not effective in keeping out moisture from wood exposed to high temperatures and humidities for long periods. Elgon Teak is the most appropriate wood for high voltage low frequency insulation purposes.

Future work in this line should:

(a) Employ artificial seasoning which allows even thick wood to be dried without it developing any cracks.

(b) Use much higher voltages in the measurement of dielectric loss tangent.

(c) Investigate the mechanical properties of wood and the effect of mechanical loads on the electrical insulation properties of wood.

(d) Investigate the effects of electric and cyclic thermal loading on the longterm dielectric strength of wood.

(e) Investigate prediction of flashover voltages from surface field calculations.

(f) Study the effectiveness of silcone varnishes in keeping out moisture from wood.

(g) Investigate prediction of the flashover voltages of a given insulator shape from the values of surface electric fields calculated.

1.0 INTRODUCTION

The electrical and the electronics industry, use a great variety of dielectric and insulating materials. The electrical industry and the several industries which supply its dielectric needs have developed side by side, and they have interacted constantly over the years in the development of new and better materials. Sometimes the demand has come from the engineer, who has found existing materials inadequate to meet his/her new more stringent requirements; in most cases the challenge has been satisfactorily met and overcome. Often the initial impetus has come from the scientist, who has developed new materials with good dielectric, thermal, or mechanical properties, which have opened up new avenues for the electrical engineer. The latter has usually been quick to exploit these new developments, and to return after a short period with further more exacting demands. From this vast, continual interplay between the parallel technologies of electricity and materials, a wide range of modern dielectric materials has evolved.

Since a comprehensive knowledge of the characteristics of any material is essential for its correct utilization, research work on materials that would make good electrical insulators continues with various materials being tried out. One of these materials, wood (

specifically, beechwood), was studied in Czechoslovakia [1] and found:

(i) to be a good insulant for various purposes when well-dried,

(ii) to lose its insulating properties almost completely when exposed to high humidities,

(iii) to be unsuitable for insulation purposes, even in temperate climate, when unimpregnated. This resulted in its use being restricted to only subsidiary insulating parts which are under no considerable electric load.

(iv) not to have its electrical properties improved enough (after impregnation with paraffin wax, oils or resins) to make it a suitable material for component parts under greater electrical load. The impregnating agent was found to mostly close the capillaries at both ends, but not to penetrate deep enough [1]; thus they are largely left unfilled, and after prolonged exposure to moisture the electrical characteristics of impregnated wood do not differ from those of unimpregnated material.

(v) to be unsuited at high frequencies, as its loss factor considerably increases with moisture content.

(vi) to be better impregnated the lesser the thickness of the wood.

(vii) to have the electrical properties of its laminates negligibly affected by machining which tends to cause damage to the surface layer of paper laminates and so make them readily pick up moisture in humid media.

In the case of wood the acquisition of basic information is complicated by the fact that wood is a product of the metabolism of a living organism, a tree, and because of that its properties are subject to wide variations, brought about by the external factors affecting the growth of a tree. Furthermore, wood is a product of many species of trees, and hence each kind of wood exhibits its own physical and chemical characteristics. It is important, therefore, to keep in mind that in dealing with wood we are confronted not with one standard, man-made material, manufactured to exact and relatively easily reproducible specifications, but with a variable substance whose basic nature is by and large beyond man's control. Variability between different kinds of wood arising from differences in anatomical structure and associated physical properties is obvious enough to be accepted without question. However, much of the variability within species is more subtle and is not immediately evident. Obvious differences from tree to tree and within single trees may appear as fast or slow growth or as variations in weight between pieces of lumber. Variation within a species is a product of a complex system of interacting factors which modify the physiological processes involved in formation of wood. Measurement of any of the properties of wood will show that there is a range of values which will approximate the normal curve of statistical distribution, provided enough samples are measured [2].

It would then seem like it is possible to get among Kenyan trees, wood that exhibits good electrical insulation properties useful for low frequency high-voltage insulation. Given the possible existence in abundance locally of this kind of wood, such a finding could have very good economic implications if local manufacture of insulation from it is a viable undertaking because it would result in:

(i) better use of our forests and,

(ii) creation of employment.

It is in this light that a study of the electrical insulation characteristics of locally available woods becomes desirable. This study will be started by first choosing woods for study in such a manner that they are representative of the various kinds of woods available within Kenya. After this, both the treated and untreated samples of these woods will be tested for their dielectric strength and loss tangents in an attempt to single out the best type of wood. Areas in which this wood could be used will then be identified and the appropriate insulator shape designed.

2.0 WOOD

2.1 INTRODUCTION

Wood is the vascular tissue of trees. Chemically,wood consists of 70% cellulose, 25% lignin and about 5% extractive [3]. The strength of wood may be entirely attributed to the cellulose and lining content while the extractive contribute to such properties as colour, odour, taste and resistance to decay.

The exact characteristics of a wood specimen is dependent on the part of the tree from which it is obtained. A tree is a woody plant that attains a height of at least 6 metres at maturity in a given locality and usually (not always) has but a single self-supporting stem or trunk [2]. The main parts of a tree are:

(i) BARK - The bark serves to protect the inner tissues from injury. It is the tissues in the cylindrical axis of a tree outside of the cambium and is composed of inner living bark and outer dead brown bark.

(ii) WOODY STEM - This consists of an outer sapwood and an inner heartwood usually distinguishable by colour. The outer (sapwood) part is made up of living cells (lighter coloured). The darker (inner) parts are made up of dead cells. It serves the purpose of giving mechanical support to the tree. The heartwood consists of gums, oils and other organic extractives. The heartwoods are usually more durable than the sapwoods. The sapwoods is more easily treated with preservatives since it is more permeable to liquids.

(iii)JUVENILE WOOD - Wood near the centre of the tree characterized by fast growth.

(iv) CAMBIUM - The tree grows by multiplication of cells in a unicellular region called an annual ring. The trees from the temperate zone have well defined annual rings while some trees growing near the equator do not even have annual rings.

2.2 CLASSIFICATION OF WOODS

2.2.1 HARDWOODS

Hardwoods, also known as dicotyledons, are much more complex in structure than softwoods because more cell types (elements) enter their composition. The timber is also generally very hard to work with. They differ from softwoods in possessing vessel elements (also called vessel members and vessel segments), which when viewed in the transverse section are called pores, hence the name porous woods. They are produced by angiosperm trees which have broad leaves e.g.oaks, ash and maple. Among the country's well known indigenous hardwoods are East African Camphor wood, Mahogany, Mvule, Elgon Olive (Teak), Cedar, Meru Oak and Muhuhu. The last is used for wood carvings and flooring-blocks [4].

2.2.2 SOFTWOODS

The conifers or softwoods are very easy to work with, but they are not as durable or reliable as the hardwoods. They are produced by gymnosperm trees and are characterized by exposed seeds that are mainly contained in cones. The trees have pines instead of leaves. They are said to be non-porous in the sense that they do not contain vessels. These are tubular intercellular spaces surrounded by secreting cells called epithelium. Resin canals extend both longitudinally and transversely though they are more conspicuous longitudinally. They appear as small openings or white spots in the transverse section especially in pines. They provide a diagnostic feature for identification of coniferous woods. Examples of softwoods are pines, spruces, firs, hemlocks and cedars [2]. In Kenya, podo and pencil cedar are the only indigenous softwoods. Cypress and pine have been established because podo is limited. The timber of cypress and pine is also more suitable for many of the purposes for which podo is used at present. On the other hand, there are certain purposes for which podo is more suitable and cypress and pine are unsuitable. One of these uses is for dairy produce boxes (especially for butter). So podo must be preserved for these special uses and cypress and pine be used for ordinary articles [4].

2.3 PHYSICAL PROPERTIES OF VALUE IN IDENTIFICATION OF WOOD

2.3.1 COLOUR

Colour in wood is due mainly to extractives. The major cell wall components, with the possible exception of cellulose, may also contribute to the colour of exposed wood surface through oxidation. Wood colour varies not only among different kinds of woods but also within a species and often even in the same piece of wood. When the colour of wood is used for the purpose of identification it refers to that of the heartwood. The colour of sapwood is seldom distinctive and hence of little or no value in identifying a given kind of wood.

However, since in the majority of woods the colour of heartwood is of a wide range of shades of brown, or grayish or reddish-brown, precise description of the wood colour is seldom possible. Therefore, in wood identification, colour description must be supplemented with other, usually structural (anatomical) criteria [2].

2.3.2 LUSTRE

This is the property of wood that enables it to reflect light (the property of exhibiting sheen). The lustre of wood depends on the angle at which light strikes the surface and the type of cells exposed on that surface. A more important cause of the presence or absence of lustre is the nature of the heartwood infiltrations. The lustre of wood is useful in the identification of wood only as a secondary feature [2].

2.3.3 ODOUR AND TASTE

Odour in wood comes from infiltration products in the heartwood or the action of fungi, bacteria, or moulds. In the later case both the sapwood and heartwood may have odour, and because of the starch deposits the odour may be stronger in the sapwood.

Only the odours due to the presence of scented infiltration materials in the wood are of assistance in wood identification,and since these are found primarily in the heartwood, only the heartwood-containing portion of the piece should be used to determine whether a distinctive odour is present.

Many woods have taste,generally bitterish, which is rarely distinctive enough to be used for identification. Incense cedar has a characteristic taste strong enough to facilitate its identification [2].

2.3.4 GRAIN AND TEXTURE

Texture refers to the size and proportional amounts of wood cells in a given piece of wood. Thus there is fine texture or coarse texture. The term grain is applicable to the direction of wood cells in relation to the longitudinal axis of the tree e.g. straight, spiral and locked grain [2].

2.3.5 WEIGHT

The weight of a piece of wood depends on

(i) The specific gravity of the wood i.e. the amount of wood substance present per unit volume.

(ii) The amount of infiltration in the heartwood.

(iii)Its moisture content.

For practical purposes only the (i) and (ii) components of the wood weight need to be considered [2].

2.3.6 HARDNESS

The relative hardness depends on the amount of cell wall present. The actual hardness is difficult to determine but relative hardness may be determined using a knife edge or thumb nail [2].

2.3.7 FIGURE IN WOOD

Figure refers to any distinctive markings on the wood though commercially figure refers to the highly decorative patterns resulting mainly from the appearance of growth increments, irregularities in the orientation of cells and uneven colour distribution [2].

2.4 WOOD IDENTIFICATION BY CHEMICAL MEANS

The chemical differences of timber are due to the kind and amount of extractives. Identification depends on detection of a substance specific to a given wood. The methods used include colour change of reagent,chromatography and quantitative analysis. The methods are often too involving for routine identification of wood species [2].

2.5 THE PHYSICAL NATURE OF WOOD

2.5.1 INTRODUCTION

The physical properties of wood are determined by the factors inherent in its structural organization. These are:

(i) The amount of cell wall substance present in a given volume of wood. This is measured by the specific gravity of the wood and gives the most useful index to the predicted physical behaviour of wood.

(ii) The amount of water present in the cell wall.this deeply affects the total physical behaviour of wood, not only because the addition of water to the cell wall changes its density and dimensions but because of its effect on plasticity and transfer of energy within a piece of wood.

(iii)The proportionate composition of the primary components of the cell wall and the quantity as well as the nature of the extraneous substances present. This is related to many of the special properties of certain kinds of wood as well as to the deviations from expected quantitative behaviour.

(iv) The arrangement and orientation of the wall materials in the cells and in the different tissues.

(v) The kind, size, proportions, and arrangement of the cells making up the woody tissue.

Factors (iv) and (v) are the cause for the large differences which are found in the physical responses of wood with respect to the grain direction [2].

2.5.2 MOISTURE CONTENT OF WOOD

Wood is an hygroscopic substance. The ability of wood to absorb or to lose water is dependent on the temperature and the humidity of the surrounding atmosphere. Therefore, the amount of moisture in wood fluctuates with changes in the atmospheric conditions around it.

The heavier the wood (that is, the higher its specific gravity) the lower its maximum moisture content. The moisture content varies from species to species and even in different parts of the same tree. Thus one should not expect the same moisture content for all the pieces tested. Moisture travels about fifteen times faster along grains than across them [2].

2.5.3 DIMENSIONAL CHANGES IN WOOD

Addition of water or other polar liquids to the cell wall substance causes the microfibrillar net to expand in proportion to the amount of liquid which has been added. This continues until the fiber saturation point has been reached. Further addition of water to the wood causes no change in the volume of the wall. Conversely, the removal of moisture from the cell wall below the fiber saturation point causes the wall to shrink. In general, shrinking and swelling in wood increase with increasing specific gravity [2]. This is true both between pieces of wood of different kinds and within single pieces in which there are local differences in specific gravity, such as those between early-wood and late-wood in the hard pines.

The observed dimensional changes in wood are unequal along the three structural directions; that is wood exhibits anisotropy. Shrinkage from the green to the ovendry condition amount to 0.1 to 0.3 percent in the longitudinal direction. In the radial direction it is about twice as great as in the radial direction [2].

2.5.4 THERMAL PROPERTIES OF WOOD

2.5.4.1 THERMAL EXPANSION OF WOOD

The coefficient of thermal expansion for the longitudinal direction (α_l) in the temperature range from -50 to +50 ^oC averages 3.39 x 10^{-6} per degree Celsius, regardless of the kind of wood and its specific gravity. In the transverse direction the expansion is about 10 times that in the longitudinal direction. For an average specific gravity of 0.46, the coefficient of radial expansion (α_r)is 25.7 x 10^{-6} per degree Celsius, while that for tangential expansion(α_t) is 34.8 x 10^{-6} per degree Celsius. α_r and α_t vary directly in a straight-line relationship to the specific gravity of the wood (direct proportionality) [2]. α_l in wood is small in comparison with that of other common solid materials. When wood is used within a narrow range of temperatures, the thermal dimensional change is often masked by dimensional changes caused by moisture fluctuations as the two effects act in an opposite sense [2].

2.5.4.2 IGNITION OF WOOD

If the supply of oxygen is unlimited, the ignition of wood begins when the temperature of the wood is approximately 273 ^oC [2].

The speed with which combustion is initiated is dependent upon the rate of accumulation of heat at the surface of the wood. Factors influencing this rate are:

(i) the size of the piece of wood

(ii) the rate of heat loss from the surface to the interior

(iii)the presence of thin outstanding edges

(iv) the rate at which heat is supplied to the surface of the wood.

Small pieces with sharp projecting edges, such as square-splint match sticks, ignite easily because a relatively small quantity of heat is necessary to raise the temperature of the whole stick, and especially the thin edges, to the ignition point. Large pieces, with rounded edges, are much slower to to catch fire because the conduction of heat to the interior of the piece keeps the surface below ignition temperature for some time. Combustion in a given piece can occur rapidly when large quantities of heat are supplied to the surfaces. However, ignition can occur also if much smaller amounts of heat are supplied to the wood over a long period of time, since the entire piece will eventually be raised to the ignition temperature.

2.5.5 ELECTRICAL PROPERTIES OF WOOD

2.5.5.1 DIRECT CURRENT(D.C) ELECTRICAL PROPERTIES OF WOOD

Dry wood is an excellent electrical insulator with d.c. resistivity of the order of $3 * 10^{17}$ to $3 * 10^{18}$ ohm-centimeters at room temperature. Moisture affects the resistivity of wood. The resistivity decreases by an approximate factor of 3 for every percentage increase in moisture content upto the fiber saturation point. At the fiber saturation point the resistivity becomes approximately that of water alone i.e. 10^{5} Ωcm [2].

Temperature also affects the conductivity of wood. The structural orientation in wood modifies d.c. resistivity independent of moisture content. The resistivity across the grains is from 2.3 to 4.5 times greater than along the grains for conifers and from 2.5 to 8.0 times greater for hardwoods [2].

Electrical conduction in wood is thought to occur primarily through migration of metallic ions held in wood as impurities. A d.c moisture meter has to be calibrated for a particular type of wood and temperature [2]. Voids lower the dielectric strength of wood.

2.5.5.2 ALTERNATING-CURRENT (A.C.) PROPERTIES OF WOOD

One measure of the insulating capacity of a material under alternating current is its dielectric constant (ε).

ε = J C R / E, where J = the current density

C = capacitance of the dielectric

R = resistance of the dielectric

E = electric field in the dielectric

This is the ratio of the charge held by a condenser in which the electrodes are separated by a dielectric material such as wood, to the charge held by the condenser with the electrodes separated by a vacuum at a given voltage. The dielectric constant of wood varies directly with specific gravity and moisture content, and decreases in a complex manner with increasing frequency of the alternating current. The dielectric constant of dry wood is from 30 to 50 times greater in the longitudinal direction than it is in the transverse direction [2].

Dry wood is a nonconductor with a dielectric constant of about 2. The dielectric constant increases with increasing moisture content. Above the fiber saturation point, the dielectric constant of fully saturated wood approaches that of water,which has a value of 81 [2].

2.5.6 MECHANICAL PROPERTIES OF WOOD

In most cases insulators are also required to bear mechanical loads. It is thus necessary to understand the mechanical properties of wood in order to effectively use wood for insulation purposes.

Wood with higher specific gravity has greater mechanical strength. Wood has a high index of rigidity in comparison with other solid structural materials and is well suited for applications that require elastic stability such as long beams and columns or stressed skin constructions. Wood however lacks high shear and compression resistance because the very distribution of wood that increased rigidity in bending reduces the shear and compression efficiency.

The polymer form of cellulose in the cell walls of wood and its microfibrillar aggregation gives wood high fatigue resistance i.e. wood can stand short duration cyclic loads for long periods of time [2].

3.0 IDENTIFICATION AND SELECTION OF WOOD FOR THE STUDY

3.1 IDENTIFICATION AND SELECTION PROCEDURE

The identification was on the basis of characteristics such as, colour, smell, texture, luster.etc. In cases of doubt experienced wood dealers at Timsales (Industrial Area, Nairobi) were consulted.

Woods that were not obtainable within the city but were suspected (because of their dense nature) to have good electrical insulating properties were obtained at an extra cost, e.g Muhugu had to obtained from Kitui at an extra cost.

The chosen species had to be representative of the softwood and hardwood categories of wood. This ensured that the study was broadbased so that its results are reliable.

After a consideration of all these factors, thirteen wood species were chosen for the study. This consisted of eight hardwoods and five softwoods.

The soft woods were: Bluegum, Pine, Cypress, Mukui and Podo.

The hardwoods were: Meru Oak, Mahogany, Elgon Teak, Muhugu, Cedar, Mvuli, Rosewood and Camphor.

Slightly more hardwoods than softwoods were chosen for the study because hardwoods were expected to have good electrical properties by virtue of their denser nature [2].

3.2 SELECTED WOODS

3.2.1 SOFTWOODS

3.2.1.1 PODO

Also called East African Yellow-Wood.Kenya has three types of Podo: *Podocarpus gracilior*, *Podocarpus milanjianus*, and *Podocarpus usambarensis*. In this study Podocarpus milanjianus, which has a pale to dark brown bark which is also smooth and fibrous, peeling in long narrow strips, was used. It was the type available at the wood dealer's shop. It is generally available in wetter and higher highland forests in Ukambani Hills, West Mt.Kenya and eastern Mt.Elgon. The timber is whitish or slightly brown. It is odourless, straight grained, fine and even in texture. It is also a wood which works without difficulties, easily painted and polished. It is liable to split when nailed at the ends, perishable and easily impregnated as it is a light wood. Podo is used for standard building and joinery in Kenya. It is used for shop counters, panel framing, display cabinets, furniture, doors and frames, bakery boards and fruit and foodstuff boxes among other purposes. Podo is an important source of plywood. Due to its resistance to acids the timber may also serve as a battery separator [4].

3.2.1.2 CYPRESS

The scientific name for cypress is *Cypressus Lusitanica*. It is also called East African Cypress or Mexican Cypress. It was introduced to Kenya in 1908 from Mexico.

When freshly cut, cypress wood has a pale pinkish cream colour which darkens on exposure to a pale brown colour. It has a fine and even texture and is light in weight. It seasons well and quickly without splitting and takes nails well though it is not durable in the ground. It does not decay in dry conditions. Boats and boxes are often made of cypress. It is the most important commercial tree in Kenya though it has suffered a major threat from aphids since late 1990 [4].

3.2.1.3 PINE

Kenya has three species of this tree. These are: *Pinus radiata*, *Pinus patula* and *Pinus caribaea*. The one used in this study is *Pinus radiata*. It was the most common of the three varieties of pine available at the wood dealer's timber shop. This species originally came from California and many large plantations have now been established in Kenya. This is a huge tree of nearly 50m in height and a girth of half a metre. The timber varies from white to light brown in colour. It is white when freshly cut but it discolours if left lying around or exposed to light and turns to light brown. The grain is straight and the texture fine and uniform. The wood is brittle and difficult to stain but it takes nails well and it can be painted or varnished successfully. It is used for shelving, ceilings, roofings, joinery plywood and utility furniture [4].

3.2.1.4 GUM OR EUCALYPTUS

Kenya has two varieties of this tree. These are the Australian Ash and the Grevillea. The one that was available at the wood dealer's shop was the Australian Ash and so it was the one used in the study. In height the tree is at least 37m. It grows fairly quickly and can reach full size in 20 - 25 years. It grows best above 1,524m and is widely distributed in Kenya. The timber is pink, hard, heavy and it warps and splits with ease. It withstands termites well so it is used for poles, especially for transmitting electricity. It is also used for rough joinery, building construction, simple furniture, lorry and brick decking and for handles. To a great extent it is used for fuel too [4].

3.2.1.5 MUKUI

Its local name is Mukui (Kikuyu and Meru) while its scientific name is *Newtonia buchanani*. It is a very large flat-topped deciduous forest tree that grows to a height of 45m or more. Branches widespreading, storeyed. Its bark is smooth and grey. It has a sharp-edged plank buttresses that is strongly developed, extending 3-4.5m.up the stem and as much outward. Its sapwood is white to pale grey-brown; the heartwood is brown or red-brown, moderately hard and heavy, easy to saw, bends readily, taking nails well, polishes highly when filled, but is not recommended for moulding or turning, is perishable in the ground and durable in water. Boards must be carefully piled to avoid warping; density about 545kg per cu.metre. airdry. The timber has been used for cabinet work, wagon-building, bridge piling and, in Tanzania for sleepers (for which purpose it is said to be very suitable). The wood is widely used in the Lake Victoria region in the construction of sewn (Sesse) canoes.

In Kenya it is found in Central Province; it is often riparian but a forest tree on the eastern slopes of Mt.Kenya; also a common constituent of mist forest on hill tops in Ukambani and Teita districts [5].

3.2.2 HARDWOODS

3.2.2.1 MVULI

Its scientific name is *Chlorophora Excelsa*. The tree is prevalent around the coast, Meru and the Lake Victoria region. The timber is yellow or brown when freshly cut and it darkens with age. It has a coarse texture producing a conspicuous grain which gives a handsome appearance of deep brown, characteristic of the wood. Other qualities of the wood are its resistance to fungi, fire and termites. It is resistant to impact and is in great demand countrywide for panelling, furniture and cabinetwork due to its high density [4].

3.2.2.2 CAMPHOR

Its scientific name is *Ocotea Usambarensis*. Its local names include Muthaiti (Kikuyu) and Muura (Meru). It is normally found in the South Mt.Kenya forests, the Aberdares and the Taita Hills. The timber is yellow or golden brown when freshly sawn and turns deep brown on aging. The grain is the marked ribbon type and the wood is of medium texture. It is a light to medium weight wood. Camphor wood is very strong and resistant to fungi and acid attack. It is, however, susceptible to termites. East African Camphor is used for paneling, furniture, railway coaches and lorry bodies [4].

3.2.2.3 AFRICAN PENCIL CEDAR

Locally, this tree is known as Cedar, Ndarakwa (Kamba) and Mutarakwa (Kikuyu). Its scientific name is *Juniperus procera*. It is an evergreen timber tree which attains a height of 40m. Cedar is well distributed in the drier highland forests like the lower slopes of Mt.Kenya.

The sapwood is white while the heartwood is red. It becomes reddish-brown after seasoning. It has a very characteristic and distinctive smell. It is a straight grained timber with growth zones which are not very plainly marked. The wood is of light to medium weight. The heartwood is very resistant to termites and is very durable wood in the ground.

Unfortunately it cracks easily and tends to be brittle at the edges. It splits when nailed, making its application for furniture rather limited. It is exported to India and Europe for pencil manufacture and used locally for building poles, flooring and telegraph poles [4].

3.2.2.4 MERU OAK

Its scientific name is *Vitex Kiensis*. Its local name is Muhuru (Kikuyu). It is common in the East Mt.Kenya forests. The wood is pale-brown, coarse textured and with well marked growth zones. It is not difficult to season and it works and nails easily. These properties together with its attractive dark coloured heartwood make it popular for furniture [4].

3.2.2.5 ELGON OLIVE (TEAK)

Its local names are Ol-loliondo (Maasai), Murguiwet (Nandi) and Musharigi (Kikuyu). Its scientific name is *Olea welwitschii* or *Steganthus welwitschii*. It is a large tree up to 30m in height. The bark is greyish, fairly rough and channeled vertically. Elgon Olive has white flowers which the tree produces numerously. Mainly the tree is available in the rain forest areas such as at Elgon, Kakamega and Kaimosi which have a fairly high altitude, 2,286 - 2,591m. Additionally the tree is prevalent in parts of the Lake Victoria Basin and East Mt.Kenya between 1,524 and 1,829m. The sapwood of the tree is usually white-yellow whereas the heartwood is brownish with dark brown streaks. The timber has straight or interlocked grain and has an even texture, it is moderately, hard, very strong and stiff and it is fairly durable in the ground and in damp places. It resists termites, is hard to saw or plane due to its hardness and is fairly easy to work. It is suitable for furniture as it polishes well despite its tendency to split with nailing. The timber is used for supports in such construction as bridge building and mining. It is also very popular for furniture, flooring and general joinery in Kenya [4].

3.2.2.6 MUHUGU

Its local names are Muhuhu (Swahili), Mvumo (Digo), Mubuubu (Kamba) and Muhugu (Kikuyu). Its scientific *Brachylaena hutchinsii*. Its a dioecious tree that grows to a height of 24m and a diameter of 0.6m. It has a fluted and often curved bole, making large dimension timber difficult to obtain. The bark is grey, smooth or rough, with longitudinal cracks. The timber is pale yellow to pale brown with characteristic storeyed structure and scented somewhat like sandalwood, straight-grained with conspicuous growth rings and very fine and even texture, strong and stiff, but failure in bending is sudden and complete. Hard but works and turns well with sharp tools, takes a high polish. Splits easily along the grain. Extremely durable in the ground and sea water: weight 960 - 993kg per cu.metre. air dry.

It is found in the Coast and Central Provinces. It occurs on red soils with moderate rainfall in the Coast Province and also in the mixed forest remnants from 1,500 - 1,800m. from Ngong to Nyeri. Occurs as a shrub on rocky hills in Nyanza Province.

The timber is of high value for all purposes where durability is essential. Its usefulness is limited by its weight, and the small sizes available. It makes an excellent floor block. As a firewood it has been used as a sandalwood substitute in cremations. Oil from the wood has a pleasant vetiver-like scent [5].

3.2.2.7 ROSEWOOD

Its local names are Muhonde, Murizika, Muinyeri, Mungagondu, Mumondo, Kamonde (Kikuyu); Mujogajoga (Meru); Njororuet (Nandi) and Omokunakuna (Kisii). Its scientific name is *Hagenia abyssinica* or *Brayera anthelmintica*. The tree grows to a height of 15 metres mountain forest. Its crown is rounded or umbrella-shaped. Bark red-brown, flaking raggedly. Its branchlets are densely villous with golden hairs, ringed by the scars of the sheathing leaf-bases, the rings at first hirsute with long-ascending hairs. The wood is dark red to red-brown, medium-soft, straight-grained with some silver grain when cut on the quarter, not durable and subject to attack by borer, of handsome appearance, used for furniture, cabinet-making, flooring; weight 593 - 641kg per cu.metre. air dry. It is common in high altitude forest from 2,700m.; one of the last trees in the heath zone. In wetter areas it may occur at lower altitudes and has been tried as a fire break round softwood plantations [5].

3.2.2.8 MAHOGANY

Its trade name is Mukusu while its scientific name is *Entandrophragma angolense*. Its a deciduous tree that grows to a height of 48 metres, with a clean bore to 24 metres. Its branches are usually few, frequently steeply-ascending. Its bark is smooth, pale grey-brown with pinkish or rusty orange patches, scaling in large or small irregular flakes which leave concave scars. Its sapwood is pale pink; the heartwood has a wide colour-range, varying from the normal dull uniform dark red or purple-brown to a pale pink very similar to the sapwood. In dark-coloured wood the cells are heavily infiltrated with gum; in light-coloured wood the gum is almost entirely lacking. The darker wood is appreciably denser, and has rather better working qualities and takes longer to season than the light-coloured wood, which is woolly and more difficult to saw. In both types the grain is broadly interlocked and produces a rather wide and often irregular stripe on the quarter-cut surface. The timber seasons slowly in air with a marked tendency to warp, and some splitting and checking must be expected; kiln-seasoning is also slow. The wood weighs 5132kg per cu.metre air dry, which is almost the same as Honduras Mahogany, but it is 10 - 20 per cent harder than that species. It is found in Kakamega forest at an altitude of 1,650m [5].

4.0 IMPORTANT ELECTRICAL PROPERTIES OF INSULATORS FOR HIGH-VOLTAGE LOW FREQUENCY APPLICATIONS

4.1 BREAKDOWN STRENGTH

Puncture strength is the electric field which causes breakdown through an insulator placed between two electrodes across which a voltage is applied. The breakdown depends primarily on the local electric stresses in the dielectric, and it is hence influenced by the shape, and to some extent by the nature and condition, of the electrodes [6].

In general the measured dielectric strength decreases with increase in the specimen thickness, and with increase in the period of application of the voltage stress [7]. The thinner a specimen is, the less voids and structural flaws it contains. Voids and flaws encourage breakdown through secondary processes such as streamers which tend to occur at field strengths lower than the intrinsic strength of the material. This explains the higher dielectric strength exhibited by thinner specimens.

4.1.1 BREAKDOWN MECHANISMS IN SOLIDS

4.1.1.1 INTRODUCTION

There are a number of possible mechanisms by means of which breakdown through an insulator can occur. Any breakdown which occurs is as a result of all or some of these possible mechanisms having taken place. The mechanisms are time dependent:

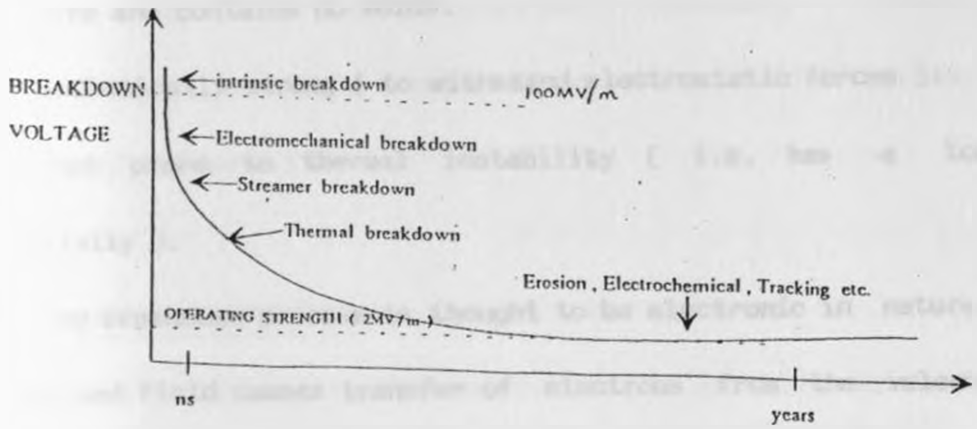


FIGURE 4.1: Time to breakdown characteristic of a solid insulating material [8].

That is, they vary from nanoseconds(ns) to years (Figure 4.1). The practical operating stress(2MV/m) of solids is much lower than the maximum possible stress(100MV/m) [8]. The various mechanisms are considered below:

4.1.1.2 INTRINSIC BREAKDOWN

The intrinsic breakdown voltage is the highest voltage a material can withstand in the absence of secondary processes such as streamers, electromechanical forces and thermal instability.

That is, it is a breakdown dependent solely on the behaviour of electrons in a lattice of the material. It can occur if the material is:

(i) pure and contains no voids.

(ii) mechanically strong (to withstand electrostatic forces).

(iii) not prone to thermal instability (i.e. has a low conductivity).

The breakdown process is thought to be electronic in nature. The applied field causes transfer of electrons from the valence band to the conduction band across the forbidden gap. The electrons get energy from the field but also lose energy through collisions in the lattice. If the net gain is positive, instability is likely to occur resulting in the breakdown of the insulation. The intrinsic strength increases with increased temperature due to the increased mobility of the charge carriers [8].

4.1.1.3 ELECTROMECHANICAL BREAKDOWN

This is a mechanical failure of insulation as a result of electrostatic forces. When an electric field is applied to a material between two electrodes, mechanical forces of attraction are developed between opposing charges. At increased voltage the thickness of the material is reduced which then results in an intensification of the electric field. This results in stronger forces of compression being developed. Above a certain critical voltage, failure of the material eventually results. Electromechanical breakdown takes place at very high stresses approaching intrinsic [9].

4.1.1.4 STREAMER BREAKDOWN

This is a breakdown occurring externally to the region in contact with the electrode surfaces. It is caused by the breakdown of the ambient before the solid material. Once the ambient breaks down, a streamer which has a high electric stress at its tip (high concentration of charge) advances towards the solid surface. The situation is then similar to a point-plane electrode system. The high fields can cause electron conduction in the solid which leads to the growth of conduction tracks in the material and its eventual failure [9].

4.1.1.5 THERMAL BREAKDOWN

Dielectric loses (resulting from dipolar relaxation and ionic conduction) in insulating materials generate heat in them.

The dielectric burns out if the rate of production is greater than the rate of cooling as the internal temperatures rise to the unstable level. For each material there is a maximum voltage that can be applied beyond which thermal instability occurs. Therefore, increasing the thickness of insulation does not indefinitely increase its withstand voltage because a limiting voltage for thermal breakdown is reached. Although a thicker insulation decreases the electric stress, it also reduces the rate of cooling from the central region of the material [9].

4.1.1.6 TRACKING

This is the formation of conduction paths across the surface of a solid material. It is caused by the presence of a conducting film on the surface of the material. A high current flows through the conducting film, heating the surface of the insulator leading to the formation of carbon tracks. This process leads to surface flashover of the material [9].

4.1.1.7 EROSION BREAKDOWN

This type of breakdown occurs when the solid insulating material has voids or cavities trapped within it. Internal discharges occur in these voids or cavities as these voids contain materials (gaseous or liquid) of lower permittivity than the surrounding material and hence of lower breakdown voltage. The discharge activity in the cavities gradually causes the cavity enlargement and eventual failure of the insulating material. Cavity enlargement or erosion results from:

(i) gases like ozone (O_3) or nitrogen dioxide (NO_2) which when produced in the cavities reacts with the solid material.

e.g. NO_2 + water $\longrightarrow$ nitric acid - very corrosive

(ii)ionic impingement of cavity walls if discharges are sustained over a period of time.

The rate of deterioration increases with applied voltage and breakdown can occur after a few days or many years [9].

4.1.1.8 CHEMICAL DETERIORATION

An insulating material can deteriorate chemically even in the absence of an electric field due to:

(i) chemical instability of the material - e.g. a material subjected to high temperatures loses its mechanical strength. This could result in a change in its chemical structure and a loss of its insulating properties. This implies that a specified temperature limit of an insulating material must not be exceeded.

(ii) oxidation - some insulating materials oxidize if exposed to UV radiation e.g. rubber and polythene. This often leads to a loss of mechanical strength and cracking.

(iii) hydrolysis - which is caused by a combination of high temperatures and the presence of moisture. This leads to a loss electrical insulating and mechanical properties e.g. in poly - ethylene - trepthalate materials.

(iv) material incompatibility - Acidic substances cause rapid degradation of cellulose materials while rubber and polypropylene deteriorate rapidly when in contact with copper at high temperatures. Also, certain mineral oils can react with rubber and PVC (polyvinyl chloride) [9].

4.1.2 METHODS OF MEASURING BREAKDOWN STRENGTH

By using suitable specimens and taking precautions to eliminate surface and edge breakdown, it is possible to measure the intrinsic dielectric strength of a material. Three methods of doing this are: (a) The 'recessed specimen' technique, (b) The McKeown technique and (c) The liquid or gaseous immersion method.

4.1.2.1 THE 'RECESSED SPECIMEN' TECHNIQUE

The sample starts as a plane disc into which is either pressed, machined or ground a spherical depression which nearly penetrates the specimen, leaving only a thickness suitable for breakdown by a reasonable voltage, say 30 -100 μm.

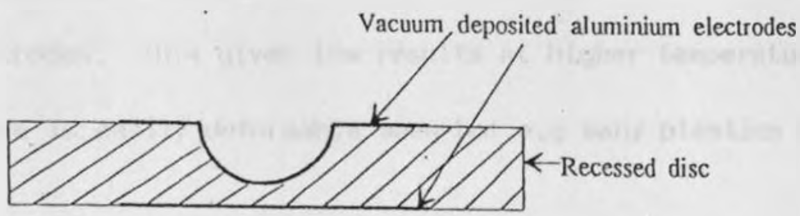


FIGURE 4.2 The recessed specimen

The spherical radius is such that the stress concentration at the apex of the depression is negligible e.g. 1 cm. The surfaces of the recess and of the opposed plane face are then made conducting by any technique which gives extremely good contact with the dielectric e.g an evaporated film of aluminium, or a graphite coating of 'Aquadag' applied by repeated spraying and polished to a continuous film. Solid electrodes do not give a perfect contact while liquid electrodes are inconvenient.

limitations of the method:

(i) The cooling of the stressed area is not very good, even if the specimen is tested in an insulating ambient liquid, and thermal failures are obtained unless the specimen has very low electrical conductivity.

(ii) The thin apex of the specimen is mechanically unsupported, and tends to buckle and become thinner under the compressive force of the electrodes. This gives low results at higher temperatures, if the sample is easily deformable when hot e.g many plastics [8].

4.1.2.2 THE McKEOWN TECHNIQUE

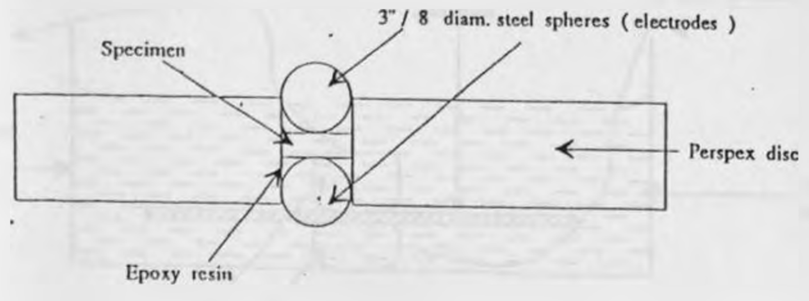


FIGURE 4.3 The McKeown Specimen

The technique uses as electrodes two ball-bearings, located within a cylindrical hole in a disc of any convenient plastic such as perspex. The lower ball is cemented into position with an epoxy resin, and the hole filled with the same resin in liquid form, which is gently heated in vacuo until it is de-gased. The sample, in the form of a thin disc, is then placed in the hole, on top of the ball, and the liquid de-gased again. The top ball is then inserted, and the whole cured until solid. The technique is extremely satisfactory at room temperature for measuring the intrinsic strength of low - loss polymers. The presence of the epoxy resin gives results which are consistently higher than those given by the 'recessed specimens' [8].

4.1.2.3 THE LIQUID OR GASEOUS IMMERSION METHOD

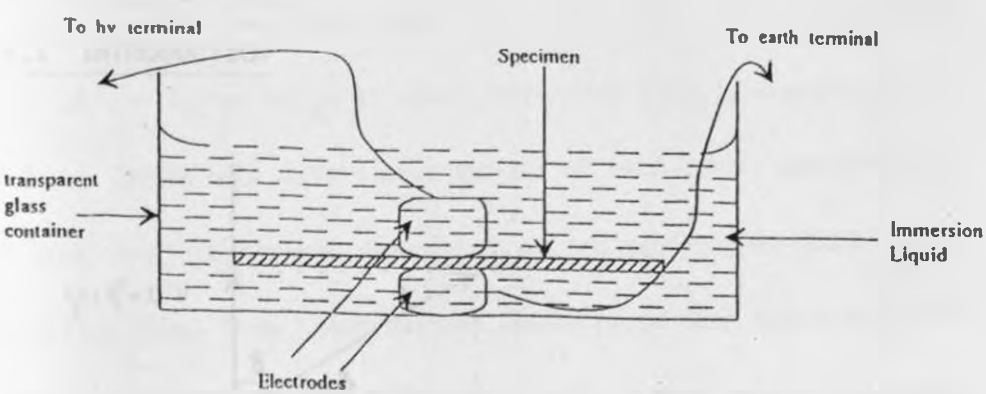


FIGURE 4.4 Liquid/Gaseous immersion arrangement

The set up is as shown in Figure 4.4. The electric strength of the immersion medium is high, and so postpones the onset of discharges to a higher voltage. The high electric strength of the immersion medium encourages puncture through the specimen instead of a flashover over the surface of the specimen. This allows many spots over a small surface area of the specimen to be tested. This method is simpler and faster than the previous two making it more preferable. This is so despite the fact that its results are the least accurate. Even so, the difference in the accuracies is not so much as to justify the use of the other methods when a large number of specimens are to be tested in a short period of time. So this method was used in this study when making dielectric strength measurements [6].

4.2 LOSS TANGENT(Tan δ)

4.2.1 INTRODUCTION

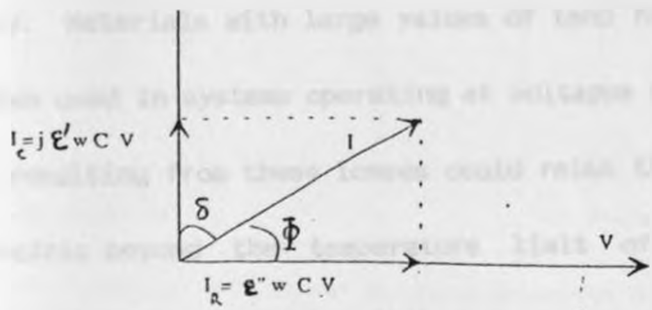
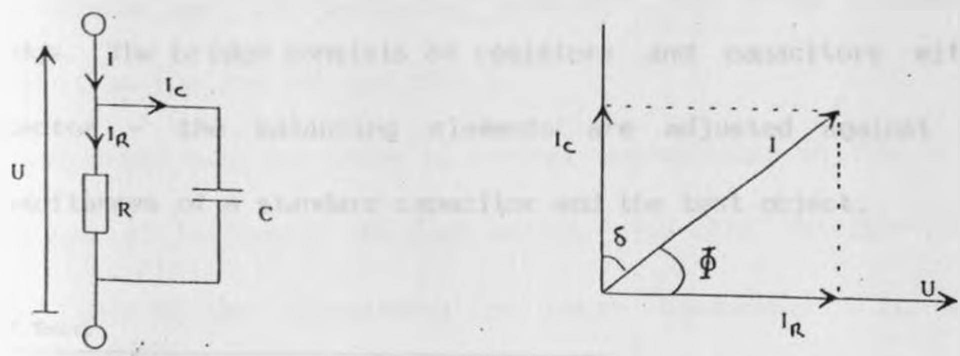


FIGURE 4.5 Components of current through a dielectric of complex dielectric constant $\varepsilon^{*} = \varepsilon' - j\varepsilon''$

When a voltage V is applied across the plates between which is placed a dielectric of complex dielectric constant $\varepsilon^{*} = \varepsilon' - j\varepsilon''$, a current I flows with a phase displacement Φ as shown in Figure 4.5. ε' gives a measure of how easy it is to pass an electric field through the dielectric, the higher its value the easier it is for an electric field to pass through the dielectric. ε'' contributes to the dielectric losses of the dielectric, the higher its value the higher the contribution to the dielectric losses. The current I_R contributes to the dielectric losses. It then follows that loss tangent is defined as $\tan\delta = I_R / I_C = \varepsilon''/\varepsilon'$ gives a measure of this current in comparison to the capacitive current and hence an indication of how lossy the dielectric material is. A large value of $\tan\delta$ indicates that the material is very lossy. Materials with large values of $\tan\delta$ have considerable losses when used in systems operating at voltages above 22kV [10]. The heat resulting from these losses could raise the temperature of the dielectric beyond the temperature limit of the dielectric material and lead to insulation failure.

Two equivalent circuit diagrams can be used to represent a lossy dielectric material under a.c:

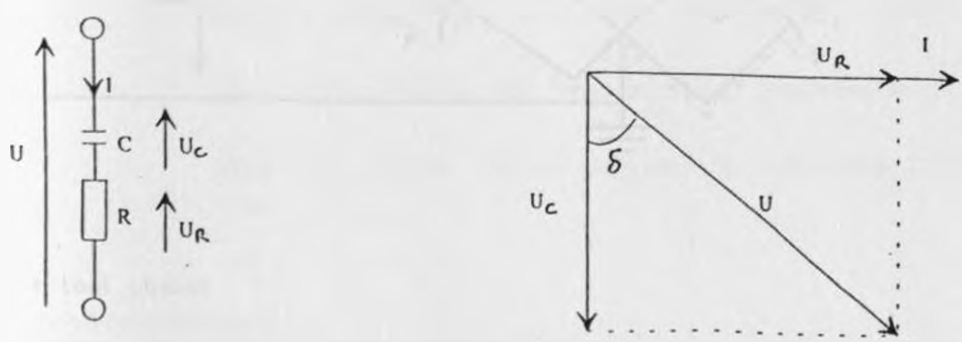
(i) Parallel representation:



(a) Circuit diagram (b) Phasor diagram

FIGURE 4.6: Circuit and phasor diagrams in parallel representation.

(ii) Series representation:

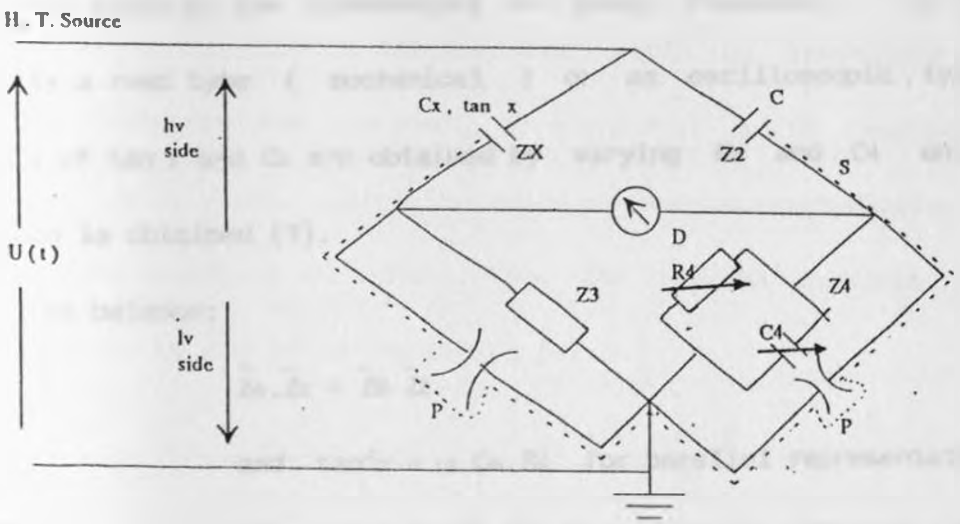


(a) Circuit diagram (b) Phasor diagram

FIGURE 4.7: Circuit and phasor diagrams in series representation

4.2.2 MEASUREMENT OF LOSS TANGENT

The dielectric loss tangent is measured using a Schering bridge. The bridge consists of resistors and capacitors with a detector - the balancing elements are adjusted against the capacitances of a standard capacitor and the test object.



C_x → Test object

C_2 → Standard capacitor

R_3, C_4 → balancing elements

D → Zero detector

S → Screening

P → Protection gap

FIGURE 4.8: The Schering bridge

The test object and the standard capacitor (loss free) are at high voltage and the balancing elements are in an earthed enclosure (on the low voltage side).

Protective gaps are there to prevent overvoltages on the LV side in case of failure of the test object. The zero detector is normally tuned to the fundamental or power frequency. It is usually a reed type (mechanical) or an oscilloscopic type. Values of tan x and C_x are obtained by varying R_3 and C_4 until balance is obtained [9].

At balance:

$$\bar{Z}_4 . \bar{Z}_x = \bar{Z}_3 . \bar{Z}_2$$

and $\tan\delta_x = \omega . C_4 . R_4$ for parallel representation

also $C_x = C_2 . R_4 / R_3$ as derived in reference [9].

4.3 FLASHOVER VOLTAGE

4.3.1 INTRODUCTION

An insulator may fail by surface flashover. Flashover voltage is the voltage at which the ambient (gaseous or liquid) around solid insulation breaks down leading to the formation of an arc, across the surface of the insulator, linking the high voltage electrode to the earth terminal. Here the electric field form is of prime importance, because this controls the voltage gradient across the insulator surface. The insulator should be shaped so as to conform as closely as possible with the electric field form. This gives the maximum economy of material. For indoor applications and voltages up to 33kV, a simple cylindrical shape closely approximates to this requirement [11]. For higher voltages the mechanical strength of the insulator would be inadequate unless very heavy sections are used. If a piece of solid insulation is inserted in a gas so that the solid surface is perpendicular to the equipotentials at all points, then the voltage gradient is not affected by the solid insulation [8].

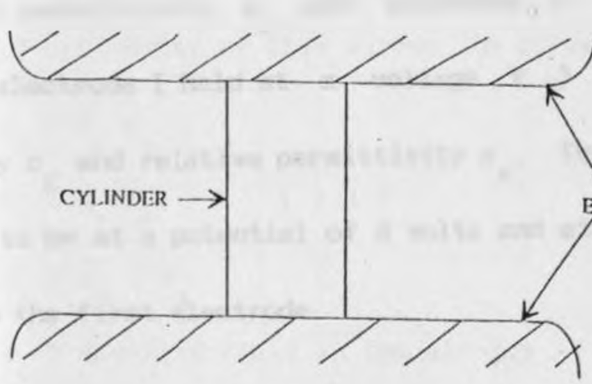


FIGURE 4.9 Cylindrical insulation and electrodes.

An example of this is a cylindrical insulator in a uniform field as in Figure 4.9. If the insulator is clean and conforms accurately to cylindrical shape, its insertion does not affect the breakdown voltage, but if these conditions are not fulfilled a substantial lowering of the breakdown voltage can occur.

4.3.2 FACTORS LOWERING FLASHOVER VOLTAGE

4.3.2.1 IMPERFECTION OF SHAPE

Field intensification results if solid insulation departs from the cylindrical shape. If an air gap exists next to an electrode, the stress there can reach up to ε_r times the mean stress in the gap (where ε_r is the relative permittivity of the cylinder material) as explained in derivation of Equation 4.5 from Figure 4.10 below. Consider the arragement in Figure 4.10 in which an air-gap (permittivity ε_1 and thickness x metres) exists between an electrode (held at a voltage V) and a solid of permittivity ε_2 and relative permittivity ε_r. The second electrode is assumed to be at a potential of 0 volts and at a distance of d metres from the first electrode.

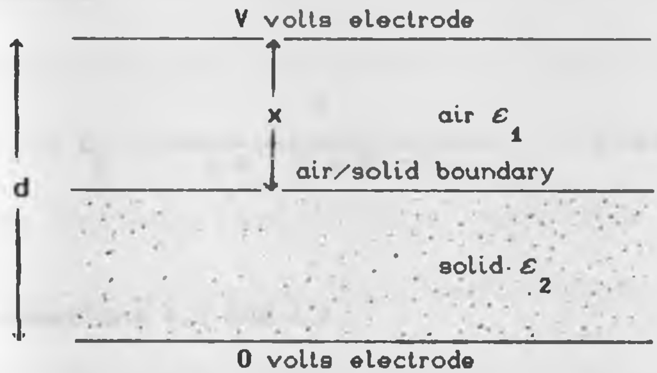


FIGURE 4.10: Diagram showing air-gap between high-voltage electrode and solid dielectric.

For the arragement in Figure 4.10,

$$V = E_1 x + E_2 (d - x) \qquad (4.1)$$

Because of continuity of flux across the air/solid boundary,

$$E_1 \varepsilon_1 = E_2 \varepsilon_2$$

so that $E_1 = \varepsilon_r E_2$ (4.2)

where $\varepsilon_r = \varepsilon_2 / \varepsilon_1$

E_1 = electric field in the air-gap

E_2 = electric field in the solid

Equation 4.1 can then be written as

$$V = E_1 x + E_1 (d - x)/\varepsilon_r$$

From which $$E_1 = \frac{\varepsilon_r V}{x \varepsilon_r + (d - x)} \qquad (4.3)$$

Similarly,

$$E_2 = \frac{V}{x\,\varepsilon_r + (d - x)} \qquad (4.4)$$

From equations 4.3 and 4.4,

$$E_2 = \varepsilon_r E_1 \qquad (4.5)$$

Ionisation of the air in the gap then arises much earlier than in the main air gap. The products of ionisation go out from the air to the surface of the dielectric and promote much earlier initiation of discharge along the surface of the insulator. Therefore, in practical insulation constructions, all measures are taken to ensure a proper contact between the electrodes and the solid dielectric. The electrodes are usually fixed to porcelain insulators with the help of a cement which ensures good mechanical strength and minimal air gaps if any.

4.3.2.2 MOISTURE

At a large value of humidity of the ambient (value of relative humidity corresponding to the condensation of moisture on the surface of the dielectric), the surface of the dielectric does not remain absolutely dry. On account of hygroscopicity of the material there is always a surface layer of adsorbed moisture possessing a very large but definite resistance. Since water possesses ion conductivity, ions start moving towards the electrodes under the influence of electric field. This leads to the formation of conducting paths on the surface of the dielectric and a lowering of the flashover voltage. The value of relative humidity at which condensation of moisture on the surface of the dielectric occurs depends on the material of the surface of the surface of the dielectric. It is much greater for perspex and cast resin than for glass or porcelain [8].

4.3.2.3 HEAVY POLLUTION

Pollution takes the form of either dirt (in industrial areas) or salt deposits (in coastal areas) that get deposited on the surface of insulators.

The mechanism of flashover is as follows. Pollution becomes deposited on the surface; this pollution may be industrial in origin, or it may be salt in coastal areas. It does not affect the performance of the insulation significantly unless it becomes moist, for example due to fog, dew or rain. The pollution then becomes conducting and heat(which increases the temperature of the film) generated by the leakage current which flows. When the temperature approaches the boiling point, there is rapid evaporation of moisture creating high resistance dry bands. Most of the applied voltage occurs across the dry band and results in a breakdown across the dry band, and a quasi-stable arc is formed and it burns in series with the surface pollution film. Initially the arcs are short and carry currents slightly less than the pre-dry band formation current. The arc roots burn in search of fresh moist areas as the film under the root dries up. This results in a transverse motion of the arc around the dry band. If the moisture precipitation is low, the dry band gradually widens (arc elongates) and the arc extinguishes at a certain length (i.e. supply voltage cannot sustain the arc voltage i.e. voltage across the arc length). A local increase in precipitation can cause formation of another discharge and the cycle repeats. If the moisture precipitation balances the loss of moisture, then a stable state is attained and the formed arc can burn for many hours (i.e. arc length does not increase in search of moisture).

The arcs /discharges may grow in length until the electrodes are bridged by a long arc - and this is known as pollution flashover [8].

Flashovers and especially pollution flashovers result in :

(i) Damage to insulator surfaces.

(ii) Generation of radio interference noise (by constant extinction and restriking of the arc)

(iii) Malfunction of certain types of equipment such as surge diverters,air-blast circuit breakers and capacitor bushings.

5.0 PREPARATION OF TEST PIECES AND ELECTRODES FOR DIELECTRIC STRENGTH AND LOSS TANGENT MEASUREMENTS

5.1 SHAPING TEST PIECES FOR DIELECTRIC STRENGTH MEASUREMENTS

(a) The pieces were made flat and smooth for proper contact with the flat surfaces of the electrodes. Using a band-saw flat pieces were obtained by making straight cuts. To obtain smooth surfaces coarse sandpaper was used to remove the rough surface and fine sandpaper used for finishing.

(b) Each specimen had a maximum thickness of about three millimeters. Such a thin specimen has less voids, less structural variability and can be made such that it does not include any flaws. The effect of these three features is to make the results from the measurements made on the specimen less variable. Such a specimen also requires a lower voltage for puncture than would a thicker specimen [1]. This reduces chances of a flashover occurring between electrodes during electric strength measurements. The thinness of the specimen also makes its impregnation with transformer oil easier [1]. Thin wood specimens can be dried quickly at high temperatures (105 ^{o}C) without them cracking; at the worst they warp [4]. This method of drying helps do away with the alternative methods of seasoning which, if cheap, take a very long time or very expensive if they take a short time [4].

(c) The surface area of each specimen was about 49 cm^2. This dimension was dictated by the dimensions of the wood pieces available from the wood dealers. The specimen pieces had creepage paths of sufficient length to prevent the occurrence of flashovers at voltage values encountered during electric strength measurements.

(d) Two pieces per wood species (one piece had its surface cut along the grains and the other had its surface cut across the grains) were used for each condition of wood studied. The two orientations (along and across the grains) were considered because the electrical properties of wood were expected to vary with the direction in which they were investigated relative to the direction of orientation of the wood grains.

5.2 PRECONDITIONING AND CONDITIONING OF THE TEST PIECES

5.2.1 INTRODUCTION

Preconditioning is the treatment of a specimen with the object of removing or reducing the effect of its previous history with respect, principally, to the temperature and humidity to which it has been exposed. This treatment (sometimes known as ' normalizing ') usually precedes conditioning of a specimen.

Conditioning is the subjection of the specimen to an atmosphere of a specified relative humidity, or complete immersion in water or other liquid, at a specified temperature for a specified period of time.

The objective of conditioning is to:

(i) Obtain greater reproducibility of test results by

- reducing the variations of the properties of the material due to the past history of the test specimens, and
- ensuring uniformity of conditions during the testing

(ii) Determine the influence of exposure to certain temperatures and humidities, or immersions in liquids, on the properties of a material, by subjecting specimens to specified conditions before or during the test or both [8].

5.2.2 PRECONDITIONING

All test specimens were dried in an oven at 105^{o}C until they attained a constant mass. This meant that most of the moisture in the specimens was removed. If it were not removed this moisture would cause a deterioration of the electrical insulating properties of the test specimens [1]. The electric strength and loss tangent test specimens took 4 days to dry to constant mass.

5.2.3 CONDITIONING

5.2.3.1 DRY SPECIMENS

The test specimens on being removed from the oven were let to cool to room temperature (21^{o}C - 23^{o}C) in a tightly sealed glass jar containing silica gel. Silica gel is a highly hygroscopic substance and so it keeps the inside of the glass jar moisture-free by absorbing all the moisture in it. The test specimens cooling in the glass jar do not reabsorb moisture. For specimens to be tested as dry wood, this conditioning after preconditioning was sufficient.

5.2.3.2 OIL IMPREGNATED SPECIMENS

The specimens were boiled in fresh transformer oil for 30 minutes, 1 hour, 3 hours and 5 hours at a temperature of 121^{o}C and a pressure of 0.105MPa. After this they were let to cool to room temperature in glass jars containing silica gel. The purpose of boiling the specimens in fresh transformer oil was to have the oil seep into the pores of the wood (i.e. impregnation of the woods with transformer oil) which would normally contain air.

5.3 ELECTRODE MATERIAL AND SHAPING

Electrodes were required for electric strength measurements and flashover voltage measurements.

In either case care was taken to choose a material which:

(a) would not lose electrons easily as this would result in erroneously low values of breakdown strength,

(b) is chemically stable so that it remains in the same chemical state for the duration of the tests. A material which burns out or easily gets oxidized is not a good choice for a high voltage electrode.

(c) is technically economical,

(d) is readily available.

Two materials were readily available, i.e.

(i) brass bars of 3.1 cm diameter and

(ii) aluminium sheets of 4 mm thickness.

Brass was selected for the electric strength measurement electrodes because:

(a) Being denser than aluminium it was possible to use a small piece to make the upper electrode that would be heavy enough to provide the compressive force to press the test specimen onto the lower electrode and so provide good electrical contact.

(b) Brass is less easily oxidized than aluminum which would require more frequent rubbing with emery cloth when used in the numerous electric strength measurements.

(c) The dimensions in which the two materials existed made it easier to obtain a shape of the electrode from brass than from aluminium. This is because the limited amounts of test specimens dictated that as many puncture tests as possible be performed on every specimen. This then meant that the electrodes had to be shaped such that it was possible to accurately select a point on the test specimen on which puncture is to occur and at the same time make the electrode free of sharp edges that cause intense electric fields.

The brass electrodes were then shaped as in Figure 5.1:

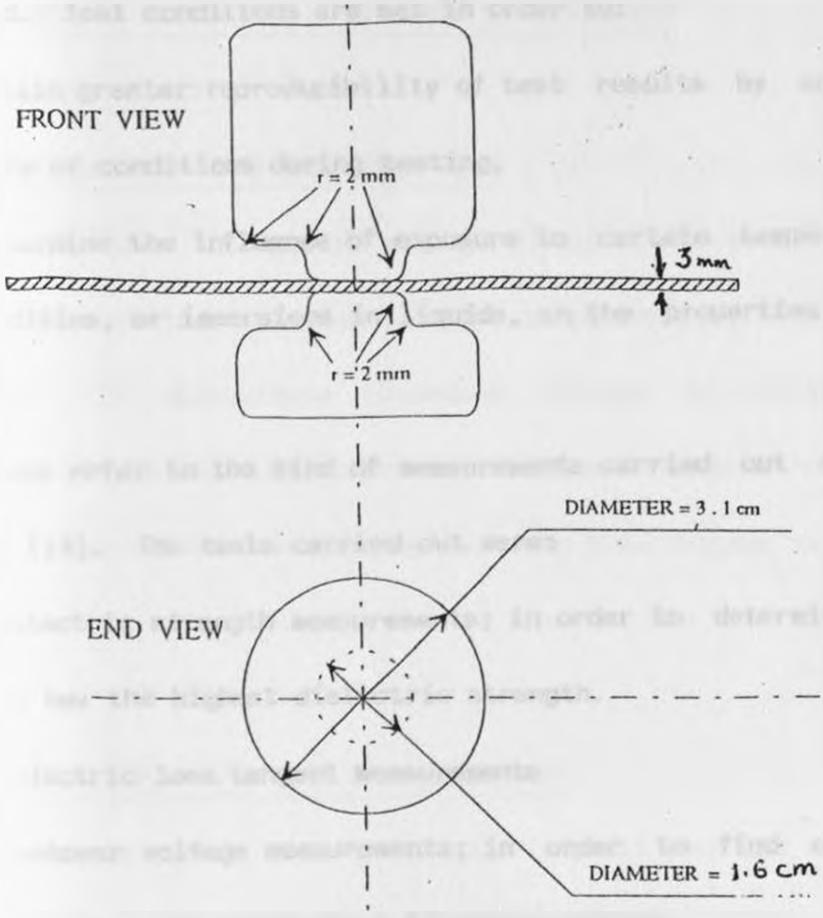


FIGURE 5.1 : Electrodes for dielectric strength tests.

6.0 TEST CONDITIONS AND TESTS

6.1 INTRODUCTION

Test conditions refer to the temperature and humidity of the atmosphere surrounding the specimen, or temperature and kind of liquid (for liquid immersion), during the time when tests are conducted. Test conditions are set in order to:

(a) obtain greater reproducibility of test results by ensuring uniformity of conditions during testing.

(b) determine the influence of exposure to certain temperatures and humidities, or immersions in liquids, on the properties of a material.

Tests refer to the kind of measurements carried out on the specimen [13]. The tests carried out were:

(a) dielectric strength measurements; in order to determine the wood that has the highest dielectric strength.

(b) dielectric loss tangent measurements

(c) flashover voltage measurements; in order to find out the insulator shape with the highest flashover voltage

(d) leakage current measurements; in order to find out the insulator shape with the least leakage current

(e) electric field analysis; in order to determine the aspects of the field plots that determine the insulator shape with the highest flashover voltage.

(f) a check on the effectiveness of a varnish coating, applied on the wood insulator, in keeping out moisture from the insulator.

6.2 BREAKDOWN (DIELECTRIC) STRENGTH MEASUREMENTS

6.2.1 CLASSES OF TESTS

6.2.1.1 THE SHORT - TIME BREAKDOWN TEST

In this test, the applied voltage is raised from zero with uniform rate such that breakdown occurs, on an average, in 10 to 20 seconds [6]. An approximate breakdown voltage is obtained by applying a voltage that causes breakdown. The required rate of rise of voltage is then obtained by dividing this voltage value by 20 seconds.

6.2.1.2 THE STEP - BY - STEP BREAKDOWN TEST

In this method of test a voltage nearest to 50% of the probable short-time breakdown voltage selected from Table 2.1 in reference [6] is applied to the test specimen for 20 seconds. If breakdown does not occur, the voltage of the next higher and subsequent steps in Table 2.1 are successively applied each for 20 seconds until breakdown occurs.

The voltage increase from each step is made as quickly as possible, and the time required in raising the voltage is included in the period of 20 seconds for the higher step. The voltage of the highest step,applied for 20 seconds without breakdown is taken as the dielectric breakdown voltage [6]. This method requires plenty of time, so is not suitable if a large number of pieces is to be tested. This factor favoured the use of the short-time breakdown in this study.

6.2.2 TEST CONDITIONS

The tests were done with the specimens immersed in fresh transformer oil at room temperature ($21^{o}C$ - $23\ ^{o}C$). The arrangement was as in Figure 6.1. The electrodes and the specimen are immersed in the transformer oil. The connecting leads are put as far apart as possible.

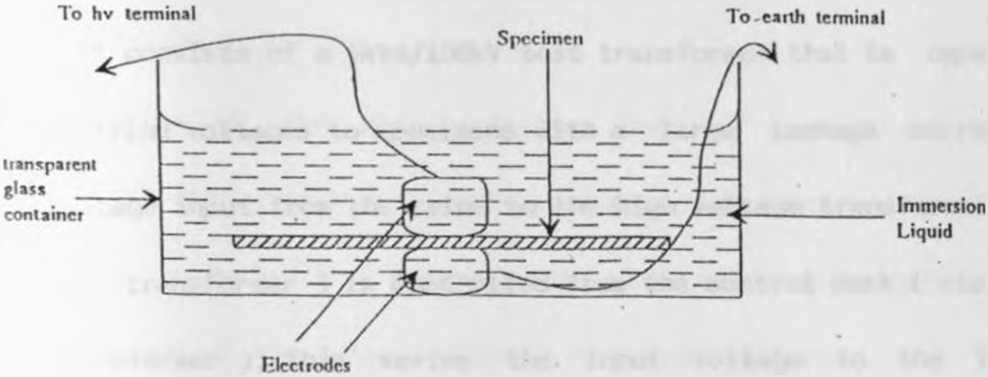


FIGURE 6.1: Test set-up.

6.2.3 THE TEST CIRCUIT

The simplified testing circuit diagram used in the dielectric strength measurements was as in Figure 6.2

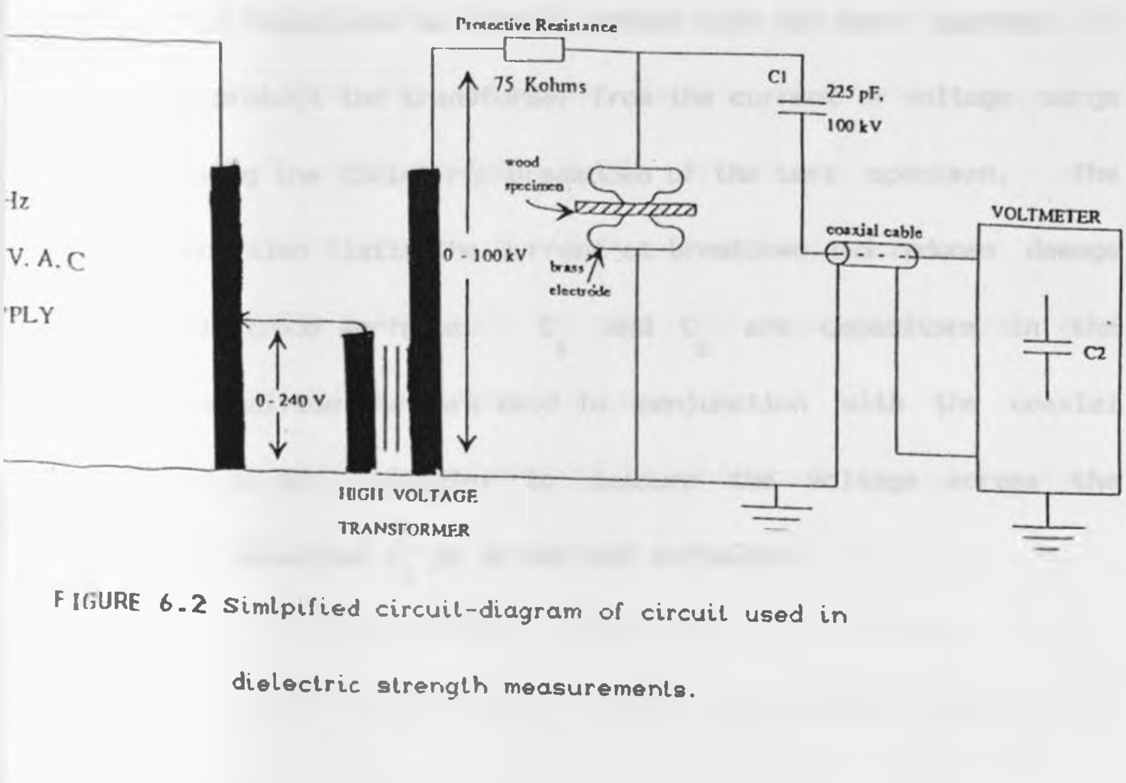


FIGURE 6.2 Simlpified circuit-diagram of circuit used in dielectric strength measurements.

It consists of a 5kVA/100kV test transformer that is capable of supplying voltages to specimens with a large leakage current. The voltage input from the mains to the high voltage transformer (the test transformer) is controlled from the control desk (via an autotransformer); this varies the input voltage to the test transformer from 0-240 volts and results in its output varying from 0-100kV. In the actual circuit is a circuit breaker capable of operating quickly in response with the dielectric breakdown of the test specimen, so as to protect the test transformer and electrodes from the current produced by the dielectric breakdown; the limiting primary current of the test transformer is 20.8 Amps. The protective resistance is used in series with the test specimen in order to protect the transformer from the current or voltage surge accompanying the dielectric breakdown of the test specimen. The resistance also limits the current at breakdown and reduces damage to the electrode surfaces. C_1 and C_2 are capacitors in the capacitive divider network used in conjunction with the coaxial cable and an RMS voltmeter to measure the voltage across the specimen; capacitor C_2 is in the RMS voltmeter.

6.2.4 TESTING PROCEDURE

Because of the high voltages involved precautions were included in the procedure to ensure safety. The procedure was to:

(a) Place the test-object between the electrodes submerged such that the axes of the lower and upper electrodes coincide.

(b) Connect the upper electrode to the high voltage transformer output and the lower electrode to ground.

(c) Pick the earth rod from the high voltage transformer output and put it at the hook above the gate to the cage.

(d) Close the gate to the cage and energize both the mains and the high voltage transformer.

(e) Gradually raise the voltage applied to the test specimen. During this time the voltmeter reading should also increase steadily. At some voltage (the breakdown voltage) the voltmeter reading suddenly decreases. Record this voltage.

(f) Denergize the mains, open the gate and using the earth rod earth all the metal parts in the cage.

(g) Leave the earth rod attached to the output of the high voltage transformer so long as you are working in the cage.

(h) Retrieve the test specimen and measure the thickness of the specimen at the black point (where breakdown occurred) using a micrometer. Accuracy to 0.1mm. Record this.

(i) Position the electrodes on a new spot on the specimen (avoid flaws) and repeat the above procedures.

For each specimen the tests are done five times and the mean value of the dielectric breakdown strength obtained. In case any One of the individual test values differs from the mean value by 15% or more, five more tests are conducted [6]. Here the dielectric breakdown strength is taken as the mean of ten test values.

6.3 LOSS TANGENT MEASUREMENTS

6.3.1 TEST CONDITION

The measurements were made at room temperature ($21^{o}C - 23^{o}C$) and non-humid conditions ($0g/cm^{3}$). That is, the tests were performed on the specimens as soon as each was removed from the non-humid glass jars containing silica gel. Performing the tests within two minutes after the specimens were removed from the glass jars meant that the specimens were not allowed time to come to equilibrium with the new atmosphere to which they were exposed.

6.3.2 TEST EQUIPMENT

The equipment used was the GenRad 1689 Precision RLC

Digibridge. The frequency at which the measurements are carried out can be selected to be of any value between 10Hz and 10kHz. It was set to carry out the measurements at 60Hz (which is also low enough to be considered a power frequency) because at 50Hz the readings were not steady probably due to the interference with the operation of the equipment by the mains frequency which is also 50Hz. This measurement of loss tangent is carried out at 1 volt and can be programmed to give (as its result for a measurement) the average of any number of readings upto 300. If the measurements were carried out at voltages greater than 1 volt (say, 2 kilovolts), ionisation of the gas in the cavities in the specimens would occur and so the values of the loss tangents obtained would be larger. For the measurements made in this case it was programmed to give the average of 50 readings. It has a digital display that indicates the values of the quantities being measured.

6.3.3 TEST PROCEDURE

(a) Switch on the Digibridge and let it go through its self-check procedure.

(b) When self-check is complete zero the Digibridge when it is on open circuit and then zero it when it is on short circuit.

(c) Put the specimen between the terminals of the Digibridge and press the knob for the loss tangent measurement. The display of the Digibridge now outputs the value of the loss tangent of the specimen. This measurement is done over five different spots of the specimen and the average value taken as the dielectric loss tangent of the specimen.

(d) Once the equipment has been zeroed it need not be zeroed again when subsequent measurements are made.

6.4 FLASHOVER VOLTAGE AND LEAKAGE CURRENT MEASUREMENTS

6.4.1 INTRODUCTION

The insulator designed was to be used at high voltages. In Kenya, the 11kV voltage is the lowest of the high voltages used in distribution of electric power from the generation plants to the users. The large number of insulators required at this distribution voltage and the lower stresses encountered (as compared to that in insulation at 66kV or 132kV) made it better to design an insulator for use at 11kV; wood is not expected to withstand the very high electric stresses encountered at voltages beyond 11 kV.

An insulator designed for use at 11kV must withstand 95kV without puncturing [7]. Under the one minute power frequency withstand test; the insulator is subjected to a power frequency test voltage for one minute and it is considered to have passed the test if it does not flashover during that period. The test is carried out both under wet and dry conditions. Under dry conditions, an 11kV insulator is required to withstand about 50kV, and about 30kV under wet conditions. An insulator is also subjected to an impulse test in which an impulse voltage is applied simulating lightning conditions. For an 11kV insulator, the peak impulse voltage applied is about 65kV [7]. The insulator flashover distance is defined as the minimum distance between the high voltage electrode and the earth electrode. This is sometimes referred to as the tight string distance. The creepage distance of an insulator is taken to be the distance, measured along the surface of the insulator, between the high voltage electrode and the earth electrode. The specification of insulators is based on the rated line voltage, though the working voltage is the line voltage divided by $\sqrt{3}$.

Design of the 11kV insulator then aims at coming up with the configuration and dimensions of the insulator that uses the least amount of wood while satisfying the above specifications.

In an attempt to come up with an optimum shape of the insulator, the vertical distance between the high voltage electrode and the earth electrode (that is , the height of the insulator) is kept constant while the shape of the insulator body is varied. The distance between the electrodes is determined by the height of the cylindrical insulator for 11kV; that is, the of a cylindrical insulator that has a flashover voltage of 50kV when dry. By measuring the flashover voltages and leakage currents of insulators so designed, one soon establishes which general shape is best. The insulator with the highest flashover voltage and the least leakage current is deemed to be the best. The insulator shape considered first was the cylindrical shape. This was because the cylindrical shape has circular symmetry which makes the chances of flashover occurring equal in all directions from the top electrode towards the bottom one. While looking for the best general shape of the insulator, the profile of the insulator body was varied while maintaining its circular symmetry.

6.4.2 TEST CIRCUIT

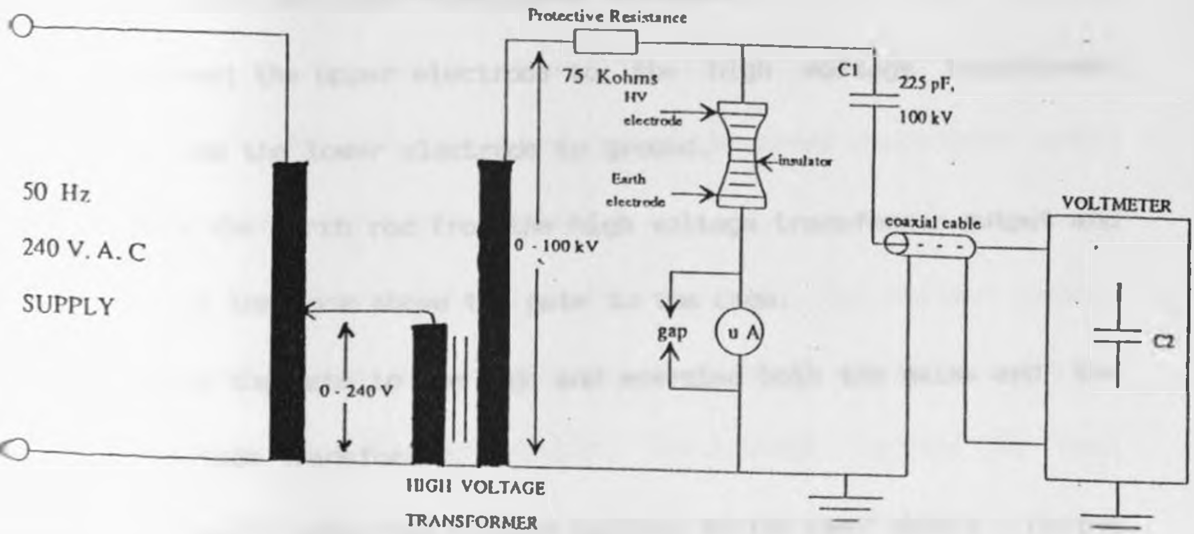


FIGURE 6.3 Simplified circuit diagram of circuit used in flashover voltage and leakage current measurements.

6.4.3 TEST PROCEDURE

The tests were carried out in air at a temperature of $21^{0}C$ - $23^{0}C$ and a pressure of about 1.01×10^{5} Pa.

Here, as in the dielectric strength measurements, high voltages are involved and so the test procedure includes safety precautions:

(a) Place the test object between the electrodes such that the axes of the lower and upper electrodes coincide.

(b) Connect the upper electrode to the high voltage transformer output and the lower electrode to ground.

(c) Pick the earth rod from the high voltage transformer output and put it at the hook above the gate to the cage.

(d) Close the gate to the cage and energise both the mains and the high voltage transformer.

(e) Gradually raise the voltage applied to the test object. During this time the voltmeter reading should also increase steadily. At some voltage flashover occurs, the voltmeter reading decreases suddenly and the transformer is denergised by the tripping of the circuit breaker. Rotate the knob used for increasing the transformer output to zero output. Re-energise the high voltage transformer and gradually raise the voltage applied to the test object until flashover occurs once more. Repeat this part of the procedure so that flashover occurs five times. The readings of the voltmeter when flashover occurs stabilises after this conditioning. Repeat five more flashovers and record the voltmeter reading for each flashover.

(f) Denergise the mains, open the gate and using the earth rod earth all the metal parts in the cage.

(g) Leave the earth rod attached to the output of the high voltage transformer so long as you are working in the cage.

(h) Retrieve the test-object and repeat the above procedures until all test-objects have been tested.

For the measurements of leakage currents, the voltage applied to the test object is raised slowly to 6.4kV ($11/\sqrt{3}$kV) and then left at this value for ten minutes. The leakage current is then read from the microammeter. In the case where the leakage current is to be monitored over a period, the voltage is maintained at 6.4kV during the whole of that time interval. In this study the time interval was chosen to be 10 hours as it was considered unsafe to leave the high voltage equipment on overnight.

6.5 ELECTRIC FIELD ANALYSIS

6.5.1 INTRODUCTION

Having decided on the best general shape (five shapes were tried out), field values are computed numerically and plots of electric field along the surfaces of the insulators considered are made. The aim of this is to discern what aspect of the field plots determines the insulator shape with the highest flashover voltage. It then becomes possible to tell the performance of several other shapes, relative to that of those already tested practically, without actually building them. This has the desirable effect of cutting down on the amount of time required to build and test the insulators as one tries to optimize their shape.

In evaluating electric field stress, the problem is to find a solution of the following equation:

$\nabla . \varepsilon \nabla U = 0$ for given boundary conditions; U is the potential.

for a homogenous dielectric system, then ε = constant and the above equation becomes the Laplacian equation $\nabla^2 U = 0$.

If space charge is present in the region of interest, then the Laplacian's equation becomes Poisson's equation: i.e. $\nabla^2 U = -\rho/\varepsilon$

where ρ = charge density

ε = permittivity.

The calculation of electric fields requires the solution of Laplace's or Poisson's equation with boundary conditions satisfied. There are three types of boundary conditions:

(i) Fixed potential boundaries (e.g. at metallic electrodes).

(ii) Zero gradient boundaries as at planes of symmetry.

(iii) Open field boundaries i.e. $U \rightarrow 0$ as $x, y, z \rightarrow \infty$

The methods used to evaluate electric field stress are:

(i) Analytical methods

(ii) Analogue methods

(iii) Numerical methods

6.5.1.1 ANALYTICAL METHODS

Analytical solutions of the Laplace equation are most useful (where they can be obtained) as the performance the system is given in a single equation. They can only be obtained for relatively simple electrode systems, where the conducting surfaces (electrodes) are cylinders, spheres, spheroids or other surfaces conforming to equipotentials surrounding some simple charge distribution [14].

For Cartesian co-ordinates:

$$\nabla^2 U = \frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} + \frac{\partial^2 U}{\partial z^2} = 0 \qquad \text{............(6.1)}$$

For Cylindrical co-ordinates:

$$\nabla^2 U = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial U}{\partial r} \right) + \frac{1}{r^2}\frac{\partial^2 U}{\partial \phi^2} + \frac{\partial^2 U}{\partial z^2} = 0 \text{............}(6.2)$$

For Spherical co-ordinates:

$$\nabla^2 U = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial U}{\partial r} \right) + \frac{1}{r^2 \sin\theta}\frac{\partial}{\partial \theta}\left(\sin\theta \frac{\partial U}{\partial \theta} \right)$$

$$+ \frac{1}{r^2 \sin^2\theta}\frac{\partial^2 U}{\partial \phi^2} = 0 \text{..........................}(6.3)$$

In practical systems, the applicability of such equations is very limited because of the irregular geometries involved. The most useful analytical techniques are:

(i) Separation of variables

(ii) Laplace transforms

(iii) Functions of complex variables

(iv) Method of images.

6.5.1.2 ANALOGUE METHODS

Because direct measurement of electrostatic potential and stress is difficult, use is made of other physical phenomena which obey the same field equations to simplify measurements. Conduction current field is used to make analogue measurements for the electrostatic field - potential measurements are simple and accurate in conduction fields. The most commonly used analogue methods are:

(i) Electrolytic tank (for two-dimension and three-dimension measurements)

(ii) Resistive paper (or semiconducting paper for two-dimension measurements).

Of these two, the electrolytic-tank method has been the most popular and versatile analogue method. This method, which is based on the analogy between field distribution and the flow of current in a conducting medium, has been successfully used for more than a century, and, with extreme care, errors can be kept to within 2%. Unfortunately, this method of solution tends to be somewhat involving because models have to be constructed, and the extension to multidielectric fields is both difficult and prone to error [14].

6.5.1.3 NUMERICAL METHODS

This method uses numerical techniques to solve the Laplace equation. With the advent of newer high-speed computers, this method of solution has become a feasible proposition. The most commonly used methods are:

(i) The finite elements method (FEM)

(ii) The charge simulation method (CSM)

(iii) The finite differences method (FDM)

Of these three methods the FDM was the simplest and sufficient, in terms of required levels of accuracy, for the evaluation of electric field stress in this study.

6.5.1.3.1 THE FINITE DIFFERENCE METHOD

This method of solution which expresses the Laplace equation in finite-difference form is used to solve partial differential equations. The principle is to subdivide the area of interest into a grid of points. The field potential difference equations (that is, $\nabla^2 U = 0$) are replaced by corresponding finite difference equations. The greater the number of grid points, the more accurate the solution but the higher the number of equations to be solved. The method is approximate, but by using sufficient points and by iteration, or repetitive application, the solution can be made as accurate as desired [15].

The basic step is to find a solution of Laplace's equation at a point by noting the slope of the second derivative of the potential U in orthogonal directions around the point. In rectangular co-ordinates Laplace's equation is given by

$$\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} + \frac{\partial^2 U}{\partial z^2} = 0 \qquad \text{...........(6.4)}$$

If the potential variation is independent of z, the problem reduces to a two-dimensional one and equation (6.4) simplifies to

$$\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} = 0 \qquad \text{...........(6.5)}$$

Consider a two-dimensional potential distribution around a point P, as in Figure 6.4.

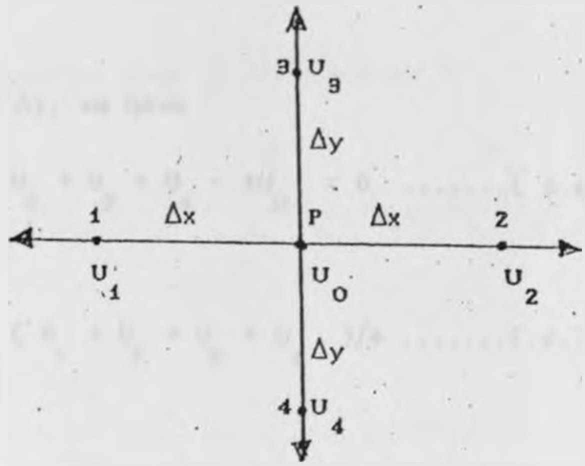


FIGURE 6.4 Potential distribution around a point P.

Let the potential at P be equal to U and at the four surrounding points be U_1, U_2, U_3, and U_4, as shown. Now(U_2 - U_0)/Δx is the slope of U between points 2 and P. Also (U_0 - U_1)/Δx is the slope of U between points P and 1. The difference of these slopes (per distance increment Δx) is approximately equal to . Laplace's equation requires that the difference in slopes of U in the x direction and the difference of the slopes in the y direction must be equal and opposite in sign. Thus, we have

$$\frac{\partial(\partial U/\partial x)}{\partial x} = - \frac{\partial(\partial U/\partial y)}{\partial y}$$

or

$$\frac{[(U_2 - U_0)/\Delta x]-[(U_0 - U_1)/\Delta x]}{\Delta x} = - \frac{[(U_3 - U_0)/\Delta y]-[(U_0 - U_4)/\Delta y]}{\Delta y}$$

letting $\Delta x = \Delta y$, we have

$$U_1 + U_2 + U_3 + U_4 - 4U_0 = 0 \quad ....(6.6)$$

and $$U_0 = (U_1 + U_2 + U_3 + U_4)/4 \quad ....(6.7)$$

That is, the potential at a point is the average of the potential at four surrounding points for a two-dimensional problem [15]. In a three-dimensional problem we would find the average of the potential for six surrounding points (four points on the same plane as the point in question, one point above this plane and another point below this plane) and the potential at P would be given by

$$U_0 = (U_1 + U_2 + U_3 + U_4 + U_5 + U_6)/6 \quad ......(6.8)$$

For this study only two-dimensional field studies could be carried out (or three-dimensional ones with circular symmetry so that they could be reduced into two-dimensional problems) as meshing packages that could handle three-dimensional problems were not available. Programs were written so as to iteratively calculate potentials within some given region. The general

2-dimensional equation used in the program is

$$\frac{\phi_1}{h_1}(h_4\varepsilon_8 + h_2\varepsilon_1) + \frac{\phi_2}{h_2}(h_3\varepsilon_3 + h_1\varepsilon_2) + \frac{\phi_3}{h_3}(h_4\varepsilon_5 + h_2\varepsilon_4) + \frac{\phi_4}{h_4}(h_3\varepsilon_6 + h_1\varepsilon_7)$$

$$- \phi_0\left[\left(h_4\left(\frac{\varepsilon_8}{h_1} + \frac{\varepsilon_5}{h_3}\right) + \frac{1}{h_4}(h_3\varepsilon_6 + h_1\varepsilon_7) \right)\right.$$

$$\left. + \left(h_2\left(\frac{\varepsilon_1}{h_1} + \frac{\varepsilon_4}{h_3}\right) + \frac{1}{h_2}(h_3\varepsilon_3 + h_1\varepsilon_2) \right) \right] = 0 \quad (6.9)$$

for ϕ and ε as shown in the Figure 6.5 below [14].

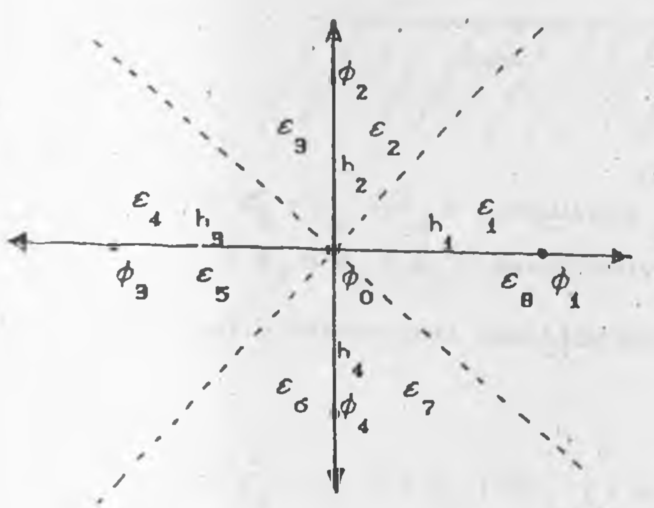


FIGURE 6. :Quantities involved in difference equations for any grid point.

The above equation had to be modified because:

(i) the region considered was subdivided into square grids so that

$h_1 = h_2 = h_3 = h_4$

(ii) there were only two permittivities (that of air and that of wood).

The equation used then took different forms depending on the insulator shape at the point of interest.

Examples:

(i) For the arrangement in Figure 6.6:

air/wood boundary

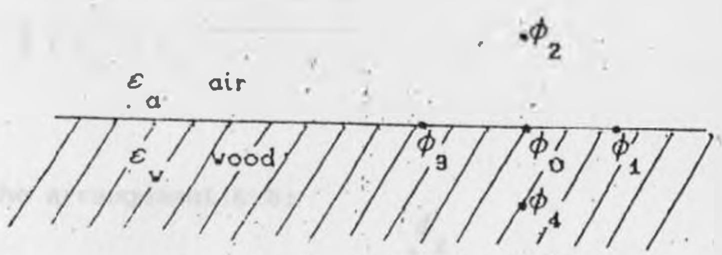


FIGURE 6.6

$\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = \varepsilon_4 = \varepsilon_a$ = permittivity of air

and $\varepsilon_5 = \varepsilon_6 = \varepsilon_7 = \varepsilon_8 = \varepsilon_v$ = permittivity of wood

the general 2-dimensional equation becomes

$$\phi_0 = \frac{\phi_1 (\varepsilon_a + \varepsilon_v) + \phi_2 (2\varepsilon_a) + \phi_3 (\varepsilon_a + \varepsilon_v) + \phi_4 (2\varepsilon_v)}{4 (\varepsilon_a + \varepsilon_v)}$$

(ii) For the arrangement in Figure 6.7:

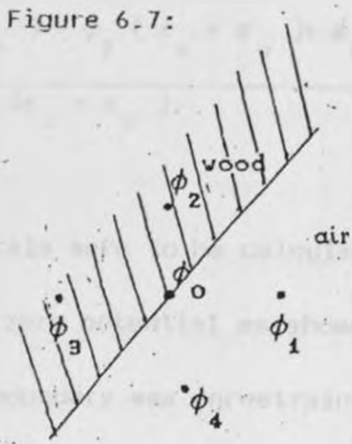


FIGURE 6.7

the general equation becomes

$$\phi_0 = \frac{\phi_1 \varepsilon_a + \phi_2 \varepsilon_w + \phi_3 \varepsilon_w + \phi_4 \varepsilon_a}{2 (\varepsilon_a + \varepsilon_w)}$$

(iii) For the arrangement 6.8:

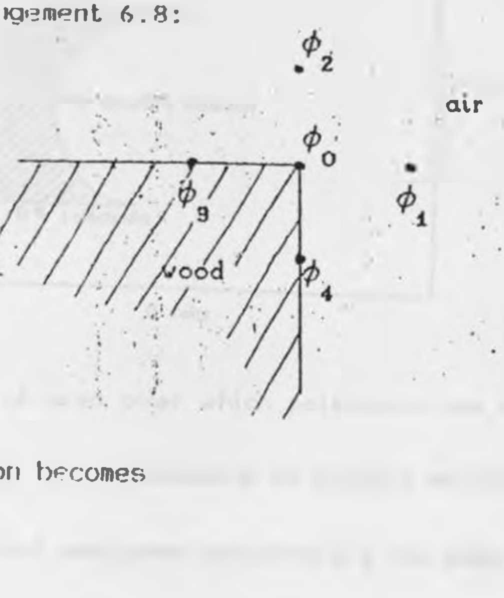


FIGURE 6.8

the general equation becomes

$$\phi_0 = \frac{\phi_1 (2\varepsilon_a) + \phi_2 (2\varepsilon_a) + \phi_3 (\varepsilon_a + \varepsilon_w) + \phi_4 (\varepsilon_a + \varepsilon_w)}{2 (3\varepsilon_a + \varepsilon_w)}$$

The area over which potentials were to be calculated was bound by distant boundaries held at zero potential as shown in Figure 6.9. The potential of the left boundary was unrestrained as it also lay within the area for which potentials were to be calculated (this left boundary was actually an axis of symmetry). The plates' potentials were held at 100 volts (for the upper plate) and 0 volts (for the lower plate) as shown in the figure. The dielectric shown in the figure has a concave surface.

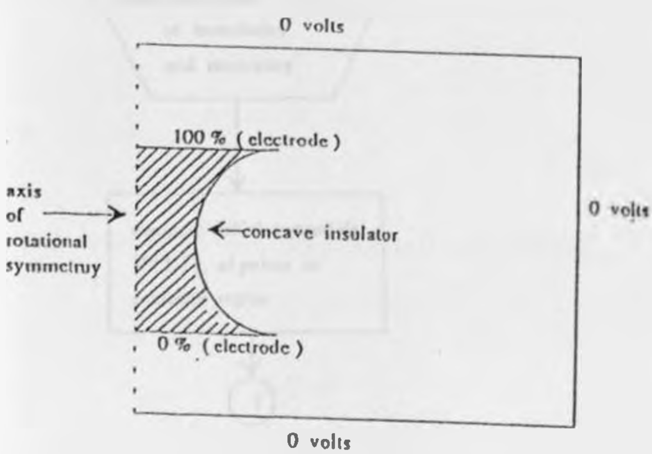
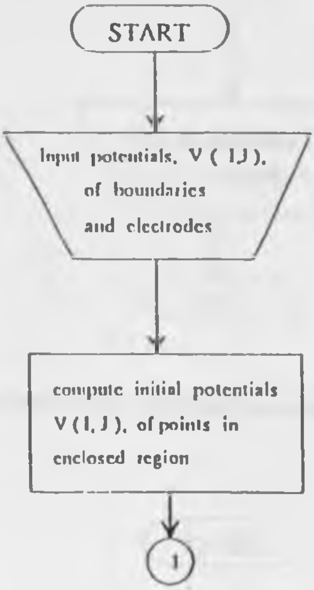


FIGURE 6.9 Layout of area over which potentials are calculated.

In evaluating the potentials of points within this region , potentials were first assigned arbitrarily to them and the actual values (to the desired accuracy) arrived at through iterations. Throughout the iterations, the lower plate (electrode) and all boundaries of the region except the left boundary were held at zero volts potential while the upper plate (electrode) was held at 100 volts potential. The flow-charts describing the computer procedures implemented are shown in Figures 6.10 and 6.11. The actual programs used are in the appendix.



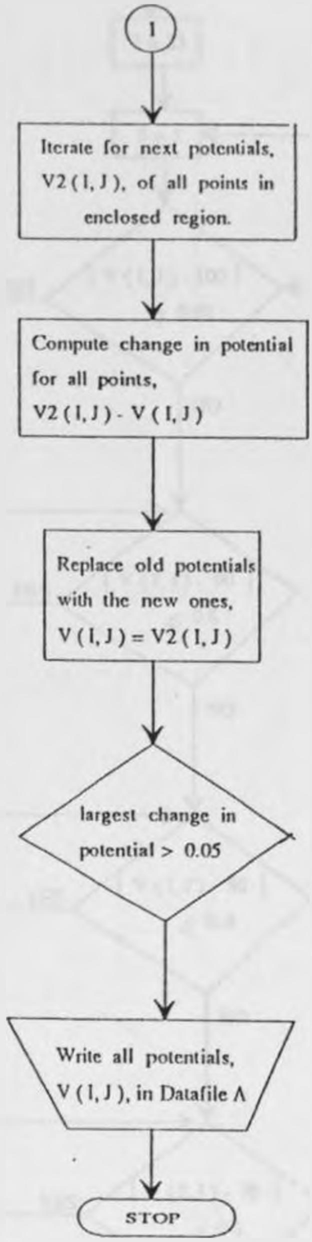
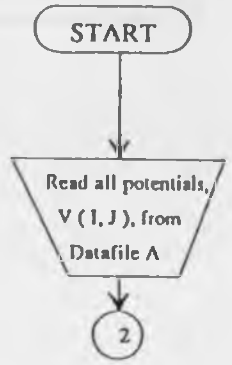
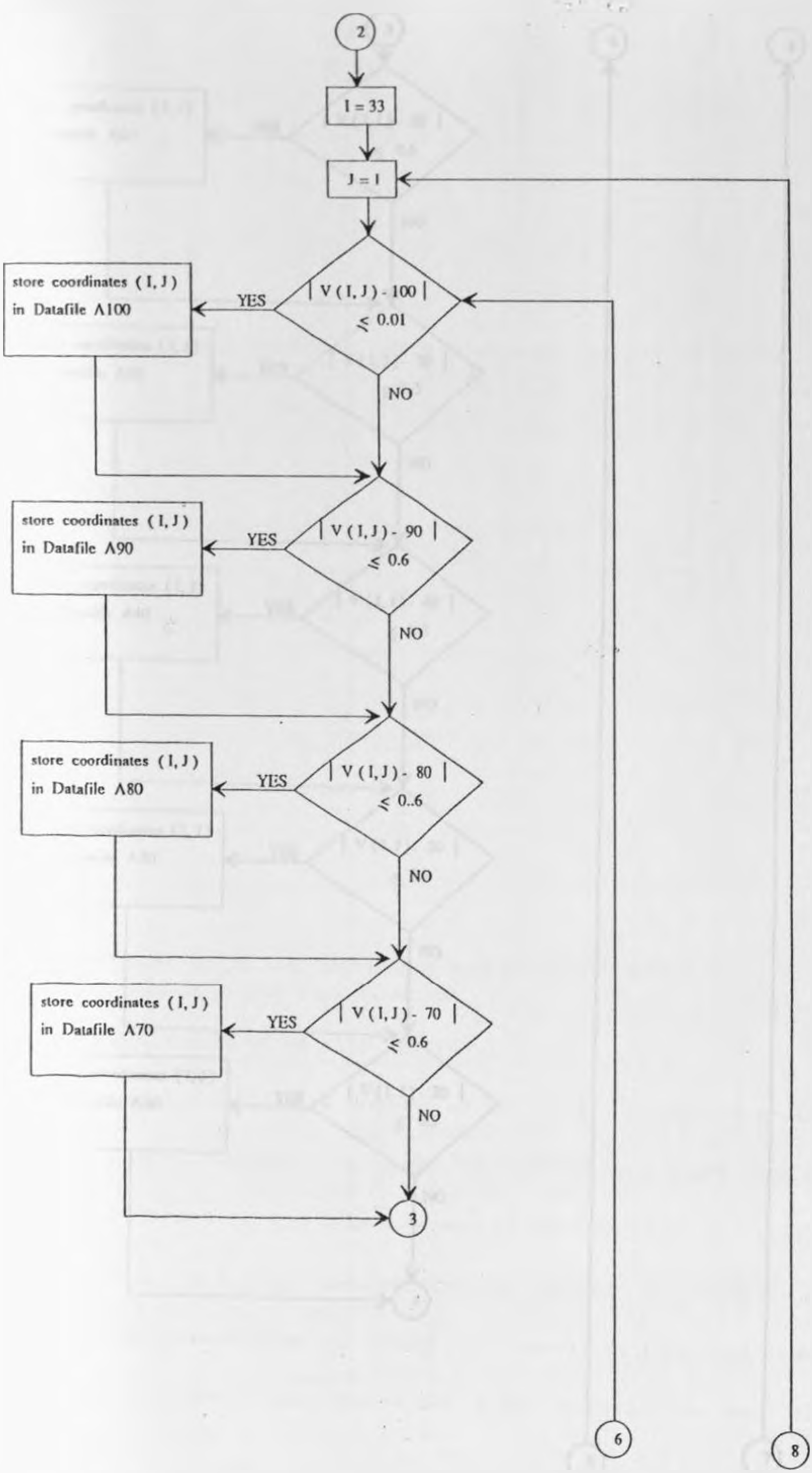
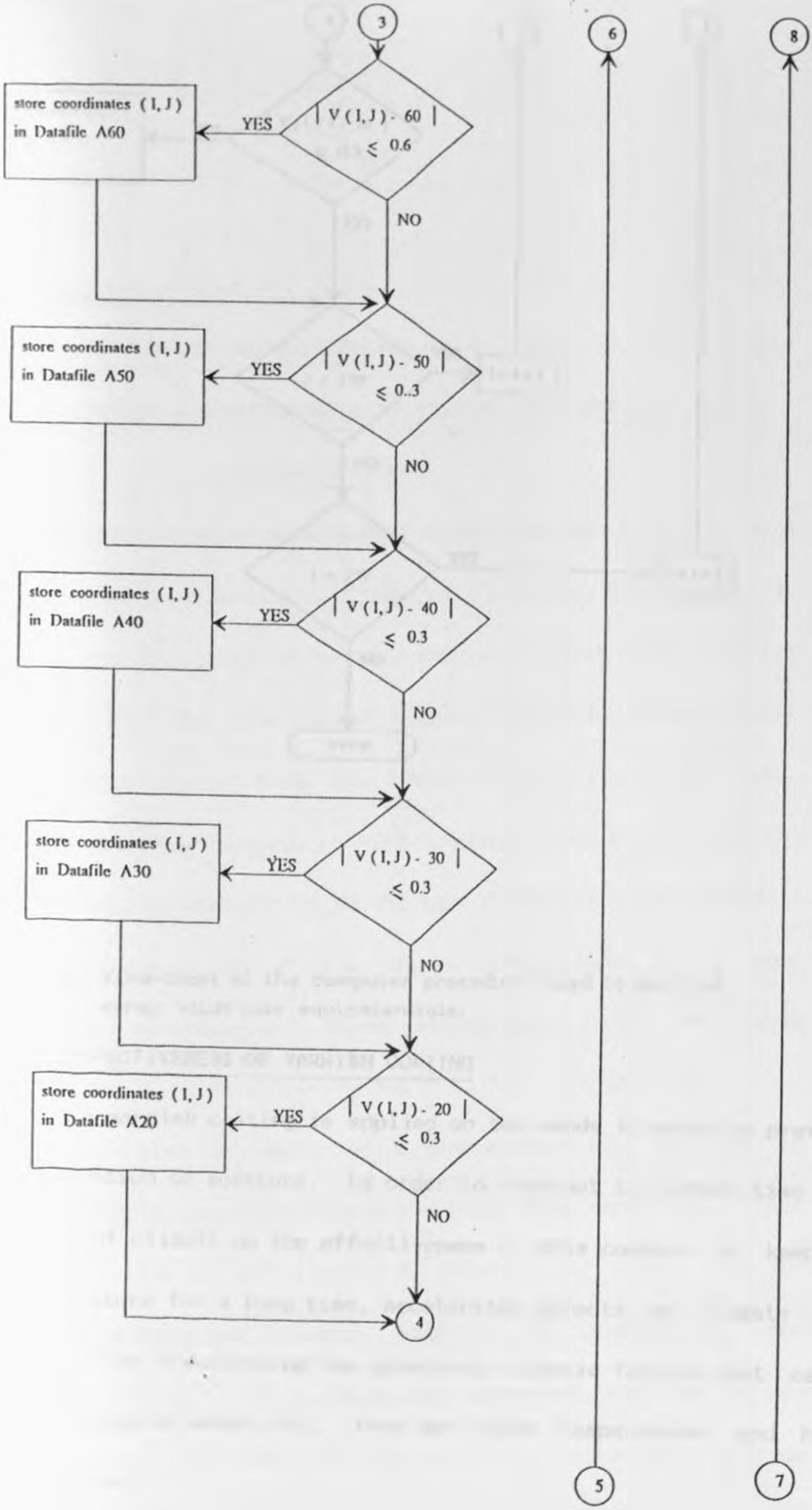


FIGURE 6.10:Flow-chart of the computer procedure used to calculate potentials.




2
I = 33
J = I
| V (I, J) - 100 | ≤ 0.01
YES
store coordinates (I, J) in Datafile A100
NO
| V (I, J) - 90 | ≤ 0.6
YES
store coordinates (I, J) in Datafile A90
NO
| V (I, J) - 80 | ≤ 0..6
YES
store coordinates (I, J) in Datafile A80
NO
| V (I, J) - 70 | ≤ 0.6
YES
store coordinates (I, J) in Datafile A70
NO
3
6
8


3
store coordinates (I, J) in Datafile A60
YES
| V (I, J) - 60 | ≤ 0.6
NO
store coordinates (I, J) in Datafile A50
YES
| V (I, J) - 50 | ≤ 0..3
NO
store coordinates (I, J) in Datafile A40
YES
| V (I, J) - 40 | ≤ 0.3
NO
store coordinates (I, J) in Datafile A30
YES
| V (I, J) - 30 | ≤ 0.3
NO
store coordinates (I, J) in Datafile A20
YES
| V (I, J) - 20 | ≤ 0.3
NO
4
6
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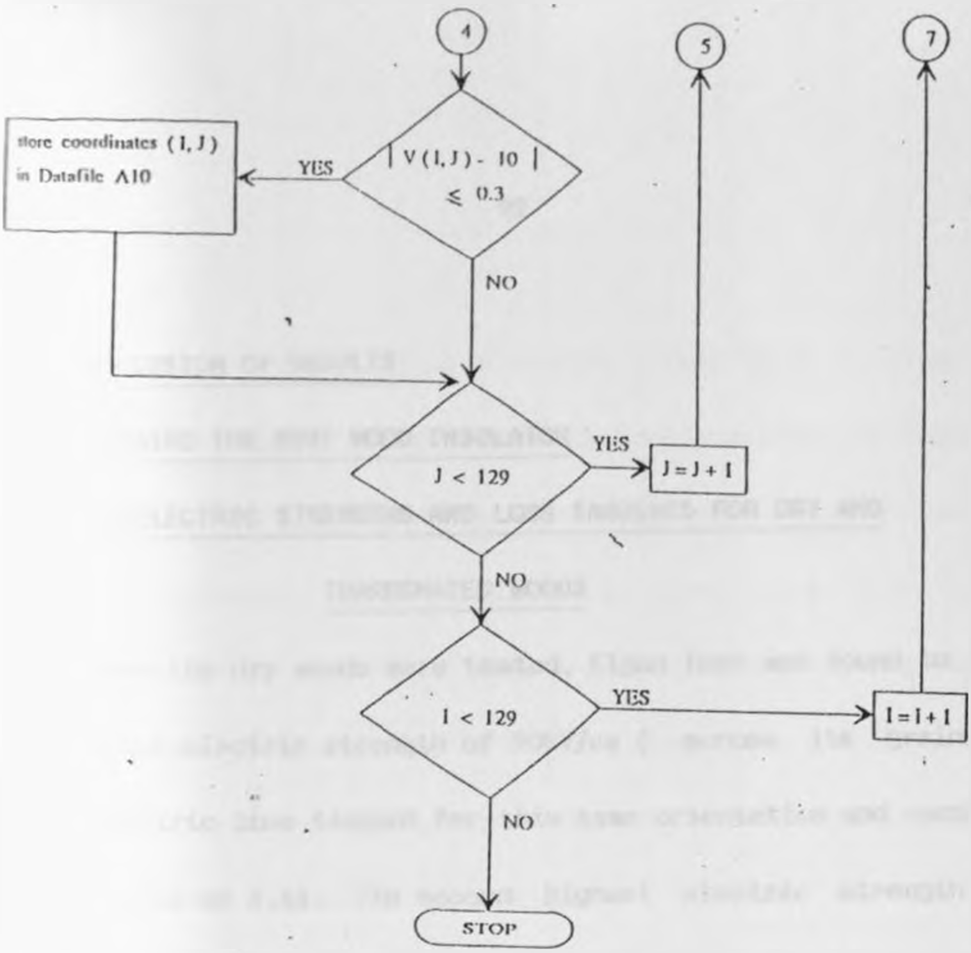


FIG 6·11 : Flow-chart of the computer procedure used to sort out array v(I,J) into equipotentials.

6.6 EFFECTIVENESS OF VARNISH COATING

A varnish coating is applied on the woods in order to prevent reabsorbtion of moisture. In order to find out in a short time the effect of climate on the effectiveness of this coating in keeping out moisture for a long time, accelerated effects of climate are obtained by intensifying the governing climatic factors that cause degredation of materials. These are high temperatures and high humidities.

7.0 DISCUSSION OF RESULTS

7.1 CHOOSING THE BEST WOOD INSULATOR

7.1.1 DIELECTRIC STRENGTHS AND LOSS TANGENTS FOR DRY AND IMPREGNATED WOODS

When the dry woods were tested, Elgon Teak was found to have the highest electric strength of 90kV/cm (across its grains). Its dielectric loss tangent for this same orientation and condition was found to be 4.6%. The second highest electric strength was also exhibited by Elgon Teak, i.e 79kV/cm (along its grains) with a corresponding loss tangent of 4.8%. Mahogany which exhibited the lowest dielectric strength of 13.8kV/cm (along its grains) had a dielectric strength of 28kV/cm across its grains. Its loss tangents corresponding to these values were 7.2% and 5.5% respectively. Results are in Tables 7.1, 7.2, 7.3 and 7.4.

Impregnating the woods with transformer oil resulted in increased dielectric strengths and decreased loss tangents. This change is similar to that observed by Rychtera [1]. For all the woods studied there was a common trend in the variation of the dielectric strengths and loss tangents with duration of boiling in transformer oil. The dielectric strengths increased to a maximum value and then dropped (Table 7.1). It is possible that the initial increase in dielectric strengths of the woods was caused by the impregnation getting better with longer periods of boiling. This occurred upto some point at which the woods attained maximum dielectric strength. Boiling beyond this point might have caused destruction of the wood fibres (as a result of their being exposed to prolonged heat) resulting in reduced dielectric strength.

The dielectric loss tangents decreased to a minimum and then increased with duration of boiling. The time for maximum dielectric strength coincided with that of minimum dielectric loss tangent (Tables 7.1 and 7.2). This is as would be expected in theory; for a given specimen a lower dielectric loss tangent corresponds to a less resistive current to capacitive current ratio. This implies that, for the same thickness of dielectric, for breakdown to occur higher electric fields would be required for the dielectric when it has a lower loss tangent.

The time of boiling required to obtain a specimen with maximum dielectric strength varied for different kinds of wood. For some woods such as, Meru Oak, Muhugu, Cedar, Mvuli, Rosewood, Podo and Camphor, the time of maximum dielectric strength along the grains coincided with that of maximum strength across the grains. These times were: 3 hours, for Meru Oak, 1 hour for Muhugu, 3 hours for Cedar, 1 hour for Mvuli, 3 hours for Rosewood, 1 hour for Podo and 1 hour for Camphor. For Bluegum, Mahogany, Elgon Teak, Pine, Cypress and Mukui maximum electric strength along the grains occurred at a time different from that at which it occurred across the grains. Most of the woods for which the two times coincided were hardwoods while most of those for which they did not were softwoods. It would be expected that minimum dielectric loss tangent and maximum dielectric strength occur at the same time as boiling in transformer oil progresses. Softwoods are less dense than hardwoods and so are more porous. This then means that the seepage of oil into softwoods should occur more easily and faster than into hardwoods. It is then possible that as boiling continued the softwoods got burnt at the surfaces and the burning could have extended to some depth in the wood. The burning of wood converts the wood into carbon which is conducting so that the effective (non-conducting) insulation thickness was decreased. While this thickness of insulation required less voltage to cause its puncture, the measured thickness of the insulation included the conducting carbon layers. This would explain why the dielectric strengths were not maximum when the loss tangents were minimum. This effect is less in the case of hardwoods as the impregnation is difficult and so the hot oil does not seep deep enough to destroy a significant thickness of the wood. So for the hardwoods maximum dielectric strength occurred at the same time as minimum loss tangent. Another possible explanation is that the impregnation of the softwoods resulted in a totally different material and hence a different relation between loss tangent and breakdown voltage.

The first four woods, arranged in the order of the one that attained the highest dielectric strength to the one that attained the minimum, were:

(i) Muhugu, 311.1kV/cm across grains and 222.2kV/cm along grains after 1 hour of boiling in transformer oil.

(ii) Elgon Teak 291.7kV/cm across grains and 93.3kV/cm along grains after 1 hour of boiling in transformer oil.

(iii) Podo 230.8kV/cm across grains and 148kV/cm along grains after 1 hour of boiling in transformer oil.

(iv) Cypress 210kV/cm across grains and 105kV/cm along grains after 3 hours of boiling in transformer oil.

For all the woods examined, the dielectric strength across the grains was higher than that along the grains except for Muhugu, Pine, Mvuli and Podo for which the reverse was true after 5 hours of boiling in transformer oil. The observed higher dielectric strength across the grains than along the grains is expected because the ions in the nutrient substances in the wood can only move through the capillaries which are oriented parallel to the axis of the tree trunk [12]. These ions would then serve to enhance the conductivity of the wood along the grains only. This would then mean that the dielectric strength of wood would be lower along its grains than across its grains.

The corresponding dielectric loss tangents of these woods were:

(i) Muhugu, 2.1% across grains and 1.8% along grains.

(ii) Elgon Teak, 2.5% across grains and 3.1% along grains.

(iii)Podo, 2.4% across grains and 5.5% along grains.

(iv) Cypress, 0.3% across grains and 3.4% along grains.

These four woods were selected for further study by way of investigating the effect of a varnish coating, applied on them , on their dielectric strength and loss tangents.

7.1.2 DIELECTRIC STRENGTHS AND LOSS TANGENTS FOR VARNISHED WOODS

Once the dry woods had been varnished and the varnish let to dry the dielectric strength of Elgon Teak across its grains rose from 90kV/cm to 121.9kV/cm while that along its grains dropped from

79kV/cm to 52.2kV/cm. In this varnished state the dielectric strength of Elgon Teak was lower than that of Muhugu which now had a dielectric strength of 130.6kV/cm across its grains.

For woods boiled in transformer oil for 0.5 hours and 1 hour, the varnish had the effect of lowering the dielectric strength. The varnish had the effect of raising the dielectric strengths of woods that had been boiled for 5 hours. For dry woods and wood boiled for 3 hours the effect of the varnish was mixed, that is, for some woods it lowered the dielectric strength while for others it raised it.

For woods boiled in transformer oil for 0.5 hours and 1 hour the varnish had the effect of increasing the dielectric loss tangents. For dry wood, wood boiled for 3 hours and 5 hours the effects of the varnish on their dielectric loss tangent was mixed. The effect of the varnish on the dielectric strengths and loss tangents of the treated and untreated woods is observable in thin wood specimens (less than 3mm as used in this study) where total penetration of the wood by the varnish is possible. The effect of the varnish would not be significant for thick wood specimens which are necessary if wood is to be used as a material for insulators for high voltages. So the effects of a varnish coating on the dielectric strength and loss tangent of wood is not very important for wood used in high voltage insulation. The varnish is only useful in keeping out moisture.

7.1.3 THE BEST WOOD INSULATOR

In choosing the best wood from which to make the insulators, Elgon Teak was preferred to Muhugu because Muhugu:

(i) is very difficult to machine as it is extremely hard so that making insulators from it would be difficult.

(ii) chips off easily

(iii) is very expensive

(iv) is less abundant than Elgon Teak and most of the quantities available are used extensively in the making of wood carvings.

7.2 OPTIMIZING THE INSULATOR SHAPE

7.2.1 FLASHOVER VOLTAGES AND LEAKAGE CURRENTS

An 11-kV insulator should have a flashover voltage of about 50kV when dry [7]. In trying to find out the best general shape, the shape that was first tried out was the cylinder (untreated wood). A cylinder of height 14cm was found to have a flashover voltage of 53kV (which is about 50kV) as shown in Table 7.5 (

shape (a)). The heights of the subsequent shapes tried out was maintained at 14cm while the diameter of the top surface maintained at 5cm. The different shapes tried are shown in Table 7.5, and were:

(a) the cylindrical shape (shape (a))

(b) three convex shapes (shapes (b), (c), and (d))

(c) three concave shapes (shapes (e), (f), and (g))

(d) a shape with a convex top and a concave bottom (shape (h))

(e) a shape with a concave top and a convex bottom (shape (i))

The results of flashover voltage and leakage currents for these shapes are shown in Table 7.5. It was noticed that the more the insulators bulged out, the lower their flashover voltages and the higher their volume leakage currents became such that the concave insulators were found to be of the best general shape. This is probably because the thinner the insulator body (that is, the more constricted the insulator body) between the electrodes, the smaller the cross-section are through which leakage current can flow and hence the smaller the leakage current of the insulator. The more concave the insulator (that is, the thinner its middle), the higher was its flahover voltage and the smaller was its volume leakage current. As for the insulator with concave and convex parts, it was found that its flashover voltage was higher (61kV) when the concave part was next to the high voltage electrode than when the convex part was next to it (52kV). It is possible that when the convex part of the insulator was next to the high voltage electrode the electric field along the surface of the insulator is higher than for the shape with the convex part next to the earth electrode. This would then mean that with the convex part next to the high voltage electrode the high fields developed would lead to the breakdown of air (at the point of highest field strength along the insulator surface) at lower voltages than would be the case when the convex part is next to the earth electrode; once breakdown occurs at a point on the insulator surface, it propagates and leads to a flashover across the insulator surface. In both cases the leakage current was about 51 μA dry wood (Table 7.5, shapes (h) and (i)).

7.2.2 ELECTRIC FIELD ANALYSIS

A study was then undertaken to evaluate the variation of the electric field along the surface of an insulator in order to establish a relationship between the profile of an insulator and its flashover voltage. So field and equipotential plots were made for a cylindrical, a convex and a concave insulator with the aim of discerning what aspects of the plots would determine the insulator with the highest flashover voltage. By noting the insulator profile that gives rise to the electric field distribution that results in highest flashover voltage, a relationship between an insulator profile and its flashover voltage could be deduced. These plots are made for insulators of the same height. The extent to which they bulge out or cave in is not exactly the same as it is in the practically tested shapes; the shapes are only useful in discerning the differences in the field and equipotential plots for a cylindrical, a concave and a convex insulator. Also, while the plots can be used in comparing the flashover voltages of the various shapes, the plots cannot be used to predict accurately the flashover voltages. The results of the field and equipotential plots are in Figures 7.1, 7.2, 7.3, 7.4 and 7.5. The equipotential plots were made for an assumed potential of 100V at the high voltage electrode and zero volts at the earth electrode. The 90% equipotential is not shown (except in the air-gap equipotential plots) because the software package used to plot the equipotentials could take a maximum of 10 graphs. These 10 graphs have been chosen to be the surface of the insulator and equipotentials of

100%, 80%, 70%, 60%, 50%, 40%, 30%, 20% and 10%.

The convex insulator had the highest maximum field strength of 4.4V/mm at the high voltage electrode (Figure 7.1). Between the electrodes, the field was lower (a minimum value of about 0.3V/mm) and of an almost flat profile. At the earth electrode the field rose to about 1.8V/mm. Even though the dielectric arrangement is symmetrical there is no symmetry in the curve because there can be no symmetry in the potential distribution as one end of the insulator is held at 100 volts while the other at 0 volts; the electric field is calculated along the surface from the high voltage electrode towards the earth electrode. The cylindrical insulator had the second-highest maximum field strength of 2.9V/mm at the high voltage electrode (Figure 7.1).

The variation of the field for the cylindrical insulator was generally like that for the convex insulator. Between the electrodes it dropped to a minimum of 0.6V/mm and then rose to 1.0V/mm at the earth electrode. The concave insulator had the least maximum field strength of 2.0V/mm somewhere in the middle of the distance along its surface between the electrodes (Figure 7.1). The field plot for this shape was completely different from those of the other two shapes. It rose from a low value at the high voltage electrode to a peak somewhere in the middle and then dropped to a very low value (almost 0V/mm) for much of the distance next to the earth electrode.

A possible explanation for the observed field behaviour can be obtained by first examining the electric field characteristics of two extreme electrode configurations between which lie the electrode configuration used in this study; these two configurations are the point-point electrode configuration and that consisting of two infinite parallel plates. The electric field distribution between two oppositely charged point charges is as shown in Figure 7.1. It is high at the two point charges and low between them:

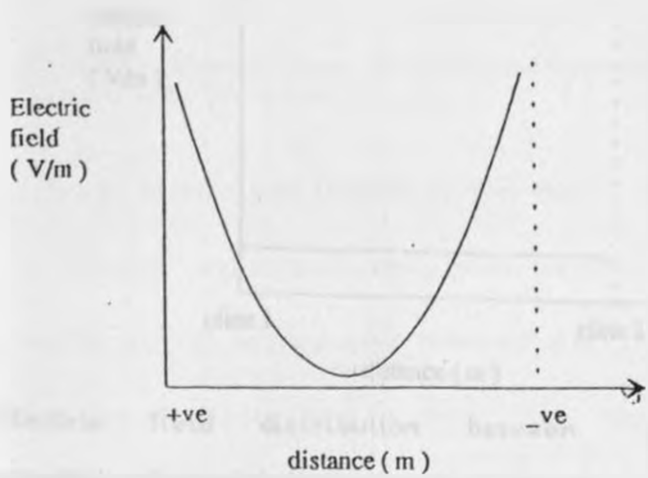


FIGURE 7.1 : Electric field distribution between two oppositely charged point-charges.

$$E = \frac{q}{4\pi\epsilon}\left[\frac{1}{r^2} - \frac{1}{(d-r)^2}\right]$$ is the equation of the graph in Figure 7.1.

where q = charge at each point

ϵ = permittivity

r = distance from positive charge

d = distance between the two charges

E = electric field, V/m

The electric field versus distance plot between two oppositely charged infinite parallel plates is a straight horizontal line [15] as shown in Figure 7.2:

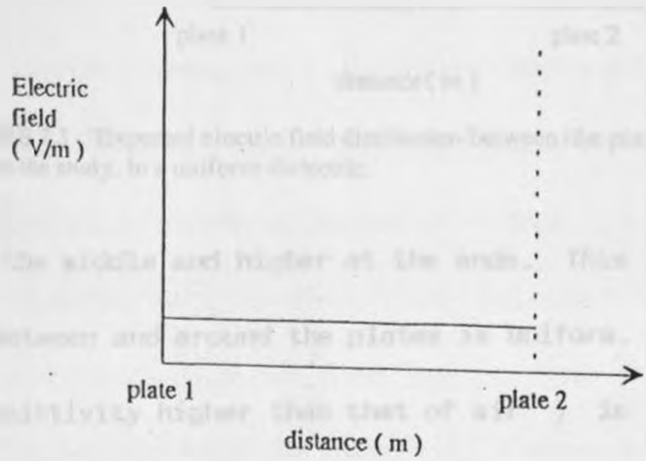


FIGURE 7.2: Electric field distribution between two oppositely charged infinite parallel plates.

$E = \frac{2V}{d}$ V/m is the equation of the graph in Figure 7.2.

where V = absolute value of potential at one plate

d = distance between the plates

The electrode configuration used lies between these two extremes so that the profile of the electric field distribution between the plates should be between the ones in Figures 7.1 and 7.2, as shown in Figure 7.3:

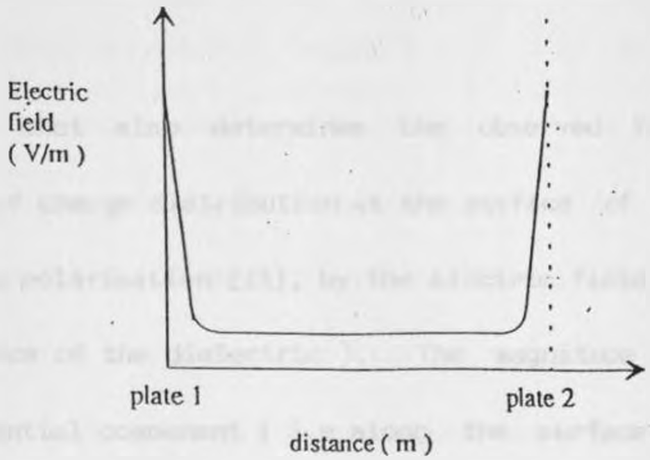


FIGURE 7.3 : Expected electric field distribution between the plates, used in the study, in a uniform dielectric.

It is flat in the middle and higher at the ends. This is so if the dielectric between and around the plates is uniform. When a dielectric (of permittivity higher than that of air) is placed between the plates the electric flux is drawn into the dielectric leaving less field intensity at the surface of the dielectric. This is as observed by Kraus [15]. The electric field is strongest along the axis of rotational symmetry of the dielectric and is weaker at points away from this axis. The thicker the middle of the insulator the less pronounced is the drawing in of electric flux and hence the smaller the electric field at the insulator surface. For the concave insulator this effect is so pronounced to an extent that the electric field at the insulator surface at the middle part is higher than it is at the surface near the electrodes.

A second factor that also determines the observed field distribution is that of charge distribution at the surface of the insulators (caused by polarisation [15], by the electric field, of molecules at the surface of the dielectric). The magnitude and direction of the tangential component (i.e along the surface of the insulator) of the electric field at the insulator surface determines the direction in which polarisation takes place and hence whether the electric field resulting from polarisation will aid or oppose the main field. For the same voltage at the high voltage electrode the magnitude of the tangential component of the electric field decreases as the insulator becomes less convex; that is, it is highest for the convex insulator, lower for the cylindrical insulator and least for the concave insulator.

In fact for the concave insulator at the insulator surface near the electrodes this tangential component acts in a direction almost opposite to that for which it acts in the case of both the convex and cylindrical insulators. A charge of polarity opposite to that of the adjacent electrodes is formed at the insulator surfaces near the high voltage and the earth electrodes and this results in the high fields at surfaces near the electrodes for both the convex and cylindrical insulators (Figure 7.1). The higher value of tangential component in the case of the convex insulator results in it having a higher field near the electrode (Figure 7.1). Along the insulator surface between the electrodes the electric field caused by the surface charges opposes that of the main gap; this effect is greater in the case of the convex insulator than for the cylindrical insulator (the main gap field lines near the surfaces of the insulators curve outwards and so are along the surface of the convex insulator, unlike for the cylindrical insulator for which only a component of the field acts along its surface (Figures 7.4 and 7.5)) and could explain the lower field in the case of the convex than in the case of the cylindrical insulator. In the case of the concave insulator charge of the same polarity as that of the high voltage electrode is formed on the surface near high voltage electrode (the same is the case for the surface near the earth electrode) so that the field near the electrodes is weak; for the concave insulator the component of the electric field along the insulator surface near the electrodes acts towards the adjacent electrodes as shown in Figure 7.6.

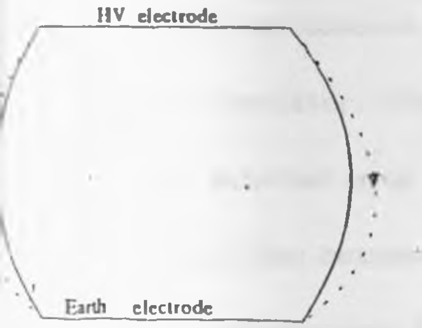


FIGURE 7.4 : Main gap field along surface of a convex insulator.

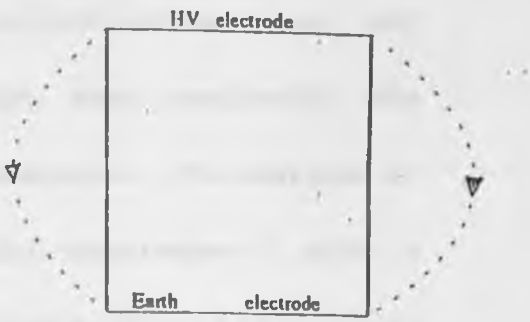


FIGURE 7.5 : Main gap field along surface of cylindrical insulator.

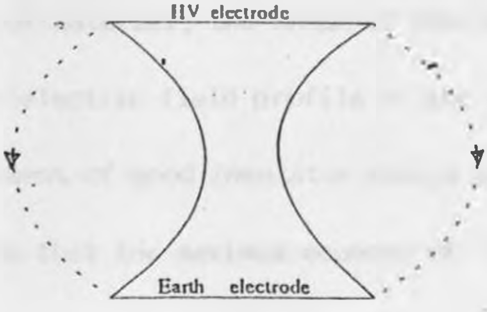


FIGURE 7.6 : Main gap field along surface of concave insulator.

The field resulting from polarisation in the case of the concave insulator acts in the same direction, along the surface between the electrodes, as the main gap field; this could also account for the observed peak value, along the surface between the electrodes, of the electric field distribution for the concave insulator.

The insulators arranged in the order of decreasing flashover voltage are: the concave insulator, the cylindrical insulator, and the convex insulator. The same order holds when considering the economy of material used in making the insulators. The envelope of the electric flux between the two circular electrodes (with a dielectric between them) is like the curved surface of the concave insulator so that the order of the insulators starting with the one that conforms least with this field form is: the convex insulator, the cylindrical insulator and the concave insulator. It is then observed that for maximum flashover voltage of an insulator and maximum economy of material, the shape of the insulator body should conform with the electric field profile of the gap. This agrees with the requirement of good insulator design as given in reference [11]; this states that for maximum economy of insulator material, the shape of the insulator should conform as closely as possible with the shape of the electric field profile of the gap.

At this stage it seems like only the peak value of the field plots determines the flashover voltage of an insulator; that is, the higher the peak value of the field plot the lower the flashover voltage of the insulator (Figure 7.12). In order to understand better the relationship, further shapes have to be tested. After noting this relationship between the field plots, equipotential plots and the flashover voltages, it seemed like an insulator with an even higher flashover voltage could be obtained by combining appropriately the features of the cylindrical, convex and concave insulators that seemed to result in their having low field strengths over some regions of their surfaces. These features seemed to be:

(a) the smooth curving of the insulator edge into the electrodes as exhibited by the concave insulator.

(b) the thick middle portion in the case of both the cylindrical and the convex insulators.

Two insulator shapes (as in Table 7.7) were tried out. Their field plots are in Figures 7.6 and 7.7; they have been drawn together with those of the insulators from which their shapes were derived for easy comparison. Their flashover voltages turned out to be higher than for the individual shapes from which their shapes were derived. The modified convex insulator (Table 7.7, shape (a)) had a flashover voltage of 54.6kV as compared to the value of 48kV for the convex insulator (Table 7.5, shape (c))from which it derived its shape. The modified cylindrical shape (Table 7.7, shape (b))had a flashover voltage of 58.8kV as compared to the value of 53kV for the cylindrical insulator (Table 7.5, shape (a)) from which it derived its shape. These two new shapes have field plots that have zero field strength at the electrodes; the surfaces of the insulators where the peaks occur are next to the concave regions of the insulators (Figures 7.6 and 7.7). These values of flashover voltage are less than the value for optimum concave insulator, which is 84.3kV. This then means that the best shape is that of the concave insulator in terms of flashover voltage and economy of insulator material. Looking at all the field plots together with the flashover voltages of the corresponding shapes, it is seen that the higher the peak value of the field plot of an insulator shape, the lower the flashover voltage for that shape, Table 7.10.

The optimum concave insulator Table 7.5 (shape (e)) has a flashover voltage of 84kV which is well beyond 50kV, the required flashover voltage of an 11kV insulator under dry conditions. So to help come up with the possible dimensions of an 11-kV insulator, the effects of insulator height, concavity and electrode diameter were investigated. This was done by:

(a) Keeping the diameter of the middle part of the concave insulator constant at about 2cm and varying its height in order to obtain an insulator with a flashover voltage of about 50kV (an 11kV insulator should have a flashover voltage of about 50kV when dry). It was not possible to make concave insulators with the middle part of thickness less than 2cm because the vibrations of the lathe machine (used for shaping the insulator) resulted in the cracking or breaking of this middle part. Also insulators with a middle part of a thickness less than 2cm would be mechanically weak. Insulators of height 9, 10 and 11cm were tried. The insulator of 10cm height was found to have a flashover voltage of 51kV and so the insulator in Table 7.6 (shape (b)) was found to be the optimum insulator. These results are shown in Table 7.6.

(b) Making field plots of concave insulators of various degrees of concavity. The field plots are shown in Figures 7.8 and 7.9. It is seen from these plots that the more concave an insulator the lower is its maximum field strength. Going by earlier deductions this implies that the more concave an insulator is, the higher its flashover voltage shall be (Table 7.5). From these plots it is also seen that the more concave an insulator is, the lower the values of the field strengths next to the electrodes (Figure 7.8).

(c) Making field plots for an insulator with various diameters of electrodes. The field plots are as shown in Figure 7.10. It is seen from these plots that the smaller the diameter of the electrodes the lower the value of the maximum field strengths next to the electrodes. From Table 7.9, it is seen that an insulator has a higher flashover voltage the smaller the diameter of the electrode used with it. This could be as a result of the increased creepage path between the electrodes when electrodes of smaller diameters are used

From the obtained field plots it can be said that the insulator with the highest flashover voltage is the one that is most concave and with electrodes of smallest diameter.

7.3 THE BEST INSULATOR SHAPE

7.3.1 INSULATOR DIMENSIONS

There are many possible dimensions for an 11-kV insulator, a possible set is as shown in Table 7.6 (Configuration (b)). A limit as to the extent of concavity (that is, the thinness of the middle of the insulator) of the insulator is imposed by the magnitudes of the mechanical forces expected on the insulator while in service; the larger the mechanical forces the thicker the middle of the insulator should be.

7.3.2 INSULATOR CHARACTERISTICS IN VARIOUS CONDITIONS

The variation of the leakage current of this insulator (dry wood)with time (over a period of 10 hours) is as shown in Figure 7.11. With the applied voltage maintained at $11/\sqrt{3}$ kV the leakage current rose from 50.6μA to a peak value of 64.5μA after 1 hour. It then dropped gradually to a value of about 41.5μA after 10 hours. The initial high values of current are due to displacement (charging current) and absorption currents (which gradually decays to zero) leaving only the true conduction current (the leakage current). The absorption current is due to gradual stretching of the electron bonds (in the insulator) after the main displacement has occured until balance is reached between the applied stress and the resistive effort [11]. Attempts to reduce the leakage current of the insulator by making ridges on it, resulted in reduced flashover voltage (from 51kV to 47kV) for dry wood, Table 7.11. Introduction of ridges on the insulator surface has the effect of creating many small concave surfaces in between the ridges so that many smaller concave surfaces are superposed on the initial big concave surface; this could have resulted in more field distortion (than in the case when there were no ridges on the insulator surface) along the surface of the insulator (in the smaller concave surfaces) resulting in a lower flashover voltage for the insulator with ridges.

Impregnating the insulator with transformer oil lowers the flashover voltage from 51kV to 49kV. It also increases the leakage current from 54μA to 60μA, Table 7.11. Impregnation, even though it increases the electric strength of laminates (which are better impregnated because of their thinness) is not of much use for thick insulators because the oil does not seep deep enough into the insulator body so that much of the insulator is left unimpregnated.

Moisture which causes the insulation properties of the insulator to deteriorate is kept out by coating the insulator with an oil varnish. The varnish coating was observed to lower the leakage current from 54μA to 51μA and the flashover voltage from 51kV to 49kV, Table 7.11. The lowering of flashover voltage by the varnish coating is expected because the varnish coating gives a smooth surface that covers the characteristic rough surface of uncoated wood; a rough surface results in a larger creepage distance (that is, distance along the surface of an insulator over which flashover occurs) which requires higher voltages if flashover is to occur [7]. It is also possible that the varnish coating affects the charge distribution profile of the insulator by trapping more charge, resulting in more field distortion and a lower flashover voltage.

7.4 EFFECTIVENESS OF THE VARNISH COATING

In order to check how effective the varnish coating would be in keeping out moisture over long periods, the varnish coating was subjected to an accelerated ageing test. It was exposed to high temperature (40^{o}C) and high humidity (about 96%) for a period of two months. For the varnish used (which was an oil varnish) moisture pick-up and swelling caused blisters to appear on the surface of the film after a period of 3 weeks. The surface darkened and became soft. After 2 months the extent of swelling was such that the whole film disintegrated and moisture got into the wood. Silicone varnishes are distinguished by exceptional resistance to moisture and high temperatures (that is, the varnishes prove satisfactory even under the most severe climatic conditions) [1]; this type of varnish was not tried in this study. These varnishes could make wood useful as an insulator by keeping out moisture which is the chief cause of the ageing of wood. If wood is to be useful as an insulator for high voltages, its use should be restricted to areas that are not exposed to high temperatures and high humidities (for example as busbar supports indoors or as supports of conductors in oil circuit-breakers). Alternatively, its use could be restricted to areas that are not under considerable electrical load.

7.5 INSULATOR ELECTRODES

So far the electrodes considered in the discussion are circular with their flat surfaces in contact with the top and bottom flat surfaces of the insulator. With electrodes of this shape it was possible to study the performance of various insulator shapes by computer using a two dimensional layout (by taking advantage of the circular symmetry of the electrode/insulator combination). 11kV bus-bars of rod-like shape are also supported on insulators. For this kind of insulator/electrode arrangement, the study has to be a three-dimensional one. Since meshing packages for three-dimensional field analysis were not available, it was not possible to study this configuration by computer methods. So shapes arrived at in this study were found to be optimum when used with circular electrodes only. But then rods were tried out practically with these insulators and it was found that the flashover voltages obtained when using them were generally lower than those obtained with the circular electrodes. As seen in Table 7.8, the flashover voltages increased slightly with increasing diameter of the rod. This is due to the fact that higher field intensities are developed at the electrodes of smaller diameters for the same applied voltage; this results in early ionisation of air and hence a flashover at lower voltages.

TABLE 7.1: DIELECTRIC STRENGTH (kV/CM) MEASUREMENTS RESULTS

	DRY WOOD	WOOD BOILED IN TRANSFORMER OIL AT 121 deg. centi. TEMPERATURE AND 0.105 MPa PRESSURE FOR:			
		30 MIN	1 HOUR	3 HOURS	5 HOURS
BLUE GUM (A)	21	80	98.3	83.3	72.4
BLUE GUM (C)	52.6	124	132	150	136
MERU OAK (A)	19.2	40.6	43.8	48.5	18
MERU OAK (C)	26.9	82.1	107.7	107.7	92
MAHOGANY (A)	13.8	51.8	73.3	44.6	44
MAHOGANY (C)	28	69.4	94.3	97.1	69
ELGON TEAK (A)	79	85.7	93.3	108.3	54
ELGON TEAK (C)	90	210	291.7	248	168
MUHUGU (A)	60	172	222.2	182	113.1
MUHUGU (C)	74.5	181.8	311.1	225	110
PINE (A)	21.3	59.3	92.6	123.1	152.6
PINE (C)	22.4	64.7	164.3	137.5	106
CYPRESS (A)	50	105	136	105	50
CYPRESS (C)	78	108	136.6	210	158
CEDAR (A)	17.6	60	62.2	97.5	87
CEDAR (C)	44.1	111.1	122.2	161.5	117
MVULI (A)	16.7	48.1	73.3	58.4	95
MVULI (C)	26.9	66.7	88.9	76.5	16
ROSE WOOD (A)	19.1	23	66.7	77.6	39
ROSE WOOD (C)	39.1	41.9	102.9	115.2	100
MUKUI (A)	18.3	55.6	65.3	48.4	39
MUKUI (C)	47.4	92.3	101.7	121.7	119.2

TABLE 7.2: DIELECTRIC LOSS TANGENT (%) MEASUREMENTS RESULTS

	DRY WOOD	WOOD BOILED IN TRANSFORMER OIL AT 121 deg. centi. TEMPERATURE AND 0.105 MPa PRESSURE FOR:			
		30 MIN	1 HOUR	3 HOURS	5 HOURS
BLUE GUM (A)	6.9	6.6	2	3.9	7.7
BLUE GUM (C)	6	5.8	5.3	4.7	5.9
MERU OAK (A)	11.1	10.3	5.3	7.7	8.4
MERU OAK (C)	6.9	6	3.6	4.2	4.7
MAHOGANY (A)	7.2	6.7	6.5	5.9	6.3
MAHOGANY (C)	5.5	4.9	4.2	4.2	5.1
ELGON TEAK (A)	4.8	4	3.1	4.1	4.4
ELGON TEAK (C)	4.6	3.7	2.5	4.8	6.4
MUHUGU (A)	3.2	2.6	1.8	3	3.1
MUHUGU (C)	3.2	2.8	2.1	2.9	3.2
PINE (A)	2.4	2.3	1.7	2.2	2.3
PINE (C)	5.6	5.5	4	4.5	4.7
CYPRESS (A)	7.2	6.6	6.1	3.4	5.9
CYPRESS (C)	2.7	2.4	2	0.3	1
CEDAR (A)	7.8	7.7	9.5	9.7	9.9
CEDAR (C)	13.4	13	9.1	9.1	8.9
MVULI (A)	6.4	5.9	2.2	3.1	3.6
MVULI (C)	5.9	4.5	4.3	5.1	8.4
ROSE WOOD (A)	10.9	10.5	4.8	6.2	8.3
ROSE WOOD (C)	6.2	5.6	3.6	5.1	6.1
MUKUI (A)	7.1	6.7	3.3	5.9	6
MUKUI (C)	6.2	5.9	5.6	5.7	5.8

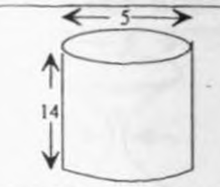
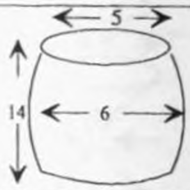
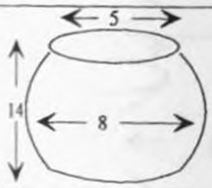
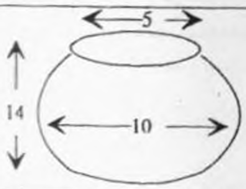
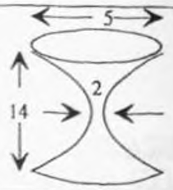
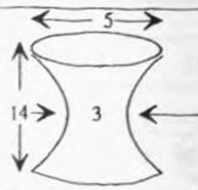
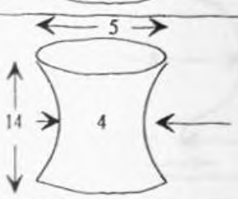
TABLE 7.3: DIELECTRIC LOSS TANGENT (%) MEASUREMENTS RESULTS FOR VARNISHED WOODS.

	DRY WOOD	WOOD BOILED IN TRANSFORMER OIL AT 121 deg. centi. TEMPERATURE AND 0.105 MPa PRESSURE FOR:			
		30 MIN	1 HOUR	3 HOURS	5 HOURS
ELGON TEAK (A)	5.5	4.2	3.5	4.2	4.3
ELGON TEAK (C)	4.4	4	3.1	5	6.7
MUHUGU (A)	3.6	3.5	3.4	3.1	3.5
MUHUGU (C)	4.2	4.2	3.2	2.6	3.1
CYPRESS (A)	12.7	12.1	10.3	8.5	5.1
CYPRESS (C)	16	15.8	7.9	6.3	8.4
PODO (A)	30.4	20.4	20.5	13.7	25.4
PODO (C)	9.7	9.7	9.5	8.6	6

TABLE 7.4: DIELECTRIC STRENGTH (kV/cm) MEASUREMENTS RESULTS FOR VARNISHED WOODS.

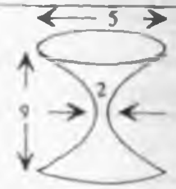
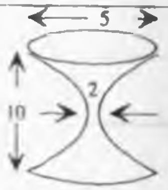
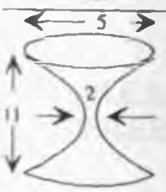
	DRY WOOD	WOOD BOILED IN TRANSFORMER OIL AT 121 deg. centi. TEMPERATURE AND 0.105 MPa PRESSURE FOR:			
		30 MIN	1 HOUR	3 HOURS	5 HOURS
ELGON TEAK (A)	52.2	62	70.5	99	123.1
ELGON TEAK (C)	121.9	142.9	200	198	140.3
MUHUGU (A)	70	116	145	163.6	136.4
MUHUGU (C)	130.6	180	218.2	235	183.3
CYPRESS (A)	51.7	71	90	118.8	135.7
CYPRESS (C)	73.3	93	112	166.5	188.9
PODO (A)	71.7	101.9	130	145	123.7
PODO (C)	98.5	100	109.3	141.6	160

TABLE 7.5 : FLASHOVER VOLTAGES AND LEAKAGE CURRENTS OF VARIOUS INSULATOR SHAPES.

INSULATOR SHAPE	FLASHOVER VOLTAGE (k V)	LEAKAGE CURRENT AT 11/$\sqrt{3}$ kV (μA)
 (a)	53	110
 (b)	50.2	123
 (c)	48	220
 (d)	45	288
 (e)	84.3	49
 (f)	65.2	53
 g)	55	97
 (h)	52	51
 (i)	61.2	52

DIMENSIONS IN CENTIMETRES

TABL 7.6 : FLASHOVER VOLTAGES AND LEAKAGE CURRENTS OF VARIOUS INSULATOR SHAPES.

INSULATOR SHAPE	FLASHOVER VOLTAGE (k V)	LEAKAGE CURRENT AT $11/\sqrt{3}$ kV (mA)
 (a)	47	66
 (b)	51	54
 (c)	56	50.6

DIMENSIONS IN CENTIMETRES .

TABLE 7.7 : FLASHOVER VOLTAGES OF THE MODIFIED CONVEX AND CYLINDRICAL INSULATORS.

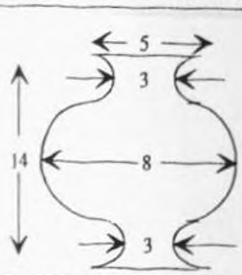
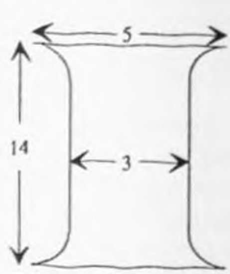
INSULATOR SHAPE	FLASHOVER VOLTAGE (k V)
 (a)	54.. 6
 (b)	58 .8

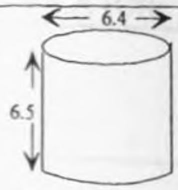
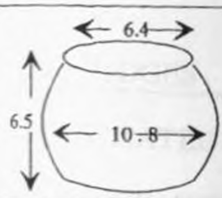
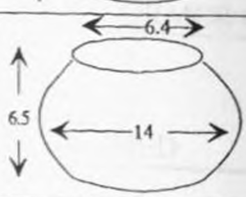
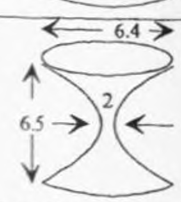
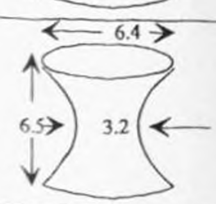
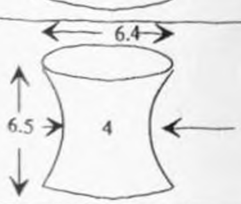
TABLE 7.8: FLASHOVER VOLTAGES OF CONCAVE INSULATOR WITH ROD ELECTRODES

ROD DIAMETER (cm)	FLASHOVER VOLTAGE (kV)
2.1	44.6
1.7	43.2
0.5	41.1

TABLE 7.9: FLASHOVER VOLTAGES OF CONCAVE INSULATOR WITH CIRCULAR ELECTRODES

ELECTRODE DIAMETER (cm)	FLASHOVER VOLTAGE (kV)
5	51
4.3	60.4
3.4	69.2
2.1	75.3
1.2	81.7

TABLE 7.10 : PEAK ELECTRIC FIELD ALOND SURFACE AND FLASHOVER VOLTAGES OF VARIOUS INSULATOR SHAPES.

INSULATOR SHAPE	FLASHOVER VOLTAGE (k V)	PEAK ELECTRIC FIELD (V/mm)
	53 *	2.9
	48 *	4.4
	45 *	6
	84.3 *	1.2
	65.2 *	2
	55 *	2.7

DIMENSIONS IN CENTIMETRES

* These flashover voltage values are for insulators of dimensions as in TABLE 7.5 . The flashover voltages of these shapes (in TABLE 7.10) were not measured as these shapes were not constructed; they were only assumed shapes during computations of fields and equipotentials by computer.

TABLE 7.11 : FLASHOVER VOLTAGES OF THE OPTIMUM CONCAVE INSULATOR

CONDITION OF OPTIMUM INSULATOR	FLASHOVER VOLTAGE (kV)	LEAKAGE CURRENT (micro amps)
DRY	51	54
WITH RIDGES	47	50
IMPREGNATED WITH TRANSFORMER OIL	49	50
VARNISHED	49	51

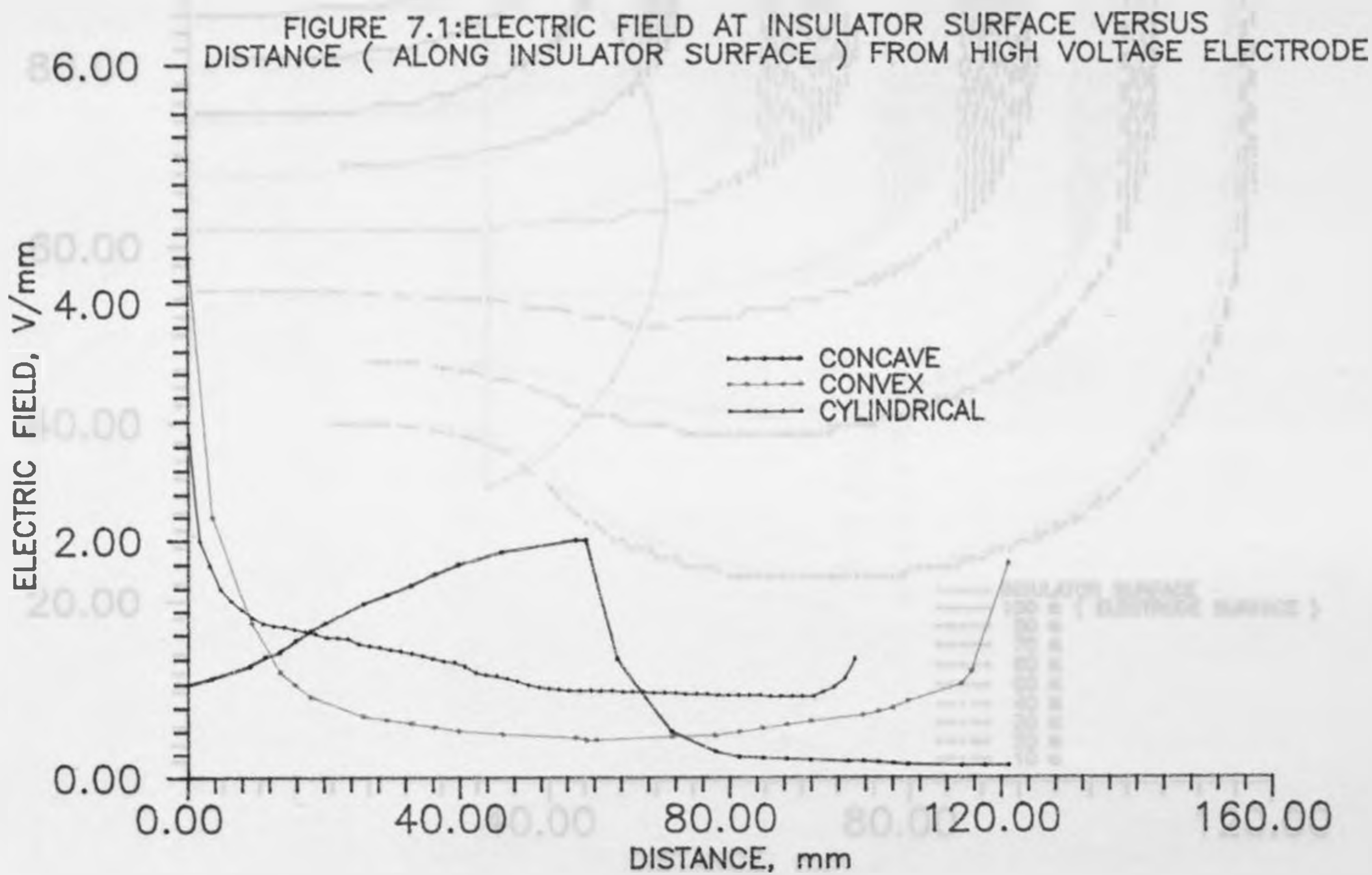


FIGURE 7.1:ELECTRIC FIELD AT INSULATOR SURFACE VERSUS
DISTANCE (ALONG INSULATOR SURFACE) FROM HIGH VOLTAGE ELECTRODE
6.00
4.00
2.00
0.00
ELECTRIC FIELD, V/mm
CONCAVE
CONVEX
CYLINDRICAL
0.00
40.00
80.00
120.00
160.00
DISTANCE, mm

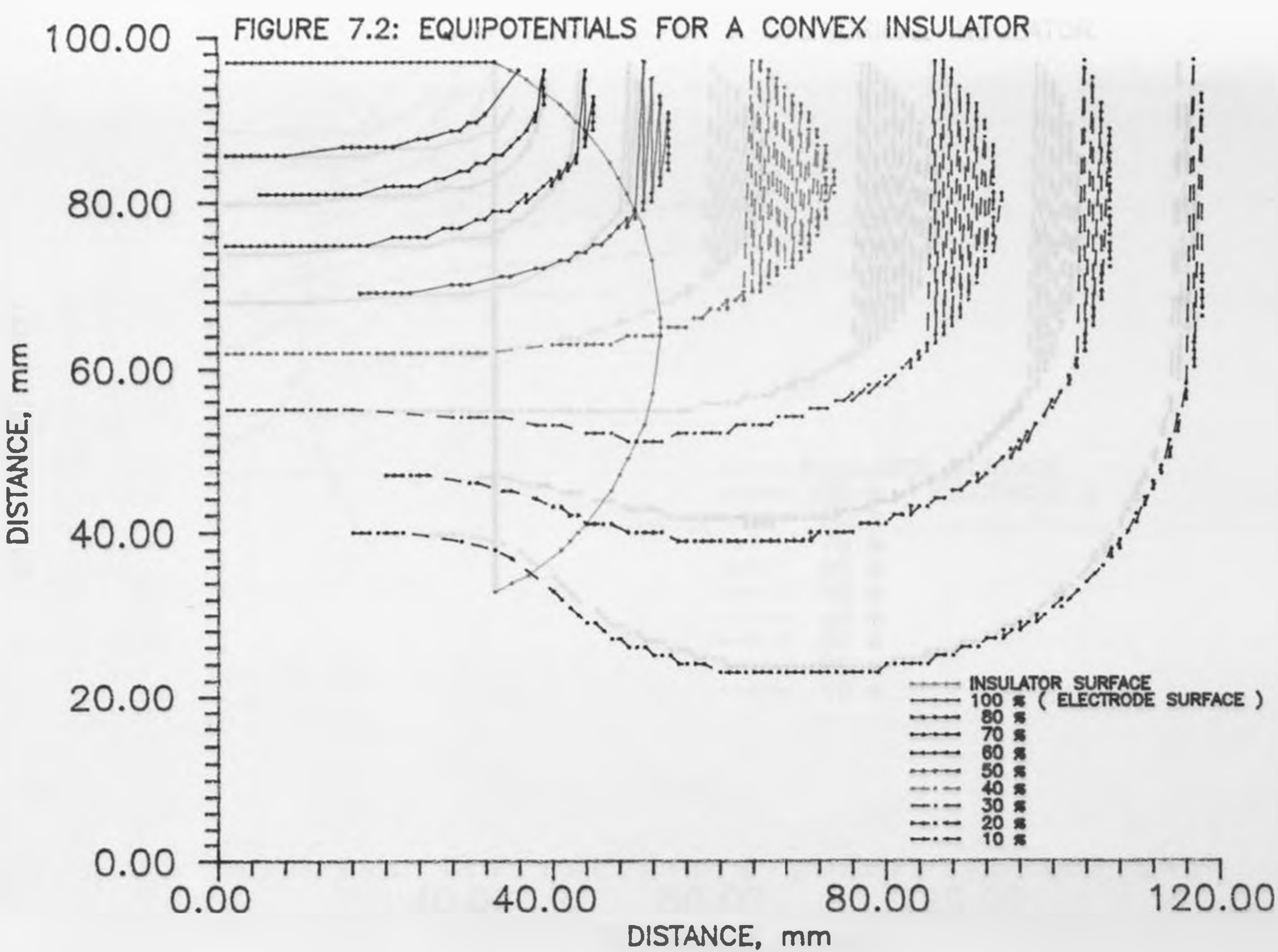


FIGURE 7.2: EQUIPOTENTIALS FOR A CONVEX INSULATOR
100.00
80.00
60.00
40.00
20.00
0.00
DISTANCE, mm
0.00
40.00
80.00
120.00
DISTANCE, mm
INSULATOR SURFACE
100 % (ELECTRODE SURFACE)
80 %
70 %
60 %
50 %
40 %
30 %
20 %
10 %

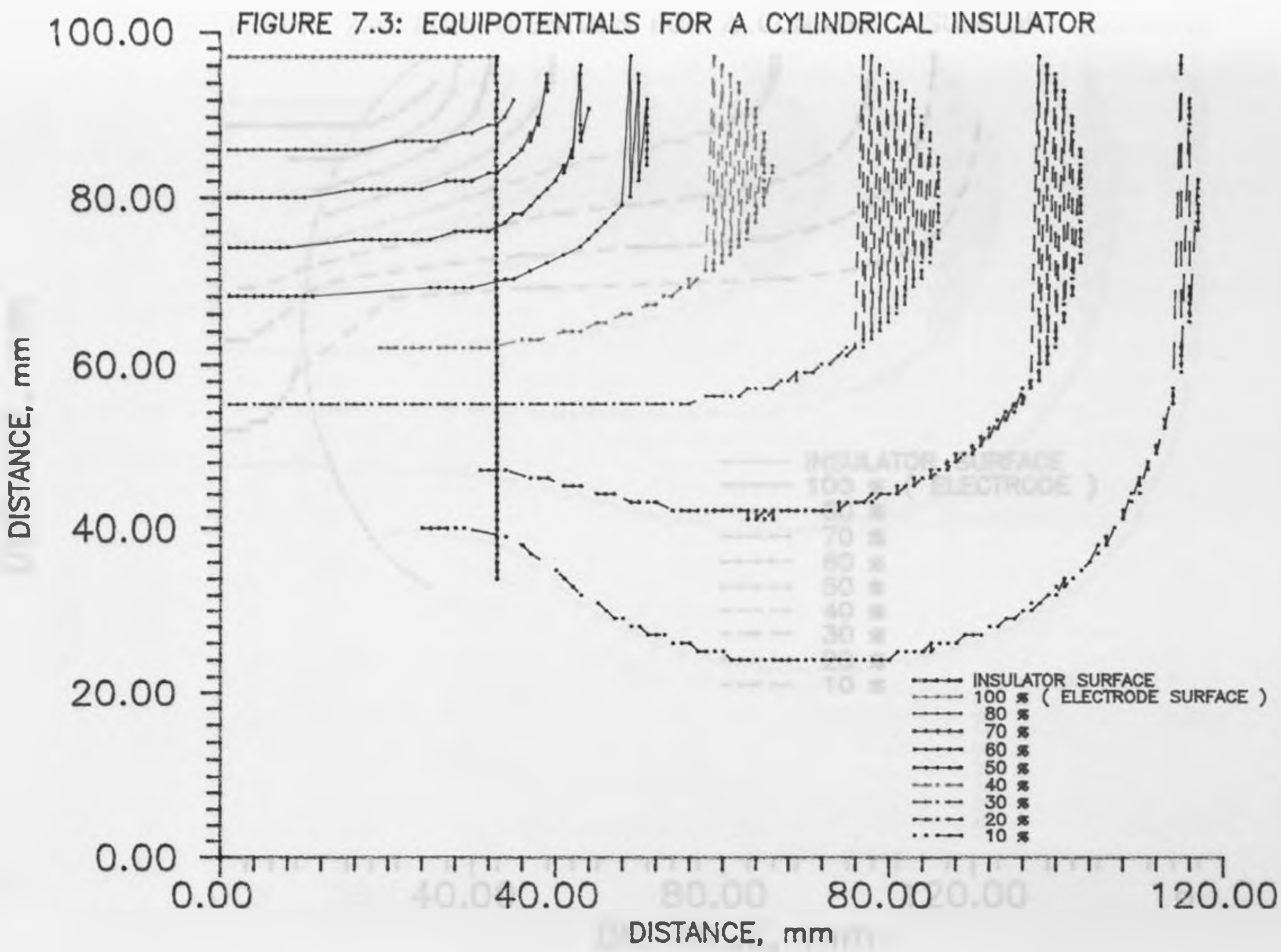


FIGURE 7.3: EQUIPOTENTIALS FOR A CYLINDRICAL INSULATOR
100.00
80.00
60.00
40.00
20.00
0.00
DISTANCE, mm
0.00
40.00
80.00
120.00
DISTANCE, mm
INSULATOR SURFACE
100 % (ELECTRODE SURFACE)
80 %
70 %
60 %
50 %
40 %
30 %
20 %
10 %

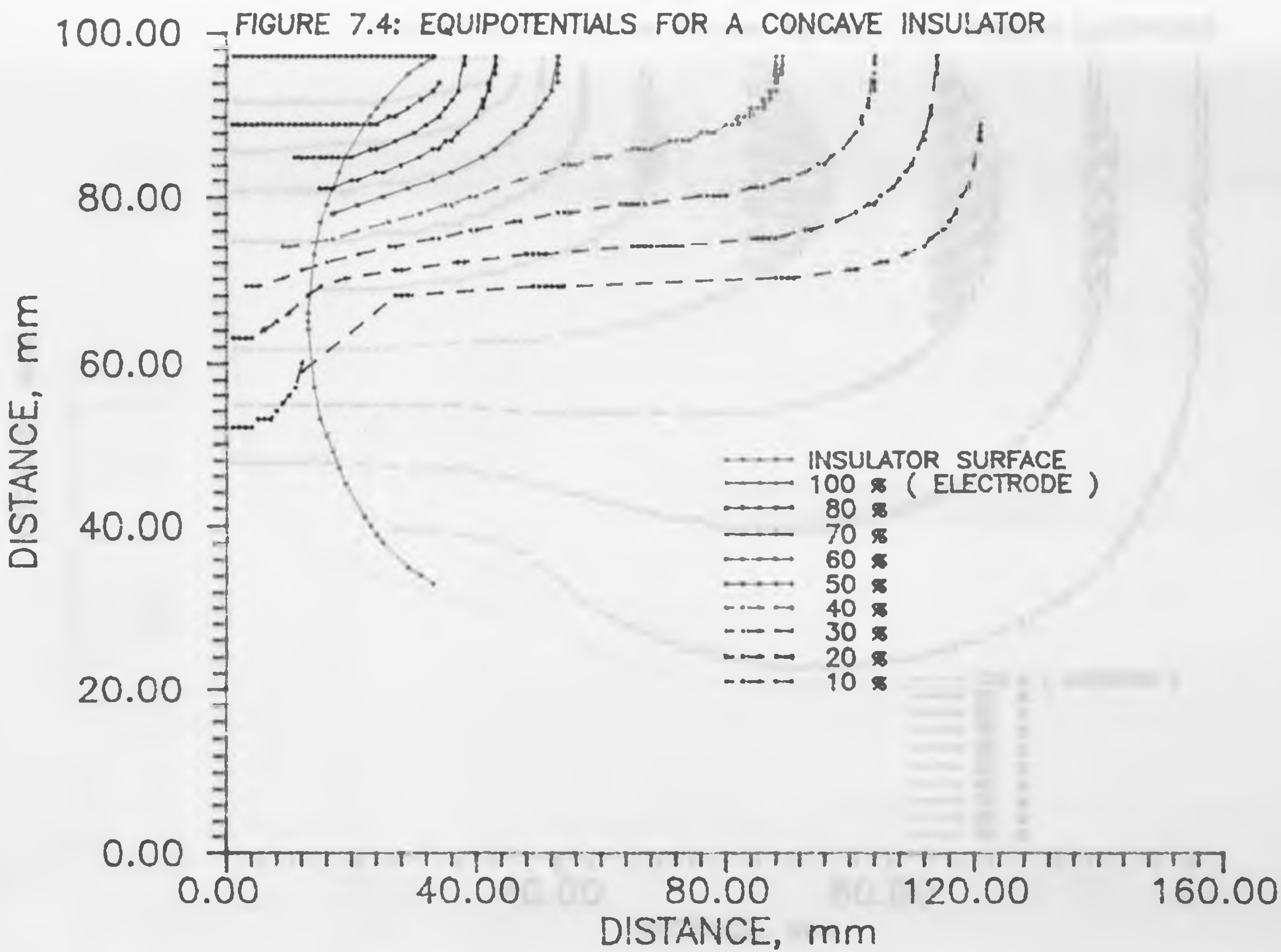


FIGURE 7.4: EQUIPOTENTIALS FOR A CONCAVE INSULATOR
DISTANCE, mm
DISTANCE, mm
0.00
20.00
40.00
60.00
80.00
100.00
0.00
40.00
80.00
120.00
160.00
INSULATOR SURFACE
100 % (ELECTRODE)
80 %
70 %
60 %
50 %
40 %
30 %
20 %
10 %

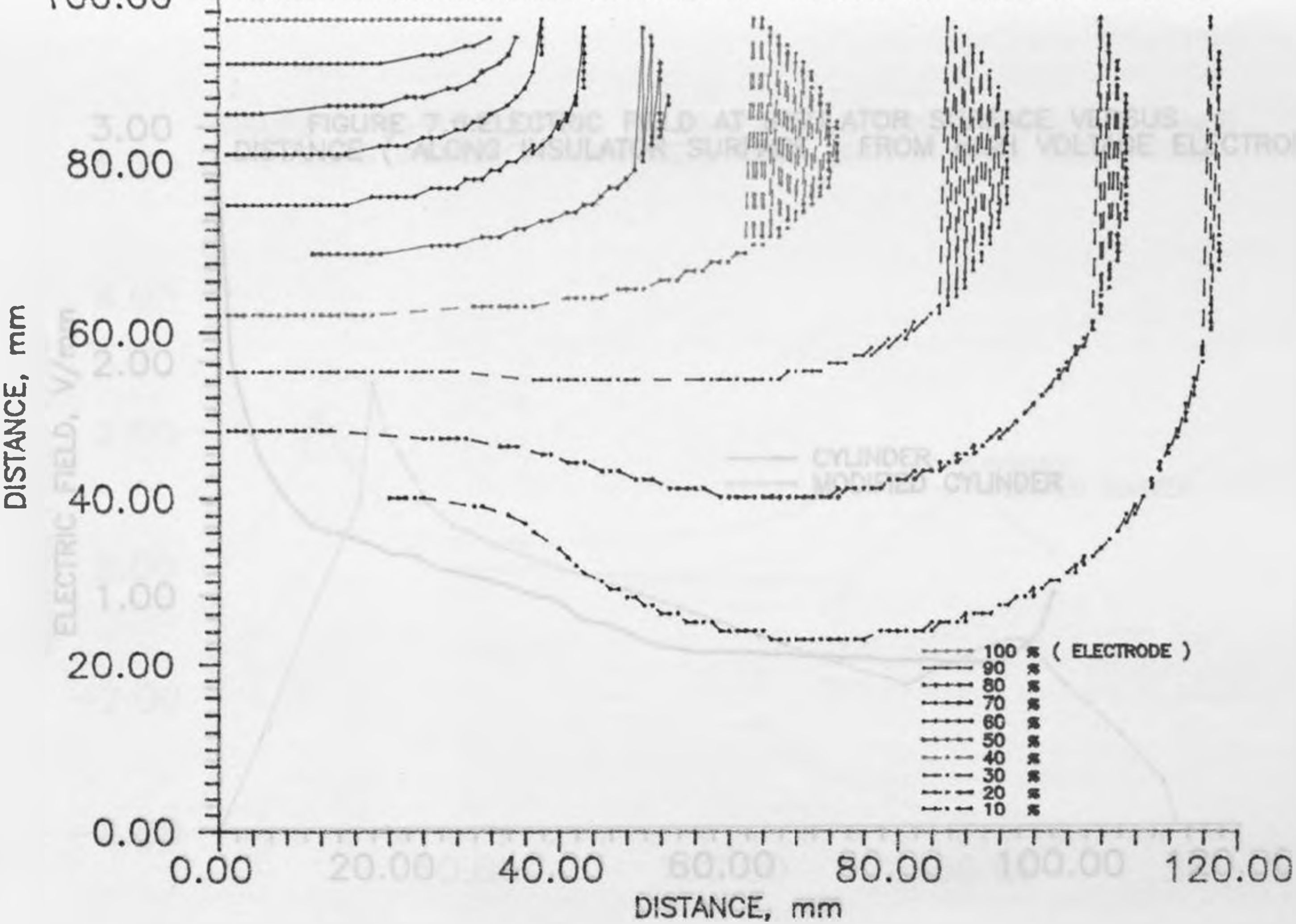


FIGURE 7.5:EQUIPOTENTIALS FOR AN AIR-GAP BETWEEN TWO CIRCULAR ELECTRODES

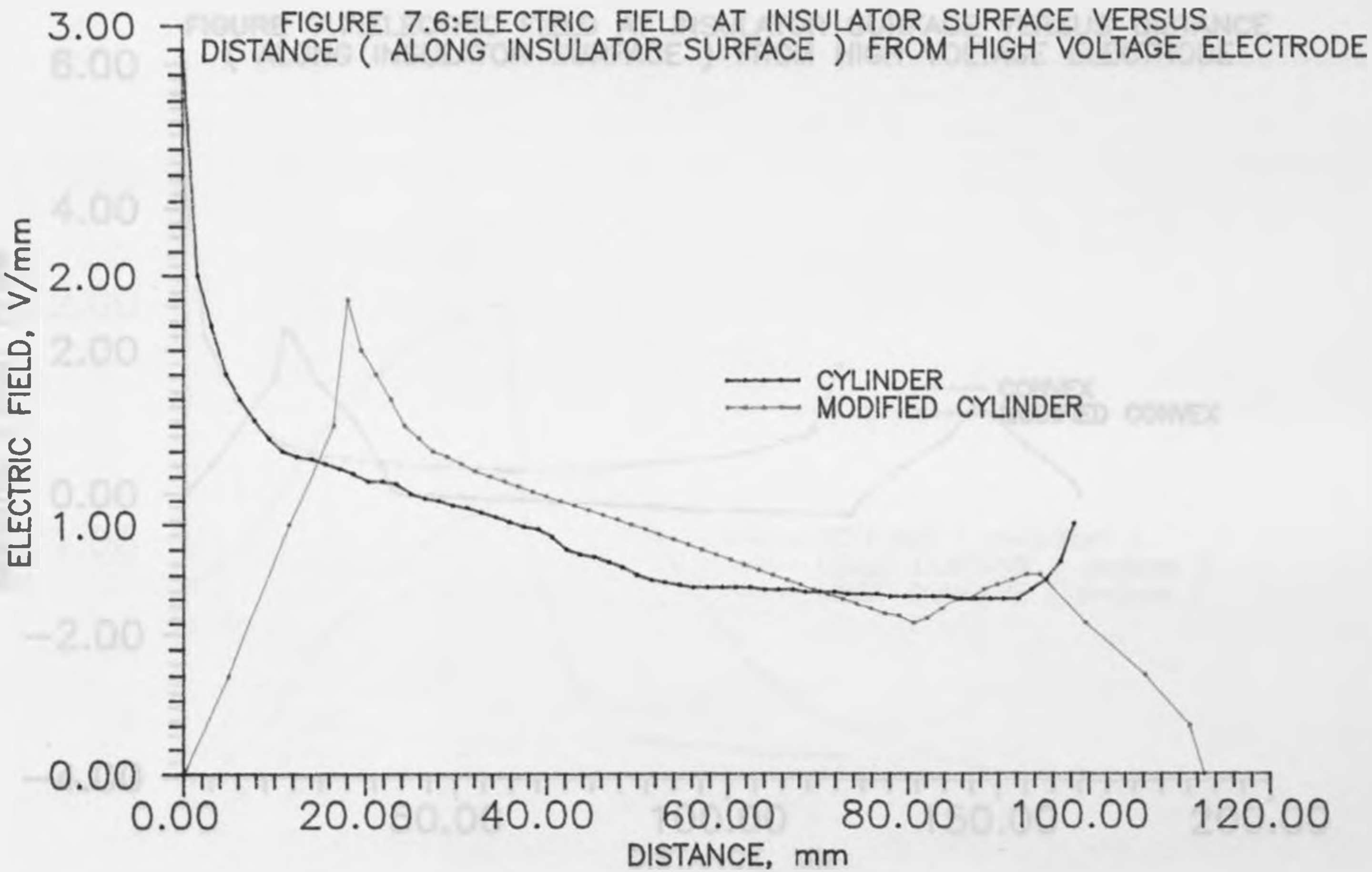


FIGURE 7.6:ELECTRIC FIELD AT INSULATOR SURFACE VERSUS DISTANCE (ALONG INSULATOR SURFACE) FROM HIGH VOLTAGE ELECTRODE
3.00
2.00
1.00
0.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00
ELECTRIC FIELD, V/mm
DISTANCE, mm
CYLINDER
MODIFIED CYLINDER

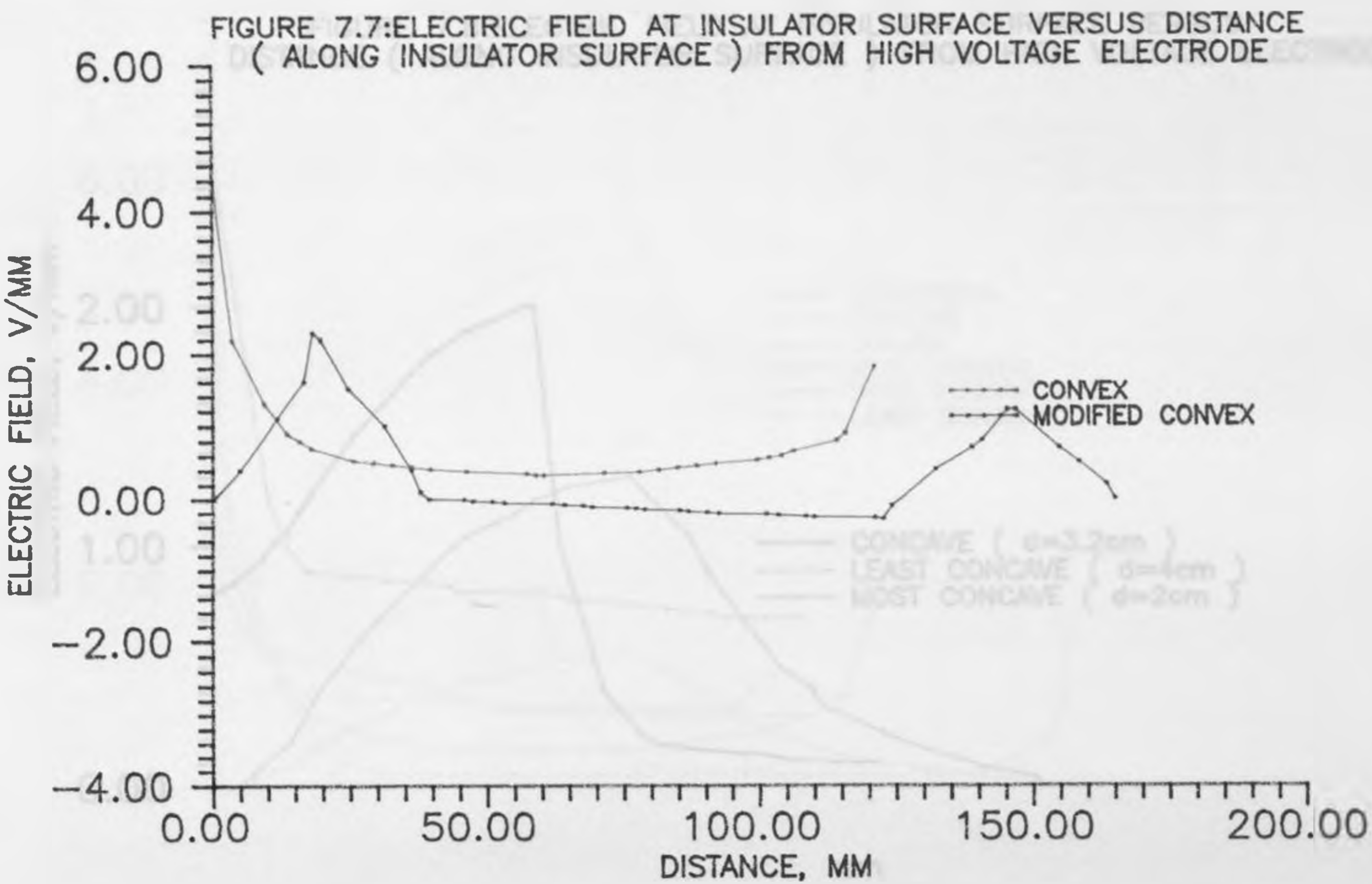


FIGURE 7.7:ELECTRIC FIELD AT INSULATOR SURFACE VERSUS DISTANCE
(ALONG INSULATOR SURFACE) FROM HIGH VOLTAGE ELECTRODE
6.00
4.00
2.00
0.00
−2.00
−4.00
ELECTRIC FIELD, V/MM
0.00
50.00
100.00
150.00
200.00
DISTANCE, MM
CONVEX
MODIFIED CONVEX

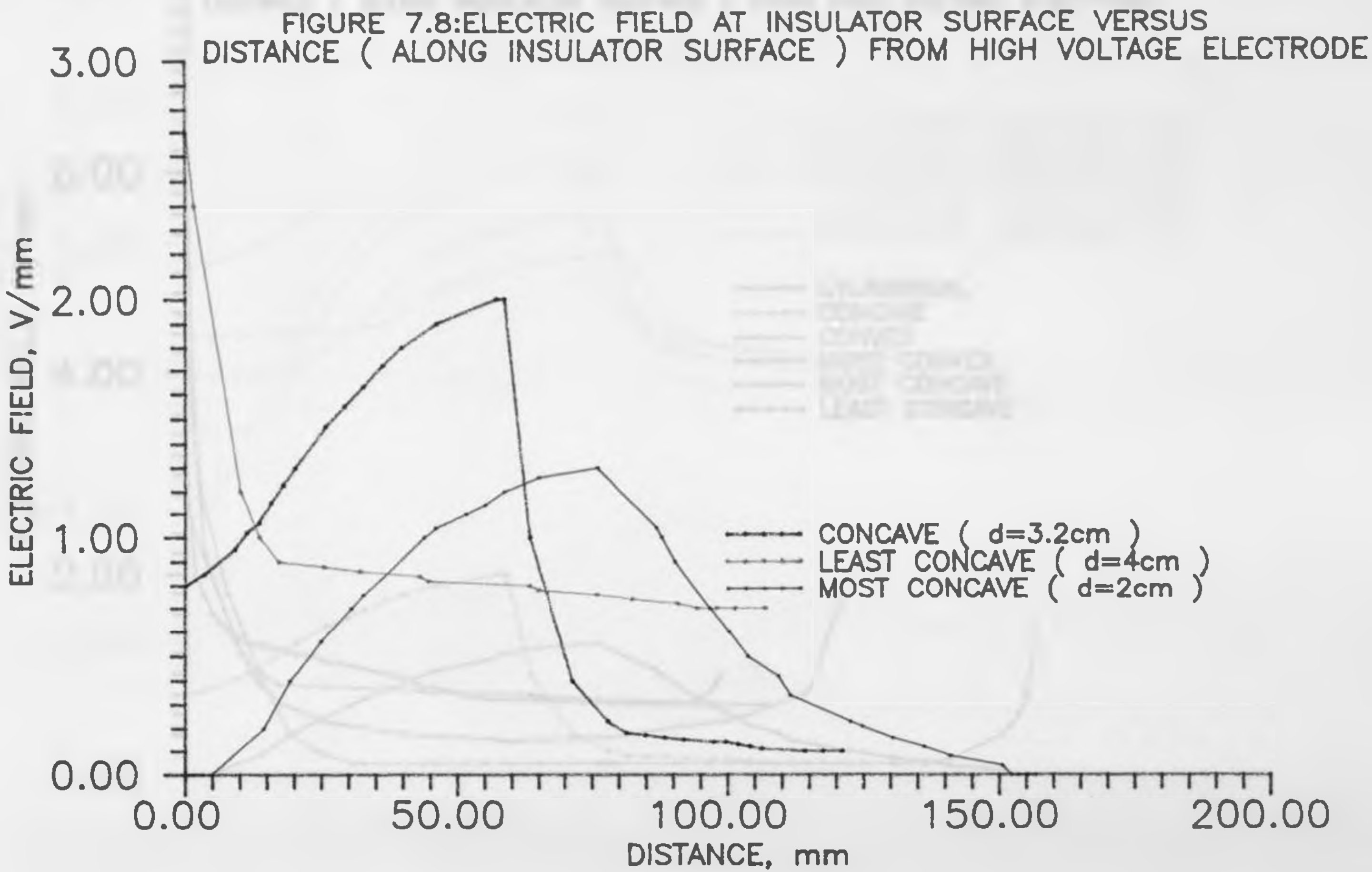


FIGURE 7.8:ELECTRIC FIELD AT INSULATOR SURFACE VERSUS
DISTANCE (ALONG INSULATOR SURFACE) FROM HIGH VOLTAGE ELECTRODE
3.00
2.00
1.00
0.00
ELECTRIC FIELD, V/mm
0.00
50.00
100.00
150.00
200.00
DISTANCE, mm
CONCAVE (d=3.2cm)
LEAST CONCAVE (d=4cm)
MOST CONCAVE (d=2cm)

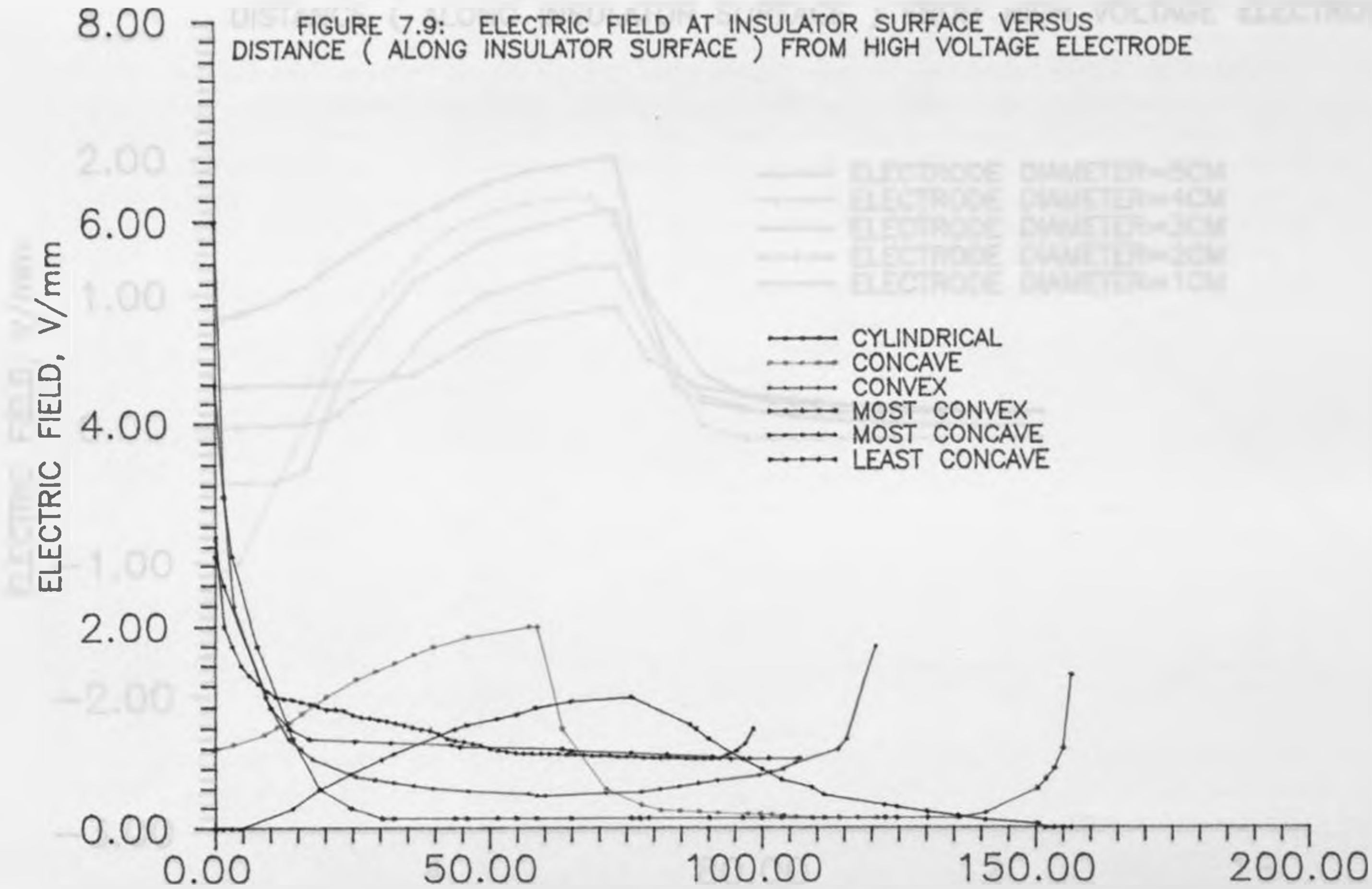


FIGURE 7.9: ELECTRIC FIELD AT INSULATOR SURFACE VERSUS DISTANCE (ALONG INSULATOR SURFACE) FROM HIGH VOLTAGE ELECTRODE

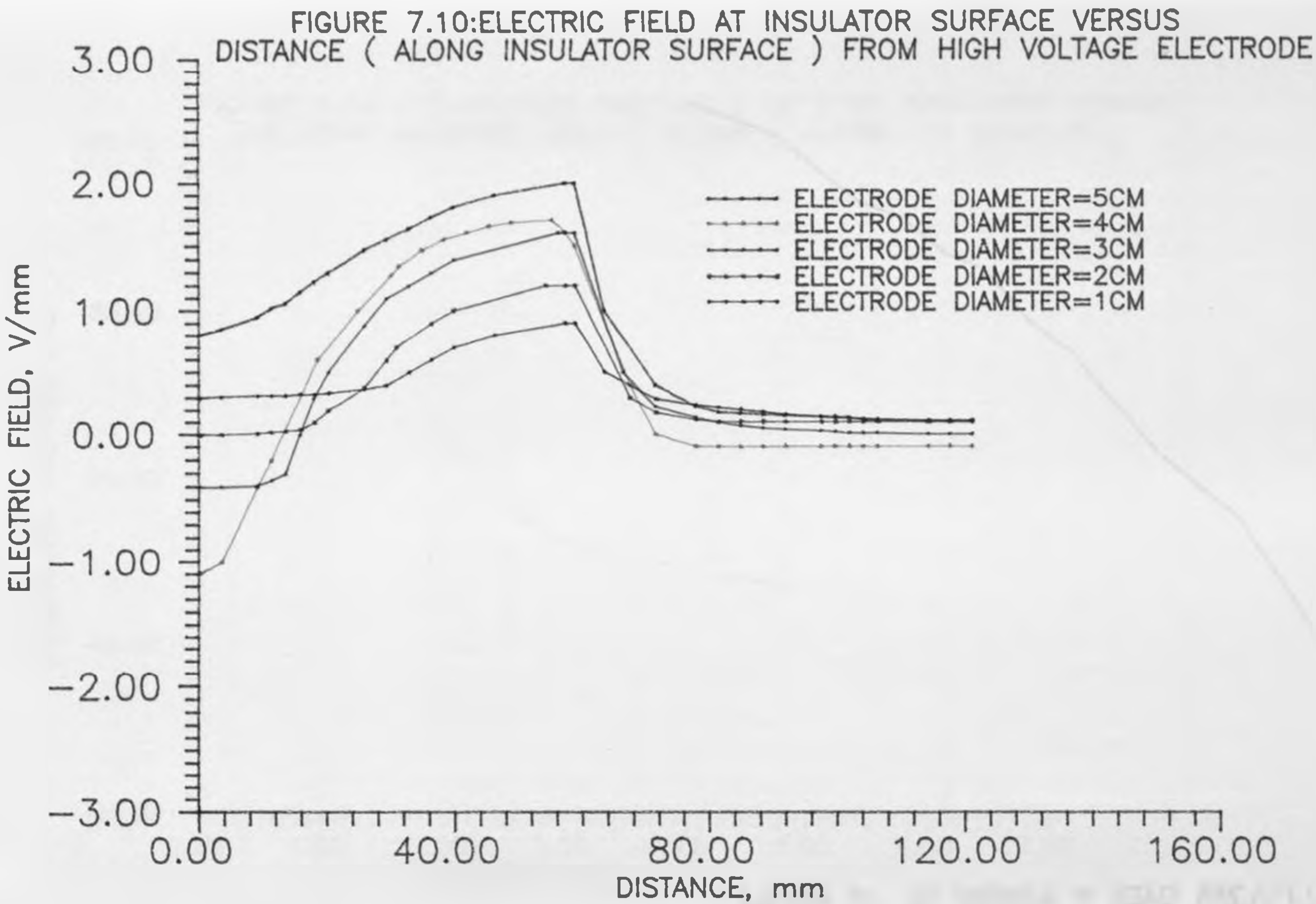


FIGURE 7.10:ELECTRIC FIELD AT INSULATOR SURFACE VERSUS
DISTANCE (ALONG INSULATOR SURFACE) FROM HIGH VOLTAGE ELECTRODE
3.00
2.00
1.00
0.00
−1.00
−2.00
−3.00
ELECTRIC FIELD, V/mm
0.00
40.00
80.00
120.00
160.00
DISTANCE, mm
ELECTRODE DIAMETER=5CM
ELECTRODE DIAMETER=4CM
ELECTRODE DIAMETER=3CM
ELECTRODE DIAMETER=2CM
ELECTRODE DIAMETER=1CM

FIGURE 7.11: VARIATION OF LEAKAGE CURRENT OF A DRY CONCAVE INSULATOR UNDER 11/√3kV OVER A PERIOD OF 10 HOURS

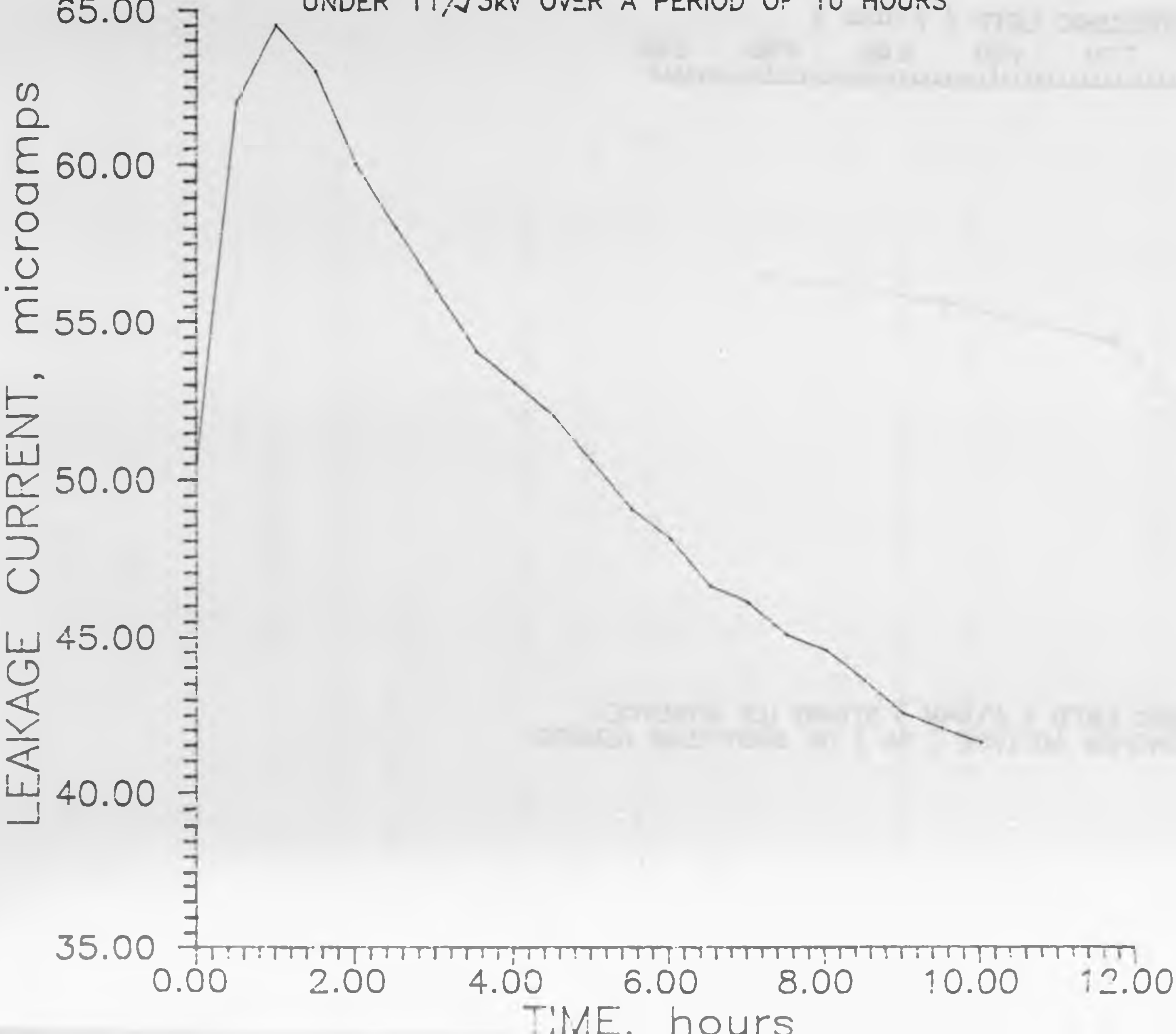
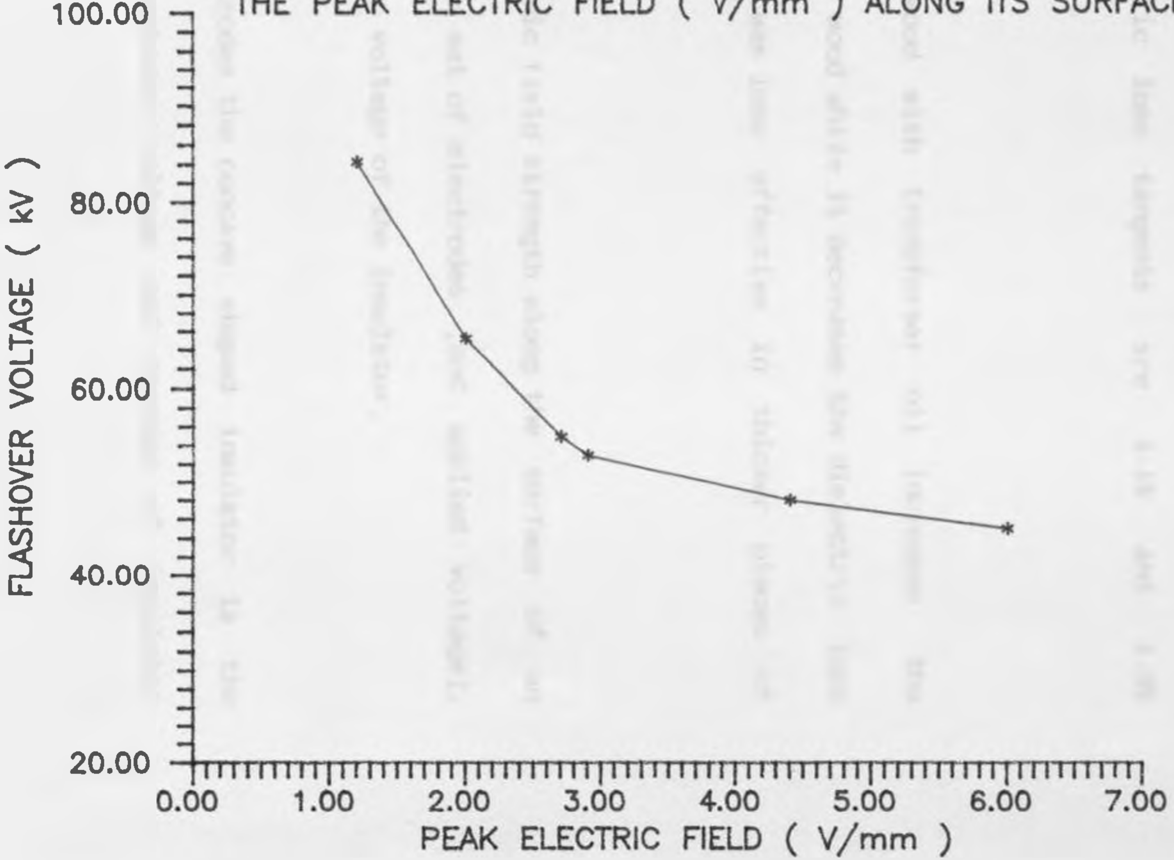


FIGURE 7.12 : FLASHOVER VOLTAGE (kV) OF INSULATOR VERSUS THE PEAK ELECTRIC FIELD (V/mm) ALONG ITS SURFACE.



8.0 CONLUSIONS

1. All the dry woods studied have higher dielectric strength across the grains than along the grains.

2. Elgon Teak was found to have the highest dielectric strength of 90kV/cm across its grains and 79kV/cm along its grains. The corresponding dielectric loss tangents are 4.6% and 4.8% respectively.

3. Impregnation of wood with transformer oil increases the dielectric strength of wood while it decreases the dielectric loss tangent. Impregnation was less effective in thicker pieces of wood.

4 The higher the electric field strength along the surface of an insulator (for a given set of electrodes ,and applied voltage), the lower the flashover voltage of the insulator.

5. With circular electrodes the concave shaped insulator is the best in terms of flashover voltage and economy of insulator material.

6. Oil varnishes are not effective in keeping out moisture from wood exposed to high temperatures and high humidities for long periods.

9.0 RECOMMENDATIONS FOR FUTURE WORK

1. Rapid removal of moisture from thick pieces of wood results in the wood cracking. In this study thin pieces (thickness less than 3mm) were found not to crack when dried rapidly (using an oven at 105^{0}C for 4 days). It is possible that minute cracks that are not visible to the naked eye are developed. Artificial seasoning should be employed even though it takes a much longer time (as long as six months). This allows the wood (however thick it may be) to dry completely without developing any cracks.

2. The **GenRad 1689 Precision RLC Digibridge** used in the measurement of loss tangent does its measurements at a voltage of one volt. This voltage cannot cause an electric field intensity, in the gas cavities, that is strong enough to initiate ionisation. This then means that the loss tangent measurements carried out in this study do not take into account the presence of any voids in the specimens. More reliable results would be obtained if the measurements were carried out at much higher voltages.

3. The mechanical properties of the woods should be looked into (that is, the tensile and compressive strengths) so that the limits

of the mechanical loading that can be safely accomodated is known. This mechanical loading could also have some effects on the electrical insulation characteristics. A knowledge of these effects is essential if wood is to be used as an electrical insulator in places where it is exposed to high mechanical stresses.

4. In some applications wood is likely to be exposed to temperatures well above room temperature at which its characteristics were studied in this study. The effects of the combined electric and cyclic thermal loading on the longterm dielectric strength of wood should be investigated.

5. Studies on the effectiveness of silicone varnishes in keeping out moisture under harsh atmospheric conditions should also be conducted.

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